

Ensuring Reliability of Reinforced Concrete Structures of "Northern Installation"

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Abstract. One of the directions in active management of the building structures design reliability is the correction of functional models of the criterial efficiency based on the specific conditions of their operation. With respect to the reinforced concrete structures of the "northern installation", such an approach predetermines the necessity to consider kinetics and statistical patterns of wear under systemic and cyclical impacts of low negative temperatures and humidity. Concurrently, the task of project assurance of equitability with usual structures of the "northern installation" for the duration of the expected service life is considered. In the first approximation, this task is proposed to be solved by correcting significant parameters of the concrete's constructive properties in correlation with the kinetics of exhaustion of the concrete's projected (controlled) frost resistance. This work presents the results of statistically representative generalization of the change in strength, modulus of elasticity and ultimate deformations in cryogenic and thawed states under cyclic impact of temperatures up to minus 40°C. Based on these results, the dynamic models of dependency of concrete's standardized characteristics on its frost's resistance exhaustion level have been developed.

1. Introduction

Active management of the reliability of buildings and structures on a design stage requires the consideration of all probable unfavorable situations during the projected period of their intended use. With respect to reinforced concrete structures intended for operation in severe climatic conditions, this calls for, in addition to regulated situations, the analysis of cases caused by the physical and time patterns of the changes in the stress-strain condition and by modification of structure and wear due to the impact of negative climatic temperatures and humidity.

An exact analytical assessment of such situations is practically impossible due to multiplicity and uncertainty of the factors of external impact as well as the ambiguity of reaction (response) of concrete and reinforced concrete elements. It seems reasonable to use engineering forecasts with the use of the models considering a stochastic character and physic-technical features of the analyzed processes of interaction between materials and environment in the time aspect [1-8].

2. Methods of research.

One of the approaches to the search for possible solutions in this area is based on the objectively confirmed, socially and economically acceptable reliability of reinforced concrete structures designed in accordance with the regulated requirements and operation under usual conditions [9,10]. With this approach, the design task of reinforced concrete structures of the "northern installation" is reduced to



the correction of regulated analytical models of the criterial dependencies of efficiency, ensuring their equitability with the elements for normal environment. Its practical realization is based on determining the necessary and sufficient coefficients of reliability γ_{di} , the use of which with the established (required) probability A_i after t years (service lifetime) for all working conditions of efficiency leads to the equation:

$$P_i \{F_i \leq \gamma_{di} R_i(0)\} = A_i \quad (1)$$

where P_i – projected probability of execution of i - parameter of operational fitness of the structure.

With a sufficient accuracy for practical purposes, the consequences of prolonged processes of frost destruction occurring to conventional and reinforced concrete can be approximated in the form of deterministic random dependences of the following type

$$R(t) = R_0 f(t) \quad (2)$$

where $R(t)$ – random function of time and random argument R ; $f(t)$ - Deterministic function characterizing the experimentally established kinetics of wear a-priori taken in the form of a linear, exponential, power or polynomial dependence. [11].

The determination of such dependencies on the basis of the experimental data of direct tests of the reinforced concrete elements is practically difficult due to economic reasons. The reliability forecast becomes possible through indirect assessment based on the analysis of various factors predetermining the kinetics of parametric failure of structures in severe climatic conditions. Based on the specific tasks of this study, such assessment can be based on the parameters of concrete and reinforcement:

- Included in the normative analytical models of efficiency of the structure;
- Sensitive to cyclic temperature-humidity impact;
- Controlled by standardized test methods.

The differential statistical analysis [12] of the parameters of the criterial equations of strength, rigidity and fracture toughness of reinforced concrete structures shows that the parameters of the strength and deformation properties of concretes most closely correspond to the above requirements given in the distribution patterns of their random realizations.

In this case, the time factor is analyzed in connection with the level of exhaustion of the resource of their frost-resistance as follows:

$$m = N_{eq} / F$$

where N_{eq} – number of cycles of climatic temperature-humidity impact which is equivalent to the standard one; F - concrete brand for frost resistance.

