Fatigue behavior of concrete in cyclic low-temperature impacts

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Abstract. Wear and tear of concrete and reinforced concrete structures in harsh climatic conditions is analyzed as a fatigue process with various cumulative failures. For the criteria of their prediction, it is proposed to use dynamic models containing the kinetics of changes of informative and sensitive indicators of the constructive properties of concrete during cyclical freezing and thawing (CFT). An experimental-analytical generalization of the measurement of the following indicators is presented: strength, components of deformations, cracking, and the energy potential of concrete destruction during the exhaustion of its frost resistance. It is proposed, as a first approximation permissible under the conditions of the onset of fatigue parametric failures, to take the level of external temperature and humidity effects equivalent to (ultimately) 85 ÷ 90% of the frost resistance mark.

1. Introduction

The principal distinctive feature of the new standard of building design [1] is the requirement of ensuring adequate reliability to the actual conditions during the design life of the structure. In the criteria of existing design methods, this means an exception with a priori established probability of the risk of occurrence of the design limit states including possible fatigue damage (deformation).

The necessity and peculiarities of taking into account the latter is that the fatigue measurements due to operational factors of fluctuating intensity at load levels lower than the values calculated by the bearing capacity lead to structural transformation and change in the initial structural properties up to the achievement of cumulative failure. Obviously, certain clarifications (adjustment) are needed for computational dynamic models of structures behavior as well as for the prerequisites used in normative methods for their calculation.

It is known that the regulatory approach to the design of concrete and reinforced concrete structures (Set of Rules 63.13330.2012) is based on the use of equilibrium equations and additional conditions that simplify calculation procedures. In particular, calculation of strength is based on replacing the actual stress distribution diagram in the compressed zone with a fictitious (rectangular) one, while the stress in the reinforcement is modeled by an empirical relationship that takes into account the deformative properties of the reinforcement and concrete.

The acceptability of such an approach, given the fatigue effects, is problematic. This is evidenced by the repeated correction of the normative models for determining the boundary height of the...
compressed zone and the results of experimental studies [2,3]. In our opinion, the observed differences are explained by the lack of consideration of the magnitude, sensitivity, and variability of deformation structures, which predetermine calculation errors upon replacing actual stress distribution diagrams on a rectangle.

The ambiguity of such procedures should be expected with probabilistic forecasts of the fatigue strength of reinforced concrete structures subjected to cyclic impacts with various associated cumulative effects. This is due to the fact that, with varying effects, the deterioration of concrete and reinforced concrete elements is an evolving time process [4,5], the intensity of which depends on their physical nature, differences, frequency and level of the resulting stress state. In addition, fatigue processes are associated with local deformations that can have positive (reduced structure heterogeneity, stress conference level, redistribution of stress, etc.) or negative consequences upon exceeding a certain level of damage accumulation.

The analysis of the specifics of fatigue deformation of concrete subjected to cyclic temperature and humidity impacts and the substantiation of the criteria parameters of cumulative failure constitute the target task of the present study.

2. Materials and methods

The kinetics of fatigue changes of the deformability of concrete was evaluated by the results of static short-term tests for axial compression of standard prismatic specimens subjected to various numbers of T-W cycles of effects (FTC). Prisms (100×100×400) and cubes were made of concrete of project class B25 (Cement:Sand:Gravel:Water = 1:1.75:2.9:0.45). The frost resistance of concrete determined according to the basic standard test method was 270 cycles. At the age of more than 180 days of normal hardening after ultrasonic calibration (rejection) of samples and 2-day water saturation, cyclic freezing was carried out to minus 42°C with thawing in water at temperatures of 18÷20°C. The sequence and duration of the daily cycle complied with the regulations of GOST 10060.0.

The periodicity of mechanical tests is taken into account in accordance with the physical laws of frost destruction, as a temporary fatigue process with ambiguous consequences, which can be conditionally divided into three stages:

a) initial, characterized by local changes with a predominance of the constructive effect;
b) metastable development (accumulation) of damage on each cycle of impact;
c) accelerated unstable destruction or pseudoplastic fracture.

The range of the corresponding cycles of thermal and humidity impacts was established by standard testing of cubes according to the basic method and was 0.3; 0.6; and ≥ 0.9 F-mark for frost resistance of concrete. At the appropriate time, prototypes were tested for axial compression in the mode of constant deformation rate of 0.05 mm/min with automatic recording of compression diagrams up to the moment of physical destruction. The absence of the procedure of preliminary centering of the samples makes it possible to obtain diagrams with a portion of the initial compaction (convexity in the direction of the deformation axis). The number of simultaneously tested prisms was 12÷18 pieces depending on the density of the results and their statistical representativeness.

3. Results and discussion

According to the objectives of this study, the kinetics of changes in the significant parameters of the structural properties of concrete in the process of exhausting the normative resource of its frost resistance is of undoubted interest (Figure 1). Significant differences mentioned earlier are clearly confirmed [6-8] such as ambiguity and non-identity of the dynamics of the strength, deformability indicators, as well as the integral assessment of resistance, indirectly estimated by the area of the $\sigma$-$\varepsilon$ diagram. This virtually eliminates the possibility of choosing a single criterion for the parametric failure of structures in the conditions under consideration and confirms the need for a differentiated approach depending on the analyzed indicators of serviceability.
Figure 1. Kinetics of changes of concrete strength and deformability in FTC.

