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IDENTIFYING THE EFFECT OF LOW-CYCLE FATIGUE OF REINFORCED CONCRETE STRUCTURES ON THE PROPERTIES OF THE REDUCING COEFFICIENT UNDER THE ACTION OF A SEISMIC TYPE LOAD

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The object of research is seismic design, and the subject of the study is the determination of the reduction coefficient. One of the important problems of earthquake-resistant design is to determine the effect of low-cycle fatigue of reinforced concrete on the reduction coefficient and determine its optimal value. This problem is not disclosed and is not specifically taken into account in the standards for earthquake engineering when determining the maximum bearing capacity of types of structures due to the lack of study of the issue. To solve the problem, a series of experimental studies were carried out on low-cycle fatigue of reinforced concrete bending elements and frame units. The range of results of the reduction coefficient values and the degree of influence of monocyclic fatigue on the properties of the reduction coefficient are obtained.

A feature and characteristic of the results obtained is that the reduction coefficient Rμ depends on the nature of the hysteresis deformation pattern and the plastic life of structural elements estimated by the plasticity coefficient μ, which is significantly influenced by low-cycle fatigue manifested at peak accelerations of strong seismic impacts. The above test algorithm, the feature and characteristics of the results obtained made it possible to solve the problem under study.

The results obtained are accepted for practical use in the action of seismic loads: on the calculation of strength taking into account new low-cycle coefficients, reduction coefficients for determining the spectra of design reactions and seismic loads, taking into account energy absorption. New reduction coefficients are proposed for determining the spectra of calculated reactions and seismic loads

Keywords: seismic resistance, reinforced concrete structures, low-cycle fatigue, reduction and ductility coefficients

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1. Introduction

The design seismic loads prescribed in the codes of some countries for earthquake engineering are lower than the seismic loads determined in the assumption of elastic deformation of structures. Such a reduction in seismic loads in the standards of earthquake-resistant design is carried out with the help of load reduction coefficients. However, during strong earthquakes, the ability of the system to plastic deformations deteriorates due to the accumulation of damage caused by the cyclic nature of impacts, so the plastic reserve of structures may be insufficient to absorb the effect of seismic load.

In the proposed article, the object of research is seismic design, and the subject of research is the reduction coefficient under the action of seismic loads. In international engineering practice, when determining seismic loads using the linear spectral method, the elastoplastic operation of structural systems is taken into account in a simplified way using decreasing coefficients of behavior *R*μ or *q* coefficient according to Eurocode 8 [1], which reduce seismic effects determined by the spectrum of elastic reactions.

In fact, the reduction coefficient Rμ depends on the nature of the hysteresis deformation pattern and the plastic life of the critical sections of the structural system elements, estimated by the plasticity coefficient of μ, which is significantly influenced by the low-cycle fatigue of materials, which manifests itself at peak accelerations of strong seismic impacts. This factor has not yet been disclosed and is not specifically taken into account in the standards for earthquake-resistant construction when determining the maximum load bearing.

The more experimental studies are carried out, the sooner it will be possible to determine the limit of the function of the dependence of the reduction coefficient on low-cycle fatigue and the value of the plasticity coefficient $K\mu = f(M, \mu)$.

Therefore, studies devoted to the determination of the reduction coefficient under the action of a seismic-type load are relevant.

2. Literature review and problem statement

In the scientific work [2], the relevance of the study of low-cycle fatigue is noted: "The fatigue strength of materials is usually distinguished from the fatigue strength of structural elements, since the properties of the latter are influenced by a number of additional factors. This distinction is particularly appropriate to consider when considering low-cycle fatigue".

However, the authors, noting the relevance of the topic under study, do not touch upon the subject of research in their work. And in the conclusion of the article [3] it is shown that a decrease in stiffness leads to a decrease in the frequencies of natural oscillations and seismic loads. On the other hand, such a decrease is due to an increase in movements, which can cause great damage or even lead to the collapse of structures. The authors do not consider the effects of low-cycle fatigue on the reduction coefficient, which play an important role in the intensity of the seismic load on structures.

Interesting results from the point of view of earthquake engineering are presented in the paper [4]. It is shown that for solving problems related to seismic resistance, the left part of the graph at a small cycle n is important, often referred to as the area of low-cycle fatigue. Using this part of the graph, the coefficient of operating conditions of *mkr* is determined, which takes into account the small number of repetitions in earthquakes of large amplitudes and the short-term nature of their active part. However, the question of the number of cycles to which the material must be subjected in order for the results of the experiment to characterize its seismicity remains unclear.

An option for overcoming the corresponding difficulties can be the studies shown in [5]. A simplified method for estimating the seismic load reduction coefficient is shown, the elastoplastic work of structural elements is taken into account in a simplified way using the reduction coefficient $R\mu$ or the coefficient q of behavior according to Eurocode, which reduce seismic effects determined by the spectrum of elastic reactions. However, the article notes: "Solutions to the problem of low-cycle fatigue are largely related to the complexity of analyzing the stress state and fracture criteria in structural elements in the occurrence of elastoplastic deformations, especially given the lack of experimental data on the cyclic plasticity of concrete. The wide accumulation of experimental data is hindered by the great complexity and labor intensity of setting up an experiment for low-cycle loads of a high level. But there are still unresolved issues: the main difficulties are associated with the large natural dispersion of strength and deformation characteristics of concrete, as well as with the need to make high-precision measurements of stresses and deformations of the concrete section, which has significant heterogeneity."

There are separate experimental studies [6–10] of the strength (fatigue) and deformation characteristics of concrete and reinforced concrete elements under the action of short-term static low-cycle loads of a high level in the plastic stage of deformation close to failure.

Their analysis shows that under a mild regime (constant load level) and high load levels, more than $0.85{\cdot}R_{pr}$ (R_{pr} is the prismatic strength of concrete), concrete behaves as a cyclically softening material up to failure. At loading levels of less than $0.85{\cdot}R_{pr}$, the behavior of concrete is characterized by three characteristic areas. At the first loading cycles, cyclic hardening of the material occurs, followed by a period of stabilization and softening of the concrete before destruction.

The low-cycle strength of concrete and reinforced concrete elements depends mainly on the level of loads, the nature and number of cycles. It has been established that at the level of loading above $\eta>0.85{\cdot}R_{pr}$, the low-cycle strength of concrete slightly decreases, and below it increases, this is practically consistent with the results of studies conducted in the USA.

The articles [6–10] present the results of experimental studies of strength (fatigue) and deformation characteristics of concrete and reinforced concrete elements under the action of short-term static low-cycle loads of a high level in the plastic stage of deformation close to destruction.

Their analysis shows, for example, in [6] that in a soft mode (constant load level) and high load levels of more than $0.85R_{pr}$ (R_{pr} is the prismatic strength of concrete), concrete behaves as a cyclically softening material up to failure. At load levels of less than 0.85 rpm, the behavior of concrete is characterized by three characteristic areas. In the first loading cycles, cyclic hardening of the material takes place, followed by a period of stabilization and softening of the concrete before breaking. But it does not consider trials in a strict mode and there is no answer to what results to expect in this case.