It becomes possible to generalize various experimental data and indirectly assess the dynamics of changes in the reliability of structures at different stages of operation in severe climatic conditions.

3. Results and their analysis

To develop dynamic models of the regulated parameters (RP) of exhaustion, the targeted tests of samples (100x100x400 mm) prepared from the concrete brand B25 and standard brand for frost resistance F270 have been performed. The comparable indicator FR in the accelerated ($T = -42^\circ\text{C}$) method of testing is 35CFT.

At the age of about 180 days, ultrasound calibration of the samples followed by water saturation, cyclic freezing in thermobaroclave TBV 8000 and thawing in water was performed. Once the required number of cycles was achieved, the samples were tested for compression and splitting in the continuous loading mode with automatic recording of the required parameters. The periodicity of testing was established considering the extreme character of the change in the strength of concrete at the CFT and the physical regularity of its frost destruction as a process of initial compaction of the structure, formation and accumulation of microfractures (Berg, O. Y.) [13].

The number of simultaneously tested samples was in the range of 12-18 items and depended on the observed distribution in the experiment results. The used loading speed and thermal insulation allowed to ignore negligible (1-3 °C) increase in temperature when testing concrete in the cryogenic state.

The restoration of the distribution density of the RP is performed using the maximum likelihood method [14], which enables one to derive asymptotically efficient probabilistic models from the samples (experimental data) of a limited volume. Concurrently, the acceptability (consistency) of the empirical and theoretical distributions was estimated by the Pearson criterion as an indicator minimizing the errors from the a-priori acceptance of the distribution hypothesis [15].

The Table 1 presents the results of statistical processing of the concrete's prismatic strength. The acceptable reliability of the normal character of its distribution in the initial and cryogenic states at all stages of frost resistance tests is confirmed. However, the probability of a gaussian approximation decreases in the process of exhaustion of the frost resistance's resource. At the final stage of the impacts, the reliability of the normal, equiprobable distribution of Laplace-Charlier is practically the same. Note that the values of the mean and normative quantiles determined from these distributions differ insignificantly (5-7%). A more significant distribution kinetics is observed in the tests of thawed concrete. By the time of exhaustion of the FR resource, the equiprobable approximation is characterized by a higher correlation with the empirical distribution than the normal one (Pearson's criterion is 0.37 versus 0.023).

Table 1. Changes of concrete strength under CFT for compaction

Condition	Level of impact, m	Approximating distribution	Pearson criterion	Statistics of distribution			
				Average, MPa	Dispersion, MPa ²	Variability, %	5% -quantile, MPa
Initial	0	Normal	0.513	24.0	9.12	12.5	19.1
	0.11	Normal	0.736	33.4	13.76	11.1	27.4
Cryogenic	0.86	Normal	0.414	22.4	11.63	15.2	16.8
	1.29	Normal	0.062	21.0	19.10	20.8	13.8
	0.29	Normal	0.270	24.5	12.10	14.2	18.8
Thawed	0.86	Equiprobable	0.370	20.2	29.71	27.0	12.5
	1.29	Equiprobable	0.051	19.1	26.11	27.0	10.6

The established transformation of the distributions is confirmed by the kinetics of the determining statistics characterized by a faster growth of dispersion, especially in the thawed state. The non-identity of their changes leads to a difference in the dynamics of the mean values and the standardized (5%) strength quantiles and, as a consequence, the differentiation of the corrective procedures (2). The processing of numerous [4,6,16,17] experimental data using the method of orderly minimization of the empirical risk [18] resulted in the following approximating dependences of the change in compressive strength:

$$\bar{R}_b(m) = R_{bo} (1 + 0,167m - 0,335m^2) \quad (3)$$

$$R_{ba}(m) = R_{ba}(0) (1 - 0,109m - 0,194m^2 - 0,106m^3) \quad (3a)$$

where \bar{R}_{bo} , $R_{ba}(0)$ – initial (prior to freezing) average and 5% quantile of the value of the prismatic strength of concrete.

A similar approach was used for analyzing the kinetics of the change in the tensile strength of a CFT when the concrete is split in the thawed state (Table 2). Approximating the normal distribution of the received data is more likely until the exhaustion of about a half of the standard FR resource. Later, the equiprobability character of the Rbt density is more reliable. The transformation of distribution functions practically does not affect significant statistics (expectation and 5% quantile), the dynamics

of which insignificantly differs until the exhaustion of concrete frost resistance. From the engineering point of view, it can be described by a polynomial:

$$R_{bt}(m) = R_{bt}(0)(1 - 0,25m - 0,31m^2) \quad (4)$$

and is significantly different from the compression resistance kinetics of concrete.

Table 2. Changes^{*)} of concrete strength under CFT for tensile.

Stage	Level of impact, <i>m</i>	Approximating distribution	Pearson criterion	Statistics of distribution			
				Average, MPa	Dispersion, MPa ²	Variability, %	5% - quantile, MPa
1	0	Normal	0.1157	3.52	0.514	20.3	2.35
2	0.285	Normal	0.6065	3.17	0.354	18.8	2.03
3	0.470	Equiprobable	0.4159	2.83	0.389	22.0	1.85
4	0.855	Equiprobable	0.5317	1.94	0.233	24.8	1.19
5	1.143	Equiprobable	0.2324	1.02	0.138	36.8	0.40

^{*)} on corresponding cycle after thawing

The practicability of multifactor control and evaluation of the process of exhaustion of the performance of reinforced concrete structures of the "northern installation" is confirmed by the specificity of the change in deformation properties, in particular, the modulus of elasticity and limit of deformation (Tables 3 and 4). In the tests performed without prior centering and continuous loading of the thawed samples, a steady decrease in the initial modulus of elasticity is observed. Moreover, after the impact of cycles corresponding to 75-80% of frost resistance, the intensity of the decline of *E_b* increases and comes to about 600 MPa per cycle of impacts. By the time of exhaustion of the FR resource (*m* = 1), the decline of modulus of elasticity reaches 34% which is almost double comparing to the corresponding figure for *R_b(m)*.

Table 3. Statistics of normal distribution of initial modulus of elasticity.

Stage	Level of impact, <i>m</i>	Average, MPa	Dispersion, MPa ²	Coefficient of variability, %	Relative change of	
					average	5% -quantile
1	0	2.99	0.232	16.1	1	1
2	0.29	2.92	0.197	15.2	0.977	1
3	0.86	2.19	0.297	24.9	0.732	0.591
4	1.29	1.35	0.221	34.8	0.451	0.264

Table 4. Kinetics of ultimate deformation of concrete at CFT.

Condition	Relative level CFT, <i>m</i>	Statistics ^{*)} of distribution			5% -quantile ×10 ⁴		Relative change	
		Average, ε×10 ⁴	Dispersion, Dε×10 ⁴	Coefficient of variability, %	Lower (min)	Upper (max)	Average	5% - quantile
Freezing	0	11.2	3.03	15.6	8.27	16.96	1	1
	0.11	10.26	3.55	18.3	7.18	14.61	0.92	0.87
	0.86	16.56	13.30	22.0	10.58	18.10	1.49	1.28
	1.29	24.70	41.07	25.9	14.21	35.22	2.22	1.72
Thawing	0	16.92	11.2	19.6	11.48	22.36	1.00	1
	0.29	20.00	12.52	17.7	14.19	25.81	1.18	1.23
	0.86	33.41	86.8	28.1	18.01	48.79	1.98	1.57
	1.29	65.71	438.3	31.9	31.3	100.07	3.88	2.73

^{*)} under Gaussian approximation of distribution

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