Energy aspects of low-cycle fatigue of fibropolypropylene concrete

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Abstract. The article discusses the issues of fatigue of conventional and fiber-reinforced cement-containing composites under low-cycle force impact that are adequate to the probable level of response of structures to background seismic manifestations. The response of the structures is analyzed as an oscillatory process whose generalized characteristic is the indicator of absorbed energy. The results of dynamic tests of prismatic samples with different levels of maximum stresses in the range \(R_{\text{crc}} - R_{\nu}\), and a zero-asymmetry coefficient are presented. The tests were carried out in a hard mode with a constant deformation rate of 0.04 mm/s and continuous cyclic recording of all internal resistance parameters. A significant increase in the fatigue life of cement-containing composites when reinforced with fibrillated short polypropylene fibers has been established.

1. Introduction
Operation of building structures is objectively associated with periodic (cyclic) dynamic impact of a variable (including alternating) intensity at a level below the calculated normative value. The corresponding response of the structures represents a damped oscillatory process whose physical laws and kinetics are determined by the ability to dissipate (absorb) energy due to the potential of internal resistance (internal friction) \([1-3]\). In this case, the heterogeneity of multiphase, polycrystalline structures with various deformation properties of the components determines the dual nature of external energy consumption on elastic (reversible) and inelastic (irreversible) consequences. This is experimentally confirmed by the presence of a hysteresis loop in the diagrams of cyclic loading and unloading \([4-16]\).

The most common and relatively objective indicator of the internal resistance of materials and structures is considered the energy absorption coefficient \(\psi\), which characterizes the fraction of energy of inelastic deformation in the total energy of the cycle of oscillatory process \([16]\). Given the features of the work and operational requirements, it is advisable to link the internal resistance of building structures with kinetics of the process of damping of forced vibrations. The latter, according to the hypothesis of W. Voigta \([5]\), is proportional to the rate of deformation. However, according to Martyshkin-Sorokin \([3]\), it depends on the absolute magnitude of the forced deformations. Despite the fundamental differences between these theoretical premises, these functional models allow us to obtain results comparable with experiments. However, the practical use of these theoretical predictions is limited and explainable \([1, 5, 6]\) in that the internal resistance is not a property of material. Its value...
varies over a wide range (see table IV.2 [16]) and depends on the type, level, duration of loading, type of structures, its stress state, history of deformation, and other factors.

The metastability of the values and the ambiguity of the forecasts of internal resistance potential predetermine the practicability of an experimental approach to its assessment giving consideration to the specifics of the likely expected oscillatory processes. Below is a comparative analysis of kinetics of the damping potential of ordinary (OB) and fibropropylene-reinforced (FPB) concrete under low-cycle impacts that are adequate to the background geo-activity of seismic regions.

2. Methodology of experimental research
Numerical modeling of oscillatory processes with the use of scaled accelerograms of various intensities [7] suggests that background earthquakes with a magnitude of 4-5 points can cause stresses in reinforced concrete structures that exceed the level of their resistance to the formation and development of microcracks. Consequently, there are objective conditions for the development of irreversible processes that reduce the conditioning quality of materials and structures.

To assess the kinetics and consequences of multiple dynamic effects, cyclic compression tests of two series of samples were carried out:

«OB» – conventional concrete with ratio of components Cement:Sand:Gravel:Water =1:1.42:3.57:0.55 and cement consumption 380 kg/m³ (II/A-3 32.5B Angarsk cement);

«FPB» – concrete of the same composition with 1.5% volumetric content of fibrillated polypropylene fibers with a diameter of 0.8 mm and length of 40 mm manufactured by Technopolymer, LLC Irkutsk.

Their fractional composition and ratio (table 1) were selected based on recommendations [8, 9] on the design of optimal dispersion-reinforced structures according to criteria of deformation interaction of the matrix and fiber as well as on ensuring the anchoring of fibers until the moment of destruction. Production of samples (cubes and prisms) and temperature and humidity conditions of 28-day storage were performed in accordance with GOST.

| Table 1. Fractional composition of concrete and fiber concrete of experimental samples. |
|-----------------------------------------------|
| Series | Gravel, kg/m³ | Sand, kg/m³ | Cement, kg/m³ | Water, l/m³ | Fiber (1.5%), kg/m³ |
|-------|---------------|-------------|---------------|-------------|-------------------|
| OB    | 1357          | 540         | 380           | 210         | –                 |
| FPB   | 1357          | 540         | 380           | 210         | 13.85             |