In the works [7, 8], the problem of developing methods for studying strength and service life at a certain number of cycles of action is considered, but the problem establishing the optimal number of cycles is not specifically solved. In the conclusion of the next work, the same author notes that the low-cycle strength and deformability of compressed reinforced concrete elements significantly depends on the level of load, the number of cycles and the eccentricity of load application. But the work does not consider the case of bending of reinforced concrete elements, which is a significant drawback of the study of the impact of seismic loads. In [9], the authors show that a possible criterion for establishing the limit number of cycles of repeated loads is the stabilization of deformations in concrete, which depends on the mechanical properties of the concrete, the dimensions of the cross-section of the element, the levels of loading, and other factors.

However, the authors do not consider the effect of low-cycle fatigue on the value of the reduction coefficient. In [10], the world scientific community discussed the results of research on the entire range of problems and issues of strength, rigidity and stability of buildings and structures under the action of seismic load. Plans were developed for further studies of earthquake engineering and construction. In particular, the prospects for theoretical and experimental study of the properties of low-cycle fatigue and the reduction coefficient were noted.

Thus, the review and analysis of the above literature sources shows that scientists have not paid enough attention to the properties and features of low-cycle fatigue, and the problems of determining the reduction coefficient have not been resolved.

But the issues related to the determination of the reduction coefficient based on experimental data on plasticity [11, 12] remained unresolved, and the results of experimental tests of reinforced concrete bendable elements and assemblies of frame structural systems with static short-term alternating low-cycle load of a high level were also not analyzed. The reason for this may be objective difficulties associated with the costly part: the manufacture of reinforced concrete structures, the purchase of testing equipment and a measuring kit, which makes appropriate research impractical. One of the ways to overcome these difficulties turned out to be participation in a competition for grant funding of scientific research.

However, the issues related to the determination of the reduction factor on the basis of experimental data on plasticity [11, 12] remained unresolved, and the results of experimental tests of reinforced concrete bending elements and joints of frame structural systems with a static short-term variable low-cycle load of a high level were also not analyzed.

In paper [13], the substantiation and explanation of the new provisions for the calculation and design of reinforced concrete structures given in the chapter of SNiP 11-21-75 is given. Groups of limit states, categories of requirements for resistance cracks, reliability assurance system, materials and their characteristics are considered. It is indicated that it is necessary to conduct experimental studies to clarify and determine the coefficients for low-cycle loading. Methods for calculating structures for various types of effects on the limit states of the first and second groups, as well as design requirements, are presented.

In article [14], based on the analysis of the seismotectonic and seismological situation, an assessment of the consequences of the earthquake in Turkey is carried out. Geotectonic processes in the region, the largest earthquakes in the recent history of Turkey are considered. A comparative analysis of the standards for earthquake-resistant construction in Turkey, Russia and the CIS countries was carried out.

The text includes many topics [15] encompassing the theory of structural dynamics and the application of this theory regarding earthquake analysis, response, and design of structures. No prior knowledge of structural dynamics is assumed and the manner of presentation is sufficiently detailed and integrated, to make the book suitable for self-study by students and professional engineers.

The results of many years of research by the Tone Research Institute of Earthquake Engineering [16] are presented. It is shown that the Institute has conducted research on seismic construction and solving problems of earthquake-resistant construction. The questions related to experimental studies of the properties of low-cycle fatigue, reduction coefficients and plasticity are not addressed, but the theoretical, fundamental aspects of this issue are considered. The reason may be objective difficulties associated with the fundamental impossibility of conducting costly, time-consuming experimental tests, which makes relevant studies impractical. An option to overcome these difficulties may be to participate in grant competitions for research funding and become their owner. This is the approach that was used in the work under consideration.

Paper [17] proposes a type of weldless brace with stable resistance to buckling to eliminate the effect of welding on low-cycle fatigue capacity. The rod is made without a weld along the entire length of the element. Three welded and three non-welded specimens were tested at different strain amplitudes, and the hysteresis characteristics and low-cycle fatigue of the specimens were analyzed. The test results indicate that the plasticity and cumulative plastic deformation of non-welded specimens are much higher than those of welded specimens, which are much closer to the material consumption indices.

In paper [18], buckling-restrained braces (BRBs) are commonly used as a kind of energy dissipator in structures, which can be quickly replaced after strong earthquakes. However, there is no reasonable and effective damage assessment method to quantitatively analyze the damage degree in a BRB. Since the cumulative plastic deformation (CPD) of a BRB is closely related to its loading history, the CPD can reflect the low-cycle fatigue life of a BRB. In this paper, two CPD curves of BRBs under low-cycle fatigue damage are presented: C-CPD curves under a constant strain amplitude (CSA) loading history and R-CPD curves under a random strain amplitude (RSA) loading history. The solving process and the shape of two curves are given. In the C-CPD curve, the influence of different fatigue parameters on the curve characteristics is thoroughly studied.

In paper [19], Hybrid Simulation (HS) is a well-established testing method that combines both experimental and analytical components to evaluate the performance of structures under extreme events, commonly earthquakes. While several configurations and systems are available around the world to conduct HS, one goal of this paper is to document the development and verification of a compact HS setup at the University of Nevada, Reno to be used for tackling new research problems and educational purposes. A new substructured HS approach is proposed for seismic testing of concentric-braced frames (CBFs) with focus on capturing brace buckling and low-cycle fatigue induced-rupture.

Paper [20] copes with earthquakes, resistant housing is crucial. Too often essential construction techniques are not applied in the most vulnerable contexts. Local construction stakeholders have a major responsibility in reducing vulnerability of the built environment.

This exploratory study investigates current seismic risk awareness in the region of Iringa (Tanzania) and discusses its implications for disaster resilience practice. This medium seismic hazard risk area presents an interesting case study to map risk awareness of key construction stakeholders.

In paper [21], to improve the seismic performance of circular concrete-filled steel tube (CFST) columns with large dimensions, circumferential stiffeners, vertical stiffeners, and reinforcement cages were suggested to be set in the columns. Seven circular CFST column specimens with four internal constructions and two shear-span ratios were designed and tested under low-frequency cyclic loading.

A review and analysis of literature and publications shows the importance of taking into account low-cycle fatigue of structures in the inelastic stage of their operation under strong seismic influences and the need for targeted experimental and theoretical research on this very urgent problem. Some experimental studies of individual elements of the strength and deformation characteristics of concrete and reinforced concrete elements under the action of static, short-term loads are becoming known from sources, which does not allow to identify the regular trends in the dependencies of low-cycle fatigue and reduction coefficient.

