Low-cycle fatigue of concrete with alternating loads

B I Pinus, A S Kustov

Institute of Architecture, Construction and Design, Irkutsk National Research Technical University, 83, Lermontov St., Irkutsk 664074, Russia

E-mail: pinus@istu.edu

Abstract. The article deals with issues related to the assessment of fatigue effects during alternating effects of the external environment. The results of an experimental statistical analysis of the strength, deformability and resistance energy of concrete after 100 cycles of variable tension in the differential range are given. Strength and modulus of concrete elasticity is established as an index relatively stable in magnitude and density of distribution. Also, significant changes in the structure, size and distribution of ultimate deformations and their components are found. To the greatest extent, this relates to the potential for plastic deformation, which is confirmed by the drop in the damping capacity and the brittle nature of concrete destruction.

1. Introduction

Long-term operation of reinforced concrete structures is objectively associated with a certain probability of stress-strain state fluctuations due to changes in the magnitude and conditions of application of loads, background manifestations of seismic activity, alternating temperature differences and other factors [1-6]. In a comparative cyclical manifestation, such impacts can be (attributed) classified as few-repeated (FRI) and the structural-mechanical changes caused by them as low-cycle fatigue. Their distinctive feature is the ambiguous cumulative nature of the consequences, as well as the interdependence of the impact magnitude (number of cycles) and the functional response of the object (type, level and range of stress drops and deformations) [7-10].

The multi-factoriality and a priori numerical uncertainty of significant parameters practically exclude an analytical approximation of such fatigue processes and justify the experimental substantiation of the fatigue limit condition criterion and its allowable change in the conditions of the expected FRI. At the same time, in the overwhelming majority of studies performed, such impacts are modeled as cyclic changes in loads with controlled values of the maximum stress level ($\eta = \sigma_{\text{max}} / \sigma_{\text{ult}}$) and asymmetry coefficient ($\rho = \sigma_{\text{min}} / \sigma_{\text{max}}$). The test results are limited and contradictory [11-13], which is explained by significant differences in the compositions, methods of loading (unloading), and measurements.

2. Results of experimental studies

Below are the results of experimental studies of changes in the structural properties of concrete after cyclic alternating loadings simulating the likely response of reinforced concrete elements in the background manifestations of seismic activity.
Prismatic samples (100×100×400 mm) made of concrete B25 (Cement:Sand:Gravel:Water = 1: 2.4: 2.5: 0.49) of standard curing conditions were tested. At the age of two months, after ultrasound calibration (Pulsar 1.2.), half of the samples (21 items) were subjected to 100 cycles of tension (Figure 1), followed by axial compression.

![Schematic test model.](image)

The loading was carried out in an automatic mode (Instron 5989 complex) with a constant pace of deformation, recording of $\sigma - \varepsilon$ diagrams, time, dissipation energy, and change in volume of the sample. In this case, the forces were monitored with a dynamometer sensor (accuracy 1 kH). Deformations were measured in the longitudinal and transverse directions with the help of special complete extensometers with an accuracy of $1 \cdot 10^{-5}$ %o. Control samples (17 pieces) were tested for axial compression with a similar loading system with a deformation rate of 0.04 mm/s. The equipment used and the loading mode made it possible to obtain complete tensile (compression) diagrams, including residual deformations after FRI cycles ($\varepsilon_{res}$) and deformation in the area of spontaneous fracture ($\varepsilon_{u,pl}$) (Figure 1).

Batches of compression diagrams of controlled and subjected to FRI samples are presented in (Figure 2). Their visual comparison indicates a significant change in the magnitude, distribution density and character of concrete after the cyclic tensile impacts of the assumed intensity. A more detailed analysis was performed using a structural model (Figure 1), which takes into account the physical characteristics of concrete behavior at various loading levels in the ascending and descending stages of resistance. In this case, $\varepsilon_0$ characterizes the initial (including residual after FRI) deformations; $\varepsilon_u = \varepsilon_0 + \varepsilon_c + \varepsilon_{pl}$ – maximum shortening in free deformations of concrete; $\varepsilon_{ult} = \varepsilon_u + \varepsilon_{u,pl}$ is the compressibility potential in constrained deformation conditions. In such model interpretation and statistical representation of testing, it becomes possible to qualitatively and quantitatively assess the fatigue effects of previous impacts.
Figure 2. Diagrams of concrete compression before (above) and after FRI.