After 3-4 months of laboratory storage, ultrasonic rejection of the samples was carried out and controlled strength indicators of concrete of both series were determined (table 2).

| Table 2. Standardized concrete quality indicators. |
|-----------------------------------------------|
| Series | Ultrasound | Prismatic | Module | Boundary | Deformations | El. |
|        | time, μcs | Strength | elasticity | level | of microdestruction | Deformations | El. |
|-------|------------|----------|------------|--------|-----------------|--------------|-----|
| OB    | 28.19      | 40.61    | 28804     | 0.47   | 0.88            | 21 159 64 66 233 |
| FPB   | 28.86      | 35.06    | 21503     | 0.32   | 0.74            | 45 170 65 61 235 |

¹Rate of deformation 0.04 mm/s; base of measurement 400 mm.

ε₀ – initial deformations;

εᵣ – elastic deformations;

εₚᵣ – plastic deformations;

ε₀ₙ – deformations corresponding to descending branch;

εᵤ – deformations corresponding to maximum strain.
Dynamic tests were carried out on test complex Instron 5989 in an automatic cyclic loading-unloading mode with a constant rate of deformation and recording of all parameters of the force impact and response of the sample. Force control was carried out with an accuracy of 1 kN with dynamometric sensor Instron 2580-305. Recording of deformations in both directions was done with the use of extensometers of motherboard series Instron with an accuracy of 1·10^{-5} u.r.d. (unit of relative deformation). In this case, longitudinal deformations were measured on a full base (400 mm). We note that the presence of a special hinge mechanism in the test complex made it possible to achieve automatic centering of loading and, as a result, obtaining full $\sigma$-$\varepsilon$ diagrams. Concurrently, on each cycle of loading and unloading, consumed energy, module of elasticity, volume changes and other parameters were monitored.

Selection of the regime of cyclic power actions was carried out taking into account:
1. results of numerical modeling of the probable consequences of background seismic activity;
2. physical laws of the development of fatigue phenomena in cement-containing composites as a process of formation, development and accumulation of microcracks [10, 11-14];
3. dependence of the kinetics of fatigue processes on the level of $\sigma_b$ and strain differential $\rho$;
4. indicators of strength and deformability of prototypes established in preliminary tests (table 2).

In total, this determined the feasibility of 3 modes of cyclic impacts with parameters $\eta = \sigma_b/R_b = 0.6; 0.7; 0.8$ with zero strain during unloading ($\rho = 0$). At all stages, the rate of loading corresponded to a constant deformation rate of the samples 0.04 mm/s. Significant response parameters were measured automatically after the first and every 10 cycles.

General view of diagrams of cyclic effects and resistance is presented in Figure 1.

![Figure 1. Diagrams of loading a) and response b) of the sample during dynamic tests.](image)

3. Results and discussions
Initial potential of internal resistance of the samples ($W$) was established during their monotonic compression up to destruction with the indicated earlier rate of deformation. It corresponded to the total area of the $\sigma$-$\varepsilon$ diagram and is analyzed taking into account the reversibility (irreversibility) of the consumed energy. It is assumed that the energy consumed in the section of conditionally elastic deformation $W_e (0-\varepsilon_{\text{max}})$ is reversible, but on the descending branch ($W_{\text{pl}}$), it is consumed on irreversible infrastructural changes. A comparative assessment of the energy potential of concrete and fiber-reinforced concrete is characterized by the data in table 3.

It is noteworthy that the increase in the static internal resistance of the fiber-reinforced composite occurs due to the predominant growth of its elastic component. It is this feature that can be a determining factor in the stability of fiber-reinforced concrete under cyclic dynamic impact.

To test this hypothesis, dynamic tests of prismatic samples made of concrete of both series were carried out. The kinetics of energy indicators at the stages of cyclic loading are presented in table 4.

Here presented are the data characterizing the behavior of the samples in the first loading cycles. It differs significantly from the corresponding indicators at the stages of steady-state cyclic impact.
According to modern concepts [10, 15], this can be explained by the one-time (initial) energy consumption on intrastructural transformation accompanied by the elimination of random stress concentrators, weak cohesive bonds, and other technologically caused imperfections. In responses of constructions, such phenomena are traced in the formation of irreversible residual deformations with ambiguous consequences. In particular, under the conditions of subsequent free deformation, a decrease in energy consumption is expected due to the decrease in the intrastructural strain-deformed state. Under constrained conditions (for example, in statically indeterminate systems), the accumulation of residual deformations contributes to the development of fatigue processes.

### Table 3. Energy parameters of initial internal resistance (MPa mm) / mm.

| Indicator | Index | Series | OB   | FPB   | FPB/OB |
|-----------|-------|--------|------|-------|--------|
| General   | $W$   |        | 105500 | 132500 | 1.25   |
| Elastic   | $W_e$ |        | 46250  | 69900  | 1.51   |
| Plastic   | $W_p$ |        | 59250  | 62600  | 1.06   |
| Relative  | $W_p/W$ |       | 0.562  | 0.472  | 0.84   |

### Table 4. Change in energy parameters during cyclic impact.

| Series | Mode $\eta$ | Value of parameters on cycles of loading |
|--------|-------------|------------------------------------------|
|        | First 100th 200th | $W_i$ | $\Delta W_i$ | $W_i | $\Delta W_i$ | $W_i | $\Delta W_i$ | $W_i | $\Delta W_i$ |
| OB     | 0.6         | 13600 | 3972 | 0.29 | 0.038 | 10538 | 958 | 0.09 | 0.009 | 10377 | 813 | 0.08 | 0.009 |
|        | 0.7         | 22157 | 8843 | 0.40 | 0.084 | 15932 | 1438 | 0.09 | 0.014 | 15400 | 1617 | 0.105 | 0.0153 |
|        | 0.8         | 20499 | 6703 | 0.33 | 0.063 | 15356 | 1273 | 0.083 | 0.012 |
|        | 0.85        | 26700 | 3300 | 0.123 | destruction |
| FPB    | 0.6         | 11904 | 3569 | 0.30 | 0.027 | 9434 | 615 | 0.06 | 0.0046 | 9126 | 717 | 0.08 | 0.0054 |
|        | 0.7         | 15632 | 5209 | 0.33 | 0.039 | 12337 | 950 | 0.08 | 0.0071 | 13508 | 1163 | 0.086 | 0.0088 |
|        | 0.8         | 18310 | 5289 | 0.29 | 0.040 | 14734 | 1005 | 0.07 | 0.076 |
|        | 0.85        | 18200 | 1570 | 0.086 | no destruction |

* $W_i$ – initial energy potential;  
* $W_i$ – consumed energy of loading in the $i$-th cycle  
* $\Delta W_i$ – hysteresis loop area of the $i$-th cycle  
* $\psi_i$ – coefficient of absorption in the $i$-th cycle

Comparing the energy costs in the 1st loading cycle ($\eta = 0.6$), we find that they, with almost the same amount of consumed energy, are equal to 13% of the initial potential of the internal static resistance of concrete and 9% of fiber concrete. However, an increase in the maximum stress level ($\eta = 0.7$) is accompanied by significant differences in readings. In samples of ordinary concrete, consumption of both external and absorbed energy sharply increases, 1.63 and 2.23 times, respectively. Similar parameters of fiber-reinforced concrete are 1.31 and 1.46 times, respectively. Both compositions are initially characterized by high damping ability ($\psi = 0.3-0.33$).

Due to significant difference in the initial resistance potential of concrete vs. fiber-reinforced concrete, the kinetics of its realization in the temporal aspect is advisable to analyze in terms of relative changes in parameters. From the fatigue degradation point of view, the most significant indicator is the change in the cost of absorbed energy $\Delta W_i$ in the cyclic process to the total potential. For the latter, the internal resistance index under monotonic loading up to the moment of destruction is adapted, which is significantly lower than the energy of cyclic loading [16].

The cyclic energy absorption coefficient $\psi$ is characterized by a nonmonotonic trend with an increase in the range and number of cycles, which is explained by the difference in the physical laws of fatigue processes with an increase in level of loading. However, in comparative terms, fiber
concrete given the adopted test base is characterized by a significantly lower portion of cyclic energy consumed on crack formation and, as a result, greater fatigue durability.

Such conclusions are more clearly confirmed by comparing the coefficients of specific energy consumption on residual consequences (hysteresis of the cycle) to the initial potential of internal resistance. Under comparable conditions of cyclic impact, they are almost 2 times lower for the fibropolypropylene composite.

4. Conclusions
1. Reinforcement of cement-containing matrices with short fibrillated polypropylene fibers can significantly increase the potential of their internal resistance and fatigue durability of the composite.
2. The kinetics of exhaustion of the fatigue strength of fibropolypropylene concrete under low-cycle impact is most dependent on the amplitude of cyclic loading.

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