The analysis of publications on earthquake-resistant construction in countries located in earthquake-prone regions shows that in engineering practice, when determining seismic loads using the linear spectral method, the elastic-plastic operation of structural systems is taken into account simplistically using a reduction coefficient or a behavior coefficient according to the Eurocode, reducing seismic effects determined by the spectrum of elastic reactions. However, the reduction coefficient depends on the nature of the hysteresis deformation diagram and the plastic life of critical sections of structural system elements estimated by the plasticity coefficient, which is significantly affected by low-cycle fatigue of materials, manifested at peak accelerations of strong seismic impacts.

This factor has not been disclosed to date and is not specifically taken into account in the norms for earthquake-resistant construction when determining the maximum bearing capacity of types of structures due to the poorly studied issue and the lack of experimental studies of the above-mentioned parameters under the action of a seismic type load.

All this allows to assert that it is expedient to conduct experimental tests, the results of which will allow to establish the qualitative and quantitative effect of low-cycle fatigue on the magnitude of the reduction coefficient under the action of a seismic type load.

3. The aim and objectives of the study

The aim of the study is an influence low-cycle fatigue and determine the reduction coefficient under the action load type of the seismic. This will allow designers to recommend the use of optimal values of the reduction coefficient when determining the intensity of the impact of seismic loads.

To achievements this aim, it was necessary to solve the following tasks:

– to experience statically definable beams with normal and prestressed reinforcement under the action of one-sided stepped increasing load until destruction and alternating low-cycle load;

– to experience statically indefinable beams with normal and prestressed reinforcement under the action of one-sided stepped increasing load until destruction and alternating low-cycle load type seismic;

– to experience series of T-shaped two-branch columns under the action alternating low-cycle load type seismic;

– to experience statically indeterminate beams to determine reduction coefficients depending on the coefficient of plasticity established under the action alternating low-cycle load.

4. Materials and methods

4. 1. Investigated object, subject and hypothesis

The object of research is seismic engineering, and the subject of the study is to determine the level of influence of low–cycle fatigue on the values of the reduction coefficient. This problem has not been disclosed and is not specifically taken into account in the standards for earthquake-resistant construction when determining the maximum bearing capacity of types of structures due to insufficient knowledge of the issue.

The hypothesis is that the reduction coefficient $R\mu$ is a function of two parameters: low–cycle fatigue M and the coefficient of plasticity μ, i.e. this dependence can be represented as follows: $K\mu = f(M, \mu)$. If the patterns of the influence of low-cycle fatigue on the reduction coefficient are determined at different, constant values of the plasticity coefficient, then the intensity of the seismic load can be determined as close as possible to the real value. If to find the limit of a given function, let's assume that it exists, a lot of experimental research is needed to build this function. As the review of articles registered on the Scopus platform shows, many scientists around the world are conducting similar experimental studies, the necessary initial data will accumulate soon.

Therefore, using an analytical formula or a mathematical model, it will be possible to determine the desired parameters, then the designers of earthquake-resistant structures will know the true values of seismic loads. Next, there is the well-known algorithm for calculating seismic resistance.

4. 2. Materials

Raw materials, equipment and measuring instruments for conducting complex experimental studies and processing the obtained data:

– A_t–V class reinforcement and 36–45 MPa concrete were used for the manufacture of reinforcement frames and prototypes of bent elements;

– special designed and manufactured test benches;

– standard laboratory equipment for tension and compression, P=500 kN;

– statically definable and indeterminate reinforced concrete beams with conventional and prestressed reinforcement;

– nodes made of reinforced concrete two-branched columns with a height from 15.6 to 18 m;

– a system of electronic sensors, strain gauges, indicators and deflection meters, power dynamometers, pumping stations with pressure gauges, digital recording devices with connecting cables, etc.;

– a personal computer with a program for processing and formatting in tabular and graphical forms the experimental results obtained.

4. 3. Methods

The scientific methods used in the study:

– when conducting a review and abstract searches of scientific literature on the topic under study, the thematic search method was used;

– static and kinematic approaches of the method of structural mechanics are involved in assigning initial data, determining calculation schemes, and determining the values of initial loads;

– when assigning the parameters of alternating low-cycle loads of the seismic type, the nature of seismic impacts was studied and analyzed according to numerous data with the determination of the number of overload and calculation cycles;

– plasticity coefficients and reduction coefficients were determined by hysteresis diagrams of deformation of experimental samples using well-known classical methods when processing experimental results;

– when processing the obtained experimental, numerical, and analytical results, a numerical-analytical method using electronic mathematical programs was used;

– the reliability of the scientific results obtained has been proved by analyzing and comparing the few results on the low-cycle strength of concrete conducted by individual researchers and in comparison with the normative values adopted in the norms of different countries.

5. Results of testing of reinforced concrete structures and determination of the reduction coefficient under the action of one-sided and low-cycle loads of seismic type

5. 1. Test results of conventional statically determined beams

Fig. 1 shows a general view of the tested statically definable beams with conventional and prestressed reinforcement.

The design limit moment for the cross-sections of both statically determined and indeterminate beams was determined from the experimental characteristics of the reinforcement and concrete, taking into account the hardening factor of high-strength reinforcement $m_{a\xi}$. Its meaning was based on the dependence of the:

$$m_{a\varsigma} = \sigma_a / \sigma_{0.2} = 1 + \left(1 - \xi_{0.2} / \xi_R\right) \cdot \left(\beta \cdot \sigma_b / \sigma_{0.2} - 1\right). \qquad (1)$$

At the same time, the value of β was assumed equal to 1. The ultimate design and experimental bending moments of statically determined beams were determined by the expression:

$$M = P \cdot L / 4, \tag{2}$$

where M is the bending moment, P is the applied load; L is the span of the beam.

The results of the tests and calculations are shown in Table 1.

Table 1 shows a comparison of experimental M_{exp} and calculated M_{calc} values of limiting moments in statically definable conventional and prestressed beams, depending on the degree of reinforcement and the level of low-cycle loads.