Table 1. Statistical data of distribution of concrete strength parameters and deformability.

| Indicators                  | Measurement | Denotation | Initial values |                        | After FRI cycles |                        |
|-----------------------------|-------------|------------|----------------|------------------------|------------------|------------------------|
|                            |             |            | Average        | Coef. of variation, %  | Average          | Coef. of variation, %  |
|                            |             |            |                |                        |                  |                        |
| Compression strength       | MPa         | $R_b$      | 27.0           | 13.7                   | 26.2             | 15.6                   |
| Tensile strength           | MPa         | $R_{bt}$   | 2.80           | 12.9                   | 2.84             | 11.6                   |
| Modulus of elasticity      | MPa         | $E_b \times 10^3$ | 8.44         | 13.3                   | 8.75             | 13.7                   |
| Initial deformations       | °/00        | $\varepsilon_0$ | 0.62           | 54.8                   | 0.53             | 76.7                   |
| Elastic deformations       | °/00        | $\varepsilon_e$ | 3.2            | 13.3                   | 3.0              | 10.6                   |
| Plastic deformations       | °/00        | $\varepsilon_{pl}$ | 0.94           | 34.2                   | 0.73             | 33.2                   |
| Pseudoplastic deformations | °/00        | $\varepsilon_{u,pl}$ | 1.24           | 41.8                   | 0.97             | 40.4                   |
| Maximum deformations       | °/00        | $\varepsilon_{b,u}$ | 4.8            | 9.5                    | 4.3              | 11.3                   |
| Ultimate deformations      | °/00        | $\varepsilon_{b,ub}$ | 6.11           | 10.0                   | 5.24             | 10.6                   |
Significant statistics of the distribution of controlled indicators of concrete properties are given in Table 1. The range of 95% probability is determined taking into account the most acceptable (by Kolmogorov criterion [14]) approximating distribution. The high probability of transformation of the latter in the process of development of fatigue processes during cyclic drops of compressive forces was indicated earlier by us [15, 16]. Here it is appropriate to emphasize that most of the parameters (before and after FRI) are approximated by various, different from the “Gaussian”, distributions with a high value of the relevance coefficient (60÷85%).

According to statistically representative experimental data on the accepted base of preliminary cyclic impacts, there are no significant changes in the strength of concrete under compression and tension for a range of values of 95% probability. Indicators of deformability and its structure are characterized by greater sensitivity to FRI. So the average values of the modulus of elasticity are relatively stable, but a clear positive asymmetry in the distribution of $E_b$ leads to a significant decrease in its 5% quantile. As for the deformations corresponding to the maximum strength ($\varepsilon_{b,u}$) and conditional limit ($\varepsilon_{b,u0}$), the reduction of their average values is 10÷14%, while 5% quantiles is 15÷20%.

In accordance with the adopted structural model of deformations, the kinetics of changes in its component parameters is assessed. There is a slight decrease in the initial ($\varepsilon_0$) and elastic ($\varepsilon_e$) deformations with a tendency to increase the spread with a positive asymmetry of the distribution. The most tangible changes occur with components that characterize the ability of concrete to plastic deformation. The decrease in $\varepsilon_{b,ult}$ is 22÷40%, and in $\varepsilon_{b,u}$ is 22÷25% with large values for indicators of the lower limit of 95% probability. At the same time, their share in the deformability decreases, which indicates embrittlement of concrete and a decrease in its damping properties.

![Figure 3](image.png)

**Figure 3.** a) reconstructed diagrams of averages $\sigma_b - \varepsilon_b$ before (—) and after FRI (— -); b) reconstructed diagrams $\sigma_b - \varepsilon_b$ based on values of 5% quantile before (—) and after FRI (— -).

Significant differences in the changes in the FRI strength and deformative characteristics of concrete emphasize the need to search for criteria of fatigue wear, taking into account the features of their joint transformation. Such is considered the energy potential of resistance indirectly estimated by the area of the compression diagram. Taking into account the established statistical factors, model diagrams $\sigma_b - \varepsilon_b$ corresponding to the average and boundary (95% of the probability range) experimental values of the monitored parameters (Figure 3) have been constructed.
The results of numerical modeling of the energy resource \( W_{pl} \) and its elastic component \( W_e \) are presented in Table 2.

| Level of probability | Elastic-plastic resistance potential \( \times 10^{-4} \) | Elastic resistance potential \( \times 10^{-4} \) | \( (W_{pl} - W_e) \times 10^{-4} \) | Damping coefficient, \( \eta \% \) |
|----------------------|------------------|------------------|------------------|------------------|
|                      | Initial state    | After FRI        | Initial state    | After FRI        | Initial state    | After FRI        |
| Average              | 996              | 863              | 133              | 432              | 393              | 564              | 470              | 56.6             | 54.4             |
| Lower 95%            | 750              | 502              | 248              | 279              | 242              | 471              | 260              | 62.8             | 51.8             |
| Upper 95%            | 1366             | 1042             | 323              | 647              | 575              | 719              | 467              | 52.6             | 44.8             |

They confirm the presence of fatigue effects from the preceding compression tests of alternating effects. This is confirmed by the decrease in the total resistance potential \( W \), averaging 13.3% and density of its distribution causing a greater (24÷35%) reduction in the parameters of 95% probability. It should be noted that the energy indicators of the elastic resistance \( W_e \) are characterized by statistical stability and a small (9÷11%) decrease. This suggests that the overall kinetics of energy resistance in FRI is determined by the ability of concrete to plastic deformation. This assumption is confirmed by the kinetics of the damping coefficient, determined by the ratio \( \eta = (W - W_e)/W \). Although its value, judging by the ratio of the average indicators of the considered parameters, is relatively stable, a significant decrease in the corresponding quantiles (> 17%) unambiguously indicates an increase in the probability of brittle fracture in the process of few-repeated alternating impacts.

