Strength kinetics of bent reinforced concrete elements in the process of deep freezing

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Abstract. The article discusses the acceptability of standardized regulatory approaches to the assessment of kinetics of the carrying capacity of bending reinforced concrete elements during cooling and freezing. Taking into account the physical consequences of frost destruction of concrete (layer-by-layer destruction) and employing numerical integration method, statistically representative samples of strength indicators for model beams were obtained, corresponding to experimental $\sigma_b(t)$-$\varepsilon_b(t)$ diagrams at various levels of freezing to minus 60°C. The necessary dependences of $\sigma_s$-$\varepsilon_s$ were taken according to recommendations of the norms. A comparative analysis of the statistics of samples obtained was performed for concretes with equilibrium (W = 1.7%) and increased (W = 3.7%) humidity with reinforcement $\mu = 0,5÷4,0\%$. The non-identity of dynamics of the bearing capacity of the bent elements and pure concrete is established. An increase in the resistance to bending is likely, and its intensity depends on humidity, temperature and reinforcement. The most significant increase is expected in over-reinforced elements. However, its implementation is problematic due to the increased likelihood of brittle fracture. Acceptable convergence of the values calculated (according to Code of Practice 63.13330) and expected with the required assurance (99.73%) at equilibrium humidity and cooling to minus 40°C is confirmed. In conditions of high moisture content and deeper cooling, the required assurance is not achieved.
The defining requirement of the current method of calculating building structures is the selection and justification of technical solutions that exclude the occurrence of regulated limit states during the design life.

It implies the need for consideration and analysis in the design of all possible situations of interaction between structures and the external environment, including steady, special (emergency) and transitional impacts. The latter could be periodic (cyclical) impacts leading to the development of fatigue phenomena with various cumulative effects. In particular, for reinforced concrete structures intended for operation in harsh climatic conditions, those effects are associated with significant changes in the stress-strain state and metastability of the structure and structural properties [1-4].

The analysis of consequences of such situations is associated with a probabilistic assessment of the kinetics of changes in the design conditions for the performance of structures at various stages of exhaustion of their frost resistance. In view of the objective (for technical and economic reasons) lack of statistically representative data of direct testing of structural elements, indirect methods based on numerical simulation of the desired indicators become appropriate. Therefore, standard functional models of strength, stiffness and crack resistance are used, as well as experimental data on changes in their significant parameters under cyclic temperature-humidity (T-W) impacts.

Checking the possibility and correctness of such an approach to assessing the strength of normal sections of bending reinforced concrete elements at the stages of deep cooling is the main goal of this study.

The “family” of $\sigma_b-\varepsilon_b$ diagrams obtained during testing of prismatic samples (more than 200 pieces) made of concrete of design class B25 (Cement: Sand: Gravel: Water: 1:1,11:2,09:0,53 with the addition of LTD). The concrete age at the time of the T-W test was more than 4 months, the weight humidity $W = 1.6\%$ (“C” series) and $W = 3.7\%$ (“B” series). Cooling (freezing) of samples took place in a freezer at a rate of 10°C/h lowering and 4-hour stabilization at the design level. The time of testing samples (no more than 5 minutes) allows us to neglect the temperature change during its holding.

The loading was carried out in the mode of ensuring a constant deformation rate (0.5 mm/min), ensuring the adequacy of deformations to the level of the applied force and the possibility of registering the downward branch of the compression diagram. In parallel, a graphical record of the dependence of stresses on the absolute deformation, as well as tables in the form of text files with numerical values of all monitored parameters, were made automatically. Being converted into the Microsoft format, they are used for the numerical simulation of the sought for strength parameters [5].

The strength of normal sections of bent elements was determined using the numerical integration of stresses based on the $\sigma_b-\varepsilon_b$ deformation models.
determined experimentally and recommended by Code of Practice 63.13330 for reinforcement. The initial assumptions were as follows:

- the validity of the hypothesis of flat sections;
- the relationship between stresses and relative deformations of concrete and reinforcement corresponds to the diagrams of their deformation at the considered stage of T-W impacts;
- the possibility of the layer-by-layer destruction of the compressed zone of concrete, when the magnitude of the limit deformations is exceeded taking into account the downward branch ($\varepsilon_{b,ult}$).

The bearing capacity of a flexible concrete element is defined as [6, 7]

$$M = \sum_{l=1}^{m} \sigma_{bl}(Z_l) A_{bl} Z_{bl} + \sum_{j=1}^{k} \sigma_{sj}(Z_j) A_{sj} Z_{sj}$$

(1)

where all standard symbols of stresses ($\sigma$), areas ($A$) and coordinates of the center of gravity position ($Z$) refer to the corresponding layer of concrete and reinforcement.