Table 1

Test results of statically definable beams

Serial number	Beam cipher	Valve prestressed level $\sigma_{sp2}/\sigma_{0.2}$	Degree of reinforcement ξ_R			Load level, η	Number of cycles n	M_{exp}, kNm	M_{calc}, kNm	M_{exp}/M_{calc}
			ξ_R	ξ_P	ξ_P/ξ_R					
I	BOO-1-1c	–	0.330	0.148	0.448	1.0	1	49.52	42.90	1.15
	BOO-1-2c	–	0.330	0.153	0.464			47.82	41.87	1.14
	BOO-2-1z	–	0.330	0.148	0.448	0.9	11	46.77	41.98	1.11
	BOO-2-2z	–	0.330	0.149	0.452			50.89	46.23	1.10
	BOO-3-1z	–	0.330	0.153	0.464	0.8	51	50.89	44.84	1.14
	BOO-3-2z	–	0.330	0.155	0.470			52.27	45.17	1.16
II	BNO-1-1c	0.432	0.387	0.348	0.899	1.0	1	50.89	42.26	1.20
	BNO-1-2c	0.432	0.387	0.328	0.848			53.53	44.56	1.20
	BNO-2-1z	0.432	0.387	0.325	0.840	0.9	11	56.00	46.30	1.21
	BNO-2-2z	0.432	0.387	0.332	0.858			56.92	45.50	1.25
	BNO-3-1z	0.435	0.387	0.339	0.876	0.8	51	56.07	43.99	1.25
	BNO-3-2z	0.435	0.387	0.329	0.850			55.02	45.92	1.20

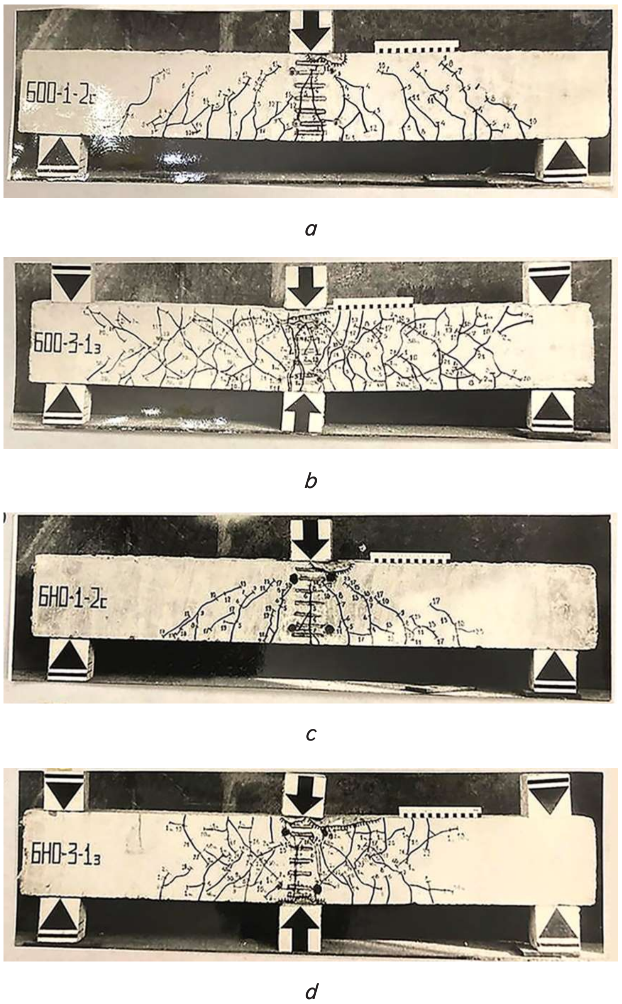


Fig. 1. General view of the tested statically definable beams with: *a* – conventional unilaterally incrementally increasing applied load until the destruction; *b* – conventional alternating low-cycle load; *c* – prestressed reinforcement unilaterally incrementally increasing applied load until the destruction; *d* – prestressed reinforcement alternating low-cycle load

5. 2. Test results of prestressed statically indeterminate beams

Fig. 2 shows a general view of the tested statically indeterminate beams with conventional and prestressed reinforcement.

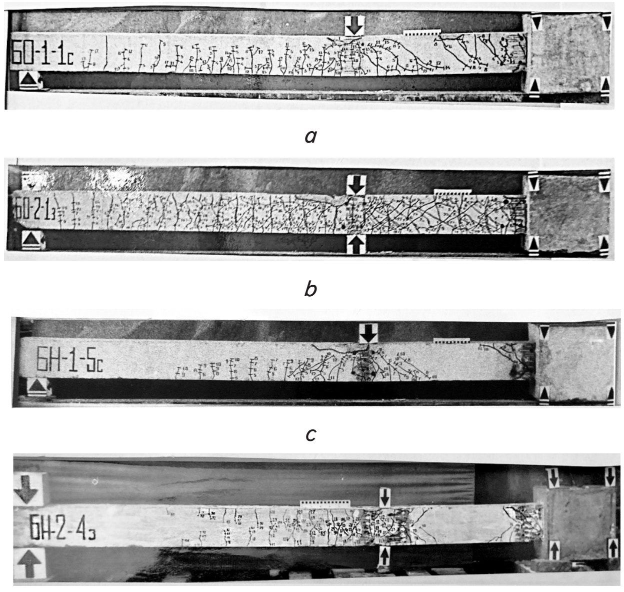


Fig. 2. General view of the tested statically beams: *a* – with conventional unilaterally increasing applied load to destruction; *b* – reinforcement alternating low-cycle load; *c* – prestressed reinforcement unilaterally incrementally increasing applied load to destruction; *d* – prestressed reinforcement alternating low-cycle load

The calculated values of the maximum loads of the prototypes were determined by the formula:

$$P_p = \left(M_p^n + M_p^o\right) / 2 / 9 \cdot L, \tag{3}$$

where P_p is the calculated values of the maximum loads; L is the calculated span of the beam; M_{calc}^n is the calculated span moments and M_{exp}^n is the calculated support moments; P_{exp} is the experimental limit loads; P_{calc} is the calculated limit loads.

Table 2 shows the main characteristics of statically indeterminate beams: with conventional and prestressed reinforcement; the level of loading; the number of cycles; experimental and calculated limiting moments in the support and span sections, as well as the ratio of the maximum experimental and calculated loads.

Table 2 also shows the calculated values of the maximum loads, taking into account the actual characteristics of the reinforcement and concrete.

Fig. 3 shows experimental hysteresis deformation diagrams for the first and last cycles of one prestressed statically indeterminate beam tested at load levels 0.8–0.9·P_{dis}.

Obtained from hysteresis deformation diagrams, the plasticity coefficient of μ from the first to 20 cycles varied within the range of 4.5–6, before breaking it was practically 10–12, as in the rest of the tested beams.