Taking into account the physical laws of frost destruction and mechanics of concrete destruction, in the first approximation, a state in which the boundaries of the lower $R_{cr}^0$ and the upper $R_{cr}^u$ level of cracking almost coincide can be considered the ultimate fatigue. Physically, it is identical to achieving such a transformation of the structure, in which further continuation of the T-W impacts is fraught with risks of unstable and accelerated destruction due to the exhaustion of the potential of plastic deformation of concrete.

Similar conclusions also follow from the analysis of qualitative changes of the concrete structure deformations in FTC. The analysis of qualitative changes in the deformative properties of concrete was performed using a three-stage approximation of the experimental $\sigma$-$\varepsilon$ diagrams with the selection of the areas of the initial compaction of the structure ($\varepsilon_0$), the elastic-plastic ($\varepsilon_b1$) and pseudoplastic ($\varepsilon_b2$) deformations. Such a model representation allows for a gradual differentiated assessment of the accumulated fatigue changes and the residual resistance potential in the conditions of ordinary (free) and constrained deformation.

Figure 2, 3 shows the curves characterizing the average numerical values of the deformation components mentioned above and their fraction in terms of the compressibility limit $\varepsilon_b$ at the stages of T-W impacts. It is noteworthy that all the deformation parameters under consideration differ in various dynamics due to the physical features of the cumulative processes taking place. So, the deformations $\varepsilon_0$ are at first relatively constant and then are rapidly increasing at the stages of FTC exceeding about 60% of the frost resistance resource. Such kinetics is explained by the gradual predominance of the destructive effects of thermal and humid effects. From the standpoint of fracture mechanics [9], this is
due to the accumulation of microstructural damage preceding the formation of main cracks. An indirect confirmation of this is the mirror dynamics of changes in $\epsilon b_2$, which characterize the potential for resistance to microcracking. The share of these deformations is constantly decreasing, which confirms the noted earlier [10-16] fact of loss of the plastic properties of concrete during cyclic temperature and humidity impacts.

Figure 2. Relative change of energy potential of total ($S$), elastic-plastic ($S_1$), and pseudoplastic ($S_2$) deformation.

The moderate kinetics of the potential of the elastic-plastic deformation $\epsilon b_1$ attracts attention. With a relatively intense initial increase, their stabilization is subsequently observed at a level of about half the maximum compressibility of concrete. Obviously, this can be explained by the limited (in terms of potential) positive effect of cumulative changes due to the formation of more dense and homogeneous structures of concrete in FTC.

Figure 3. Change of deformation components.
In view of ambiguity of changes in the FTC parameters of strength and deformative properties of concrete, it seems appropriate to take them together by analyzing a summary measure of the energy resource of resistance (S) indirectly estimated by the area of the σ-ε diagram. The relative kinetics of the total value (S) and its components in the ascending (S1) and descending (S2) deformation sections are shown in Figure 4. The extreme nature of changes in all considered parameters is observed, which confirms the fatigue patterns of concrete wear during cyclic temperature and humidity effects [17-19]. It is noteworthy that by the time the normalized frost resistance is exhausted (35FTC), the potential of the elastic-plastic resistance $S_1$ practically corresponds to the initial state, and the pseudoplastic resistance ($S_2$) decreases by 25%. This is an additional confirmation of the frosty transformation of the concrete structure characterized by a decrease in its ability to plastic redistribution of internal forces.

![Figure 4. Kinetics of fractional content of components in complete concrete deformations.](image)

In addition, we note that the high sensitivity of concrete deformability to cyclic T-W impacts indicates the need for correcting the calculated dynamic (taking into account the time factor) models for determining the strength of off-center-compressed and bending reinforced concrete elements. In particular, we are talking about the refinement of empirical dependencies resulted from the replacement of the actual curvilinear stress distribution diagrams of the compressed zone with rectangular ones [3,20].

The kinetic analysis was performed by numerical simulation for a bent reinforced concrete element of rectangular cross section with reinforcement substantially below the boundary level. The experimental values of the σb-εb diagrams at the corresponding stages of T-W impacts are taken as the initial data. The required height of the compressed zone of the element was estimated based on the conditions of uniform distribution of stresses and unchanged (equal to the initial) energy potential of the resistance. It has been established that with impacts not exceeding 60÷65% of the normalized frost resistance index, the initial design value of the “fictitious” height of the compressed zone is maintained. However, further, a sharp (25÷29%) increase in the required (according to the accepted energy criterion) height of the compressed zone is expected and, as a result, an increase in the probability of brittle sudden destruction follows [4,13,18].

4. Conclusions
Under a probabilistic prediction of durability, wear of reinforced concrete structures in severe climatic conditions can be considered as a fatigue process with various cumulative failures. It is advisable to
use $T-W$ sensitive indicators of crack formation, deformation components, and the energy potential of concrete resistance as calculation criteria for the limiting state of operational fitness for fatigue.

Prior to the establishment of standardized and differentiated specified criteria according to the operational requirements of the limitations, it is proposed to consider the maximum permissible (under fatigue conditions) level of temperature and humidity effects of the environment equivalent in effect to the exhaustion of 85% of the concrete frost resistance.

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