The section of the element is considered as a multilayer structure consisting of m - layers of compressed concrete and k - layers of stretched reinforcement. It is assumed that stresses within the layer are distributed according to a linear law, and layers at the boundaries of which $\varepsilon_{bl} \geq \varepsilon_{b,ult}$ are excluded from the research. The iteration process consists of sequential variation of the height of the compressed zone with the experimentally determined value of deformation of the extreme compressed fiber section to achieve convergence of stresses in concrete and tensioned reinforcement with an accuracy of 0.1 H.

Below is a probabilistic statistical analysis of the results of numerical simulation for a virtual bent element with a cross section of 180 × 360 mm with one-sided reinforcement (A400, $\varepsilon_e = 0.025$) in the range of values $\mu = 0.5$ – 4.0%.

Taking into account the targets and the research method used, the relative change in the expected indicators during cooling is fundamental and significant is, while their absolute values are not.

The selective kinetics of the average strength indicators of normal sections is characterized by the curves shown in Fig. 1, 2. As noted earlier [8], it is different from the kinetics of strength and deformability of concrete and also depends on the humidity and the level of reinforcement. With natural humidity, the character of changes in the moment and strength of concrete with decreasing temperature is almost the same. The difference is in the dynamics, which is determined by the level of reinforcement and, as a result, the probability of destruction along the compressed zone. Therefore at levels of $\mu \geq \mu_R$ the increase in the strength of a bent element is predetermined by an increase in the strength of concrete. However, at temperatures below – 40°C, a decrease in the moment kinetics is
noticeable, which can be explained by the appearance of new physical patterns of structural modification upon freezing of the moisture in capillary pores [9, 10].

With moisture content corresponding to the level of atmospheric saturation and amounting to about 70% of the critical level (according to V.M. Moskvin) [1], a significantly greater dynamics is observed in the moment increase at the cooling stage to 0°C and freezing to –20°C. Further, its practical stabilization is possible with the reinforcement not exceeding the border level. In all cases, there is an increasing lag in the strength of structures from concrete strength. It increases with decreasing temperature, which indicates the limited ability to realize the full potential of resistance to its deformative characteristics [11-14].

The presence of experimental and analytical samples of representative volume made it possible to carry out a statistical generalization and a probabilistic forecast of the values of the appropriate assurance. Using the standard convergence criteria [15, 16] for each of them, the most acceptable approximating theoretical distribution was established, followed by estimation of dispersion, coefficient of variation, and 0.1% quantile. The minimum values of the latter were considered a criterion for compliance with the normative (according to Code of Practice) and experimental strength data at various stages of testing [17, 18].

The dynamics of the dispersion of bearing capacity of bent elements in the process of their freezing (Fig. 3, 4) is predetermined by the initial moisture content. With its high saturation (“B” series) the monotonous continuous decrease in dispersion is most likely, especially at the stages of cooling and initial ice formation. The observed kinetics is almost independent of the degree of reinforcement.

A completely opposite picture is expected in the process of freezing of elements with equilibrium (with surrounding environment) humidity (“C” series). The cooling stage is accompanied by a sharp (more than 3-fold!) increase in dispersion, which stabilizes to (18 ÷ 65%) of the initial value with a subsequent decrease in temperature. Moreover, its value is significantly higher for normally reinforced sections. The noted features are observed in the kinetics of the coefficients of variation, which is confirmed by the comparable identity of the relative values of increase in strength predicted by the average values and minimum quantiles of any level of assurance.

Of undoubted interest is a comparative analysis of the values of carrying capacity determined by Code of Practice 63.13330 ($M_{cp}$) and the probabilistic prediction of numerical simulation data with assurance of 99.73% ($M_{0.1}$ - 0.1% distribution quantile) [19, 20]. It has been established that when reinforcing with $\mu \leq 1.5\%$, functional normative dependences give an optimistic result with an acceptable (2÷12%) excess of the calculated level of reliability and independent
of humidity and freezing temperature. With greater reinforcement, the excess of theoretical strength indicators increases, especially at the initial (+20°C) and zero stages of cooling. The opposite ratio ($M_{cp}/M_{ci} \leq 1$) should be expected for over-reinforced cross sections ($\mu \geq \mu R$), high moisture content and deep (below –20°C) freezing.