Under low-cycle loads of beams, stabilization of hysteresis deformation dia-grams occurred after the first 3 cycles and remained unchanged in shape with a slight increase in deformations until the last 3–4 loading stages. In recent cycles, the area of the hysteresis loops increased rapidly during 10 loading cycles at a level of 0.9P_{dis} and at least 50 cycles and a loading level of 0.8P_{dis}. According to hysteresis defor-mation diagrams, energy characteristics were obtained. They are characterized by the energy absorption coefficient according to the formula:

$$\psi = \Delta W / W, \tag{4}$$

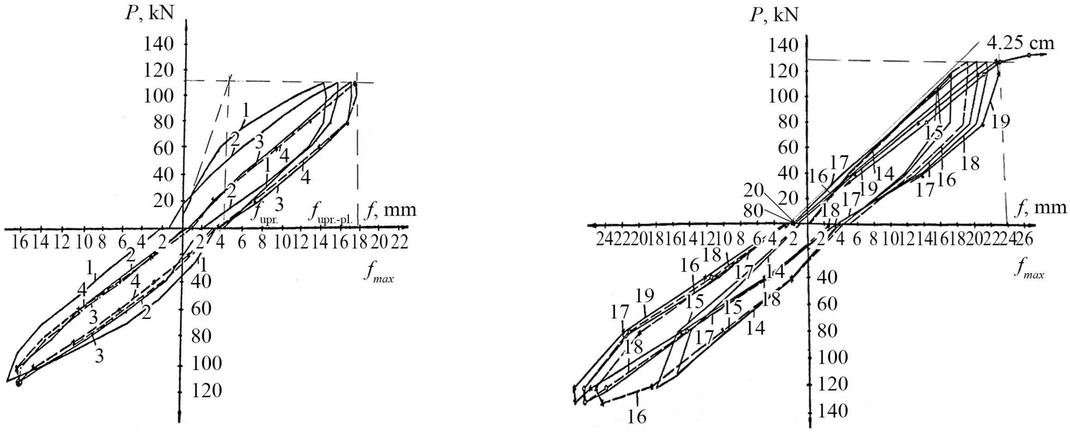
were ΔW – energy absorbed, W – energy expended.

The energy absorption coefficient ψ for one cycle of low–cycle loading in the tested beams depends on the nature and degree of reinforcement, the design scheme of the elements with steady-state hysteresis deformation diagrams averaged ψ=0.4–0.5. In beams with a ratio of ξ_{exp}/ξ_{calc}=0.9, at a low-cycle loading level of 0.9P_{dis}, the energy absorption coefficient ψ reaches a value of 0.7 in recent cycles. These data can be used in energy methods for assessing the seismic resistance of buildings.

Table 2

Calculated and experimental values of moments in supports and in the span

Serial number	Beam cipher	Valve prestress level, $\sigma_{sp2}/\sigma_{0.2}$	$\xi^{avg}_{exp} / \xi_{calc}$	Load level, η	Number of cycles, n	$M^o_{\exp}$	M^o_{calc}	M^n_{exp}	M^n_{calc}	P_{exp}/P_{calc}
						kNm		kNm		
III	BO-1-1c	–	0.460	1	1	50.92	42.16	50.97	41.15	1.22
	BO-1-2c	–			1	46.01	38.79	53.32	40.48	1.25
	BO-2-1z	–	0.460	0.9	11	47.9	42.50	53.68	39.47	1.24
	BO-2-2z	–			3	42.8*	38.79	46.22	42.16	1.10
	BO-3-1z	–	0.465	0.8	20	31.14	38.45	37.92	43.18	0.95
	BO-3-2z	–			3	30.06	41.15	47.04	39.80	
IV	BN-1-1c	0.561	0.707	1	1	51.02	35.99	36.85	35.92	1.14
	BN-1-2c	0.561			1	49.90	37.61	41.65	38.15	
	BN-2-1z	0.565	0.691	0.9	11	41.94	39.67	41.58	40.35	1.09
	BN-2-2z	0.536			11	47.03	37.79	40.19	36.84	
	BN-3-1z	0.553	0.652	0.8	51	40.43	38.63	45.04	39.03	1.13
	BN-3-2z	0.553			51	43.58	38.99	42.83	36.41	
V	BN-1-3c	0.451	0.845	1	1	37.67	45.21	50.49	46.12	1.11
	BN-1-4c	0450			1	59.4	42.17	46.46	42.86	
	BN-2-3z	0422	0.848	0.78–0.89	14–20	53.7	47.10	50.7	46.8	1.11
	BN-2-4z	0.439		0.89	12	49.54	42.63	47.30	43.59	1.12
VI	BN-1-5c	0.398	0.872	1	1	46.95	42.07	46.58	40.33	1.14
	BN-2-5z	0.398		0.9	9	23.31	45.93	37.56	40.11	0.71
	BN-3-3z	0.395	0.875	0.8	25	30.05	44.15	40.39	43.23	0.75
	BN-3-4z	0.395			6	26.13	43.03	35.5	43.33	



a *b*

Fig. 3. Hysteresis deformation diagrams of a reinforced concrete prestressed statically indeterminate beam BN-2-3z: *a* — 4 cycles; *b* — 11—20 cycles

5. 3. Testing of nodes of two-branch columns and reinforced lintels

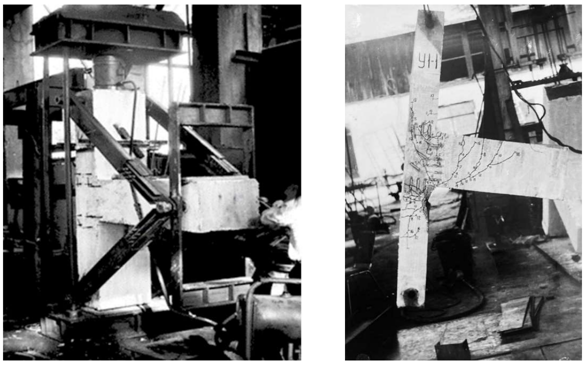
Test results of a T-shaped two-branch column differing in the standard dimensions of the branch and the reinforcement of the lintels, representing the elements of two-branch columns with a height of 15.6 to 18 m under the action of low-cycle loads of the seismic type.

Fig. 4 shows a general view of the tested units.

The main test results of the nodes are summarized in Table 3, which shows the number and coefficient of asymmetry of cycles, the level of loading, calculated and experimental limit loads, and their comparison, brief information about the nature of destruction.

Fig. 5 shows a hysteresis diagram of the deformation of one representative node tested by alternating low-cycle load.

The following parameters were obtained: the energy absorption coefficient of ψ averaged 0.46 at the design load level and 30 cycles of alternating low-cycle loading. The plasticity coefficient from the first to the last cycles varied within the range of 4–8.



a *b*

Fig. 4. General view of the tested nodes: *a* – single load; *b* – alternating low-cycle load

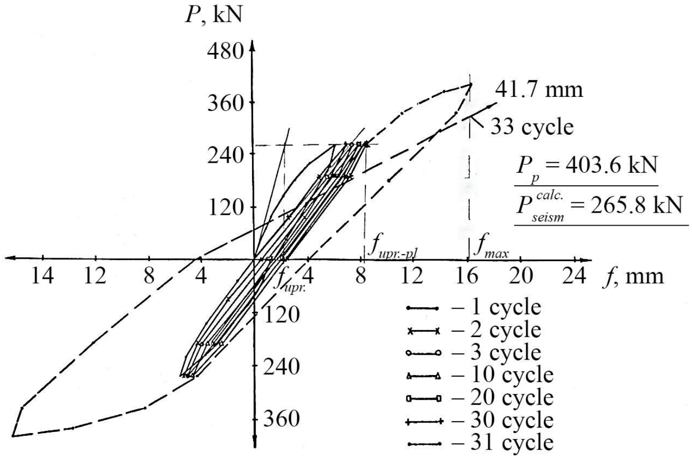


Fig. 5. Hysteresis diagram of the deformation of the node U2-3

Table 3

Calculated and experimental limit loads, their comparison, brief information about the nature of failure