3. Conclusions

1. Performance exhaustion of reinforced concrete structures can be regarded as a fatigue process of structural wear (modification) caused by few external variable impacts of various nature, magnitude, direction and intensity
2. Low-cycle fatigue of concrete is characterized by ambiguous and distinct changes in the values and distributions of normalized indicators of its strength and deformability, which determines the feasibility of their joint control and differentiation of the criteria for design situations and limit states with regard to operational requirements (conditions).
3. A distinctive feature of the considered fatigue processes is the different dynamics of changes in the average values and normalized quantiles of the indicators of the structural qualities of concrete, explained by the asymmetry of their distribution.
4. From a physical point of view, low-cycle fatigue is associated with a gradual decrease in the ability of concrete to plastic deformation and, as a consequence, to an increase in the probability of brittle fracture.

References

[1] Barashikov A Ya, Shevchenko B N, Valovoy A I and Gross 1985 Low-cycle concrete fatigue under compression Concrete and reinforced concrete 4 27–8
[2] Becheneva G V 1961 The strength of concrete with few-repeated loads Study on seismic resistance of buildings and structures (Moscow) pp 19–21
[3] Mailyan L R, Bekkiev M Yu, and Sil’ G R 1984 The work of concrete and reinforcement with few-repeated loads (Nalchik) p 55
[4] Rykov G V, Obledov V P, Mayorov E Yu and Abramkina V T 1992 Experimental studies of the processes of deformation and destruction of concrete under cyclic dynamic loads Construction Mechanics and Structures Calculation 1 10
[5] Sozonov P S and Pinus B I 2016 Statistical patterns of change in the strength of reinforced concrete structures under cyclic alternating impacts Seismic resistant construction Safety of buildings 6 33–6

[6] Rastorguev B S and Puhonto L M 1996 The main provisions of recommendations to the norms of design of structures for the impact of low-cycle short-term and long-term loads Collection of Scientific Studies Methods of calculation and design of reinforced concrete structures (Moscow: Moscow State University of Civil Engineering) p 15

[7] Arvanitaki N E 1972 On the issue of concrete strength under low-cycle loading XXXI Int. Conf. on Construction, Architecture and Technosphere Safety, Industrial and civil construction, theses (Moscow) p 25

[8] Kuzovchikova E A and Yashin A V 1976 Study of the effect of low-cycle compressive effects on the deformability, strength and structural changes of concrete News of universities. Construction and architecture 10 18

[9] Merkin A P and Fokin G A 1982 Kinetics of concrete destruction under cyclic loading News of universities Construction and architecture 1 23

[10] Kotov V A 1983 The influence of the type of stress on the ability of concrete to resist destruction in structures subjected to repeated alternating loads Dissertation for the degree of Candidate of Engineering Sciences 05.23.01 (Moscow) p 292

[11] Yashin A V 1977 Some data on deformations and structural changes of concrete under axial compression New about the strength of reinforced concrete (Moscow: Stroyizdat) p 272

[12] Grozdev A A 1978 Strength, structural changes and deformations of concrete. Collection of scientific studies Ed. By Grozdev A A (Moscow: Scientific Research Institute of Reinforced Concrete, Stroyizdat) p 297

[13] Kotov Yu I 1967 Strength of pre-compressed concrete under repeated loads In the collection: the seismic resistance of large-panel and stone buildings (Moscow: Central Science Research Institute of Building Constructions) p 159

[14] Ivchenko G I and Medvedev Yu I 2009 Introduction to mathematical statistics (Moscow: LKI Publishing house) p 600

[15] Pinus B I 2018 Consideration of cumulative effects at low temperatures impact Int. Scientific Conf. Investments, Construction, Real Estate: New Technologies and Special-Purpose Development Priorities (Irkutsk, Russia, April 26-27) vol 212

[16] Pinus B I, Kustov A S and Sergeev S I 2018 Statistical features of concrete destruction and background intensity of seismic impacts Int. Scientific Conf. Investments, Construction, Real Estate: New Technologies and Special-Purpose Development Priorities (Irkutsk, Russia, April 26-27) vol 212