**Conclusions**

1. The kinetics of the carrying capacity of bending reinforced concrete elements at low temperature and freezing is ambiguous and not identical to the dynamics of the strength and deformability of concrete. It significantly depends on the moisture content and the level of structures reinforcement.
2. Cooling and freezing of structures is accompanied by an increase in their strength of varying intensity. When reinforcement $\mu \leq (0.6 \div 0.7)\mu R$, it is within the accuracy limitations of the experimental-analytical method used. For over-reinforced elements, regardless of humidity, one should expect a substantial (more than twofold) increase in bearing capacity. However, the practical realization of this potential is problematic due to the corresponding decrease in the elastic-plastic properties of concrete.
3. Calculations based on normative functional models provide satisfactory (with assurance of at least 99.73%) convergence with the results of probabilistic analysis if the reinforcement is below the above-mentioned level. In situations of reinforcement exceeding that level and accompanied by high humidity, normative assessments of the carrying capacity of to-be-frozen structures are below the required assurance values.
Figure 1. Kinetics of strength of concrete and reinforced beams during cooling (series “C”).

Figure 2. Dynamics of increase in bearing capacity with decreasing temperature (series “B”).
Figure 3. Dynamics of change in the dispersion of moment in water-saturated elements.

Figure 4. The change in the dispersion of strength of the beams during cooling and equilibrium moisture (series "C").
References

[1] V.M. Moskvin, B.M. Kapkin, B.M. Mazur, A.M. Podvalny Resistance of concrete and reinforced concrete at low temperatures (Moscow: Stroyizdat) p 131 (1967)

[2] F.M. Ivanov Research of frost resistance of concrete, Protection against corrosion of building structures and increase of their durability (Moscow: Stroyizdat) pp 109–16 (1969)

[3] B.I. Pinus, I.V. Homjakova Structural properties of the concrete in cryogenic condition European Applied Sciences 7 pp 17–21 (2013)

[4] E.A. Guzeev, B.I. Pinus Assessment of the reliability of reinforced concrete structures at low temperatures Concrete and reinforced concrete 10 pp 9–10 (1984)

[5] B.I. Pinus, J.N. Pinus, I.V. Khomyakova Changes in the design properties of concrete during cooling and freezing Vestnik of ISTU 2 (Irkutsk) pp 111 – 115 (2015)

[6] SP 63.13330 2012 Concrete and reinforced concrete construction p 152

[7] D.J. Cook, P. Chindaprasirt A mathematical model for the prediction of damage in concrete cement and concrete research 11 pp 581-590 (1981)

[8] G.M. Vlasov, S.A. Bokarev (1984) Accounting for changes in the strength and deformation characteristics of concrete after alternate freezing and thawing Universities News "Construction and Architecture" 11 pp 112-114

[9] A.F. Milovanov, V.N. Samoilenko Accounting for influence of low temperatures at calculation of structures Concrete and reinforced concrete 3 pp 25–7 (1980)

[10] A.R. Collins The distruction of concrete by frost Journal of the Institute of civil Engeniering 23 (1994)

[11] A.N. Yudin, M.P. Konchiev, G.A. Tkachenko Deformations of compressed concrete under cyclic freezing and thawing Modern problems of construction (Donetsk) pp 12–18 (1970)

[12] G.I. Gorchakov, E.A. Guzeev, L.A. Seilanov Cryogenic destruction of reinforced concrete structures Concrete and reinforced concrete 1 pp 40–42 (1985)

[13] V.N. Durcheva Influence of negative temperature on the deformation of loaded concrete Izvestiya VNIIGa 103 (Leningrad: Energia) pp 216–222 (1983)

[14] A.N. Savitsky, V.M. Moskvin, V.N. Yarmakovskiy, M.M. Kapkin, Strength and deformation characteristics of concrete and reinforced concrete under the impact of cryogenic temperatures Increase in the durability of concrete and reinforced concrete under influence of aggressive environment (Moscow: Stroyizdat) pp 16–23 (1975)
[15] G. Kramer *Mathematical methods of statistics* (Moscow: Mir) p 648 (1975)

[16] V.V. Bolotin *Application of methods of probability theory and reliability theory in the calculations of structures* (Moscow: Stroiizdat) p 240 (1971)

[17] A.R. Rzhanitsyn *The theory of calculating building structures for reliability* (Moscow: Stroiizdat) pp 1978–1239

[18] 1974 *Recommendations for use of additional information to reduce the reliability test time* (Gorky) p 141

[19] B.I. Snarskii *On uncertainty of failures and its influence on optimization of reliability of structures* Problems of reinforced concrete constructions (Kuibyshev) pp 82–86 (1977)

[20] M.B. Krakovskiy *Algorithms of unconditional minimization methods for optimal design of reinforced concrete structures* Izvestya VUZov, Construction and Architecture pp 7–14 (1979)