Node brand	Number of cycles, n	Load level, η	The coeff. Sym ρ	P^{cycle}, kN	P^{exp}, kN	P^{exp}/P^{cycle}	$P^{cycle} / P^{exp}_{refer}$	Destruction nature
U1-1 (Refer.)	1	1	1	–	–	–	1	According to the normal cross sections of the column branch
U1-2	30	0.53	–1	147.8	220.8	1.5	0.8	According to the normal section of the column branch
	1	0.8		220.8				
U1-3	30	0.53	–1	147.8	220.8	1.5	0.8	Along the central nodal zone and the normal section of the branch
	6	0.8		220.8				
U2-1 (Refer.)	1	1	1	–	432.0	–	1	According to the normal section of the column branch
U2-2	30	0.61	–1	264.0	489.6	1.86	1.13	Along the inclined section of the column branch
	1	1.13		489.6				
U2-3	30	0.61	–1	264.0	403.2	1.52	0.93	Along the central nodal zone
	3	0.93		403.2				
U3-1 (Refer.)	1	1	1	–	408.0	–	1	Along the inclined section of the column branch
U3-2	30	0.61	–0,68	249.6	408.0	1.62	1	Along the central nodal zone
	1	1		408.0				
U3-3	30	0.61	–0,68	249.6	420.0	1.68	1.03	According to the normal cross section of the bridge and the central nodal zone
	30	0.88		360.0				
	20	0.95		388.8				
	1	1.03		420.0				

5. 4. Determination of the reduction coefficient

The values of reduction coefficients differ significantly in the norms of different countries for earthquake-resistant construction. For example, Table 4 shows the values of reduction coefficients adopted in the standards for earthquake-resistant construction in some countries (EU – Eurocode 8, USA, Japan, New Zealand and Kazakhstan) for four types of structural systems designed with medium DCM and high DCH plasticity.

These indicators indicate that each country, when determining reduction coeffi-cients by types of structural systems, depending on the plastic resource, has adopted its own methodology for determining the values of plasticity coefficients μ and their permissible limits as the main initial parameter, depending on the building materials used, types of structures and other factors. In general, the value of the reduction coef-ficient is determined on the basis of developments [15, 16] by the expression:

$$R_\mu = \mathrm{sqrt}(2\cdot\mu-1), \tag{5}$$

R_μ is the coefficient of reduction or behavior according to EN8, μ is the coeffi-cient of plasticity.

During strong earthquakes and their aftershocks, due to the intensive develop-ment of inelastic deformations in structural elements caused by the low-cycle impact of seismic loads close to the maximum bearing capacity, the plastic reserve may be insufficient. This is evidenced by the consequences of the catastrophic earthquake that occurred on February 6, 2023 in southern Turkey [14], as well as other strong earth-quakes like the Spitak earthquake in Armenia. Therefore, when determining the re-duction coefficients Rμ, it is necessary to rely on reliable values of the plasticity coef-ficients μ by types of structural elements installed under the action of low-cycle loads of a seismic nature, which differ radically from other types of loads. In this regard, the problem of determining low-cycle fatigue and the permissible limits of the mani-festation of plastic resources of structural system elements, under the action of low-cycle loads of a high level, such as seismic, remains very relevant and little studied experimentally.

Below, using the experimental values of the plasticity coefficients μ, which for the elements and nodes under study averaged 6 and 8, respectively, obtained from the results of the above experimental studies, it is possible to determine the reduction co-efficients (behavior) Rμ according to the formula (5):

– for reinforced concrete bendable elements:

$$R_\mu^{izg} = \mathrm{sqrt}(2\cdot\mu-1),\quad R_\mu^{izg} = \mathrm{sqrt}(2\cdot 6-1)-3.32; \tag{6}$$

– for reinforced concrete units:

$$R_\mu^{uzl} = \mathrm{sqrt}(2\cdot\mu-1),\quad R_\mu^{uzl} = \mathrm{sqrt}(2\cdot 8)=3.87, \tag{7}$$

by analyzing the above experimental results with the normative values adopted in the norms of some countries for reinforced concrete frames with moment frames with an average plasticity class.

Table 5 presents a comparison of the values of decreasing coefficients obtained during the analysis of the above experimental results with their accepted values in the standards of some countries for reinforced concrete frames with moment frames with an average class of plasticity.

Table 5 also shows comparisons of the values of the reduction coefficients obtained by analyzing the above experimental results with the normative values adopted in the norms of some countries for reinforced concrete frames with moment frames with an average plasticity class.

Table 4

Values of decreasing coefficients adopted in seismic standards in some countries (EU-Eurocode 8, USA, Japan, New Zealand and Kazakhstan)

Standards for earthquake-resistant construction	Types of structural systems							
	Reinforced concrete frames with instant frames		A system of reinforced concrete walls and torque frames		A system of connected reinforced concrete walls		Steel frames with instant frames	
	DCM	DCH	DCM	DCH	DCM	DCH	DCM	DCH
EN 1998-1:2004	3.9	5.85	3.6	5.85	3.6	5.4	4.0	6.5
ASCE/SEI 7-10	5.0	8.0	5.5	7.0	4.0	5.0	4.5	8.0
BCLJ (2004)	2.5	3.33	2.0	2.5	2.0	2.5	2.86	4.0
NZS 1170.5 (2005)	4.29	8.57	4.29	7.14	4.29	7.14	4.29	8.57
NTP RK (2014)	3.9	–	4.25	–	4.25	–	4.0	–

Table 5

A comparison of the values of the reduction coefficients

Earthquake-resistant building standards	Reinforced concrete frames with moment frames				
	DCM			Comparison of normative values with experimental ones	
	R_μ according to the norms	R_μ^{bend} for bendable elements	R_μ^{unit} by nodes	R_μ / R_μ^{bend}	R_μ / R_μ^{unit}
EN 1998-1:2004	3.9	3.32	3.87	1.18	1.01
ASCE/SEI 7-10	5.0			1.50	1.29
BCLJ (2004)	2.5			0.75	0.65
NZS 1170.5 (2005)	4.29			1.29	1.11
NTP RK (2014)	3.9			1.18	1.01

6. Discussion of the results of experimental studies of low-cycle fatigue of reinforced concrete bendable elements and assemblies of frame structures under the action loads type the seismic

12 statically definable beams were experienced with a cross section h=20 cm, b=15 cm and with a design span of 120 cm, reinforced with A_t–V class fittings, with a degree of reinforcement of conventional beams $\xi_P=0.46\cdot\xi_r$ and prestressed beams – $\xi_P=0.86\xi_R$ (ξ_R is the boundary height of the compressed section zone), with concrete strength R_b=44.8 MPa. The prestressing level of the armature was $\sigma_{sp2}=0.43\sigma_{0.2.}$ The load P was applied in the middle of the beam span. Fig. 1, a – with the usual unilateral increase in the applied load until destruction (Fig. 1, (1), (2), Table 1).

Four (4) beams were tested in 50 cycles at the level of low-cycle loads $P=0.8\ P_{des}$ (P_{des} – is destruction load). Fig. 1, b – reinforcement alternating low-cycle load and 10 cycles at $P=0.9\cdot P_{dis}$ and cycle asymmetry coefficient $\rho=-1$, as well as unilaterally applied load until destruction reference samples for comparison (Fig. 2, 3, (3), Table 2).

The strength of normal cross-sections has been established with reliable use of the permissible deformability of reinforcement and concrete in the plastic hinges of structural elements. The energy absorption coefficient ψ has been determined, it must be used on average $\psi=0.45$, characterizing the hysteresis dissipation of energy, to determine the decrements of oscillations in calculations for seismic effects.

According to the same method, 20 statically indeterminate conventional and prestressed beams were tested, with a cross section h=20 cm, b=15 cm and a design span of 270 cm, reinforced with A_t–V steel, with a degree of reinforcement of conventional beams $\xi_P=0.46\xi_R$ with a concrete strength R_b=35.6 MPa. Prestressed beams with a degree of reinforcement of $\xi_P=0.68\ \xi_r$ and $\xi_P=0.85-0.87\xi_r$ were also tested with concrete strength within R_b=36–44 MPa. The level of rebar distribution in the beam is $\sigma_{sp2}=0.40-0.56\sigma_{0.2}$ ($\sigma_{0.2}$ is the main indicator of high-strength reinforcement). The load P was applied in thirds of the beam span at a distance of 90 cm from the pinched support (Fig. 2, 3, (3), Table 2).

From the analysis of the results, it follows that the bearing capacity of conventional beams tested at a load level $P=0.9P_{dis}$ is mainly reduced from 4 % to 10 %, and the bearing capacity of prestressed beams remains almost equal to the standard sample, unless premature destruction along the inclined section (symbol *) occurred.

At a load level of $R=0.8R_{dis}$ in both types of beams, the load-bearing capacity practically does not decrease. These results on low-cycle strength are consistent with the conclusions of [5, 6, 9] that the limit for reducing the low-cycle strength of concrete and reinforced concrete elements is $R=0.85\cdot R_{pr}$. Fig. 1, 2 show that in beams without prestressing the reinforcement, cracks spread over the entire length, unlike prestressed beams, where respectively the deflections were larger and the stiffness and endurance were lower.

In plastic hinges of conventional statically definable beams, at a low-cycle load level of $P=0.9\cdot P_{dis}$, reinforcement deformations reached equal ε_1=2.4 %, at a level of $P=0.8\cdot P_{dis}$, ε_2=0.65 %, and at failure, respectively, ε_1=–4.43 % and ε_2=3.17 %.

In prestressed prototypes, with an applied load equal to $P=0.9{*}P_{dist}$, the deformations of the reinforcement reached 1.1 % and with a load level equal to $P=0.8\cdot P_{dist}$, the deformations were 0.5 %, and when the prototypes were destroyed, the deformations of the reinforcement were 3.47 % and 2.88 %, respectively. The relative limiting deformations of concrete (ε_{lim}) of the extreme fibers of the compressed zones of critical sections in conventional beams reached ε_{lim}=0.45 %, and in prestressed beams they reached ε_{lim}=0.38 %. Deformations of reinforcement and concrete in plastic joints of statically indeterminate beams developed on average almost within the same limits.

Thus, in the plastic joints of beams without prestressing, the deformations of the reinforcement at the level of low-cycle loads of $0.9P_p$ in comparison with the level of $0.8P_p$ exceeded 3.7 times, and in prestressed beams –2.2 times.

In both cases, the strength properties of the calculated cross-sections were realized in excess of the calculated values, due to greater hardening of high-strength reinforcement, taking into account the coefficient $m_{a\xi}$. Obtained from hysteresis deformation diagrams (Fig. 3), the coefficient of plasticity from the first to the 20th cycle varied within the range of μ=4.5–6, before destruction it amounted to μ=10–12 practically, as in the rest of the tested beams. Under low-cycle loads of beams, stabilization of hysteresis deformation diagrams occurred after the first n=3 cycles and remained unchanged in shape with a slight increase in deformations until the last n=3–4 loading stages.

In recent cycles, the area of the hysteresis loops increased rapidly during 10 loading cycles at a level of $P=0.9{*}P_{dis}$ and at least at 50 cycles and a loading level of $P=0.8{*}P_{dist}$. According to hysteresis deformation diagrams, energy dissipation characteristics were obtained, characterized by the energy absorption coefficient according to the formula (4). The energy absorption coefficient Ψ for one cycle of low–cycle loading in the tested beams made up averaged Ψ=0.4–0.5. Depending on the nature and degree of reinforcement, the design scheme of the elements with steady-state hysteresis deformation diagrams, In beams with a ratio of $\xi_p/\xi_R=0.9$, at the level of low-cycle loading $P=0.9\cdot P_p$, in recent cycles the absorption coefficient the energy level reached a value of Ψ=0.7.

These data can be used in energy methods for assessing the seismic resistance of buildings.

T-shaped nodes of two-branched columns.

Three series of nodes were tested, differing in the standard sizes of the branch and the reinforcement of the bridges, representing elements of two-branched columns with a height from h=15.6 to 18 m under the action of low-cycle loads of the seismic type. The obtained hysteresis diagrams of deformation of nodes are of practical value for the analysis of elastic-plastic deformations and their plastic resources, similar in operation to the extreme nodes of multi-storey frame buildings under the action of seismic loads. Fig. 4 shows a general view of the tested nodes (Fig. 4, a–c, 5, Table 3).

The main test results of the nodes are summarized in Table 3, which shows the number and coefficient of asymmetry of cycles, the level of loading, calculated and experimental limit loads, and their comparison, brief information about the nature of destruction.

Three loading modes were used in each series consisting of 3 prototypes to identify the influence of alternating signs, low cycles and load levels.

The first mode is a single loading of nodes U1-1, U2-1 and U3-1 until destruction, the results of which were accepted as reference.

The second mode – nodes U1-2, U2-2 and U3-2 were subjected to n=30 cycles of alternating loading at load levels $\eta_{1,2}$=0.53 and 0.61 from the reference and corresponding calculated seismic loads on the column lintels, after which the nodes were brought to destruction.

The third loading mode increased the load level from $\eta_{1,\,2}$=0.53–0.61 to $\eta_{3,\,4}$=0.8–0.95 of the value of the corresponding reference loads and the cycles were repeated until the load-bearing capacity of the prototypes was exhausted.

It can be seen from Table 3 that the experimental destructive loads of the P_{exp} exceeded the P_{cycle} corresponding to the calculated values of seismic loads by more than 1.5 times with low-cycle alternating loads of nodes. The ultimate strength of the nodes after cyclic loads brought to destruction in relation to reference samples (P_{cycle}/P_{des} standard) of the first series decreased by 20 %, and the second and third series were equal to the reference. The deflections of the samples, at a low-cycle load of the calculated level in comparison with the reference, increased 1.6 and 1.51 times for the nodes of the first and second series, respectively, and decreased for the third series. Fig. 5 shows a hysteresis diagram of the deformation of one representative node tested by alternating low-cycle load.

The following parameters were obtained: the energy absorption coefficient of ψ averaged ψ=0.46 at the design level of η loads and n=30 cycles of alternating low-cycle loading (Fig. 5). The plasticity coefficient from the first to the last cycles varied within the range of $R\mu$=4–8.

The results of the presented experimental studies were used to clarify the magnitude of the reduction coefficients in the current regulatory documents on earthquake-resistant construction, since they need to be reasonably revised or clarified.

Reduction coefficient.

The values of the reduction coefficients differ significantly in the norms of different countries for earthquake-resistant construction. For example, Table 4 shows the values of reduction coefficients adopted in the standards for earthquake resistant construction in some countries (EU-Eurocode 8, USA, Japan, New Zealand and Kazakhstan) for four types of structural systems designed with medium DCM and high DCH plasticity (Table 4).

These indicators indicate that each country, when determining reduction coefficients by types of structural systems, depending on the plastic resource, has adopted its own methodology for determining the values of plasticity coefficients and their permissible limits as the main initial parameter, depending on the building materials used, types of structures and other factors. In general, the value of the reduction coefficient is determined on the basis of developments in the expression: (5), (6).

During strong earthquakes and their aftershocks, due to the intensive development of inelastic deformations in structural elements caused by the low-cycle impact of seismic loads close to the maximum bearing capacity, the plastic reserve may be insufficient. This is evidenced by the consequences of the catastrophic earthquake that occurred on February 6, 2023 in southern Turkey, as well as other strong earthquakes such as the Spitak earthquake in Armenia.

Therefore, when determining the reduction coefficients $R\mu$, it is necessary to rely on reliable values of the plasticity coefficients μ by types of structural elements installed under the action of low-cycle loads of a seismic nature, which differ radically from other types of loads. In this regard, the problem of determining low-cycle fatigue and the permissible limits of the manifestation of plastic resources of structural system elements under the action of low-cycle high-level loads such as seismic remains very relevant and little studied experimentally.

Below, using the experimental values of the plasticity coefficients μ, which for bent elements and assemblies averaged 6 and 8, respectively, obtained from the results of the above experimental studies, the reduction coefficients (behavior) $R\mu$ were determined according to the formula (5), (6).

Table 5 presents a comparison of the values of the reduction coefficients obtained by analyzing the above experimental results with the normative values adopted in the norms of some countries for reinforced concrete frames with moment frames with an average plasticity class.

As can be seen from Table 5, the reduction coefficients in the norms of the presented countries for reinforced concrete bent elements with average ductility exceed the experimental values from 18 to 50 %, and for nodes up to 29 %, with the exception of the norms of Japan, in which these indicators are lower by 25 % for bent elements and 35 % for nodes.

At the same time, the reduction coefficients determined by the experimental values of the plasticity coefficients obtained from hysteresis deformation diagrams of the tested nodes correspond to the parameters adopted in the norms EN 1998-1:2004 and NT PRC (2014), and for bent elements they are 18 % lower.

According to Japanese standards, structures are designed practically as low-plastic DCLS in order to prevent or limit elastic-plastic deformations in the elements, so that damage does not occur during severe earthquakes that occur very often and thereby eliminate the cost of repair and restoration work after seismic events. This is achieved by the widespread use of seismic isolation systems, various types of dampers and vibration dampers in construction, the effectiveness of which has been proven by the consequences of many earthquakes, as a result of which the load-bearing structures of buildings remain earthquake-resistant.

In the norms of Republic of Kazakhstan, as in most countries, with a two-level calculation, damage to structures of varying degrees is allowed, depending on the class of responsibility of buildings, taking into account economic rationality. The calculation of buildings on the first level is performed for weak and moderate earthquakes, and on the second level for strong seismic effects.

According to the first level of calculation, it is envisaged to preserve the operational suitability of buildings without significant damage to load-bearing structures, and according to the second level of calculation, damage and destruction of individual structural elements are allowed, but not leading to their collapse and loss of life, loss of valuable equipment. In addition, according to the norms of Kazakhstan, unlike in some countries, load-bearing structures of buildings are designed with low DCL or medium DCM plasticity classes, excluding the high plasticity class DCH due to the lack of experimental and theoretical studies for the reasonable adoption of appropriate reduction coefficients.

Thus, the values of the reduction coefficients (behavior) in determining seismic loads according to the norms for reinforced concrete bent elements of frame systems with an average plasticity class should be taken equal to R_μ=3.3, for nodes R_μ=3.9.

At present, there are not enough data from experimental studies on the effect of low-cycle fatigue properties and the reduction coefficient on the value of the reaction spectrum of structures to offer specific and accurate values for their calculations. The limits of applicability of the results of studies depend on specific geological, geographical conditions, and on the strength of the seismic load. However, the obtained experimental and calculated values correlate well with the standard values within the territory and space under consideration. During strong earthquakes and their aftershocks, due to the intensive development of inelastic deformations in structural elements caused by the low-cycle impact of seismic loads close to the ultimate bearing capacity, the plastic reserve may be insufficient. This is evidenced by the consequences of the catastrophic earthquake that occurred on February 6, 2023 in southern Turkey, as well as other strong earthquakes like the Spitak earthquake in Armenia.

Therefore, when determining the reduction coefficients R_μ, it is necessary to rely on reliable values of the plasticity coefficients of μ for the types of structural elements installed under the action of low-cycle seismic loads, which differ fundamentally from other types of loads. In this regard, the problem of determining low-cycle fatigue and permissible limits of manifestation of plastic resources of elements of structural systems, under the influence of low-cycle loads of a high level such as seismic, remains a very relevant and little-studied area in terms of experimental research.

7. Conclusions

1. It is recommended to take the low-cycle coefficient of 0.9 for prestressed and 0.85 for conventional structures in the calculations of bending elements and joints of reinforced concrete frames. The energy absorption coefficient is taken ψ=0.45 to determine the decrements of oscillations.

2. The results of experimental studies conducted on 32 bent conventional and prestressed reinforced concrete statically definable and indeterminate beams, 9 full-size nodes, under the action of low-cycle high-level seismic loads, allow to recommend for bent elements and nodes of reinforced concrete frames with moment frames with an average plasticity class designed for seismic zones. Energy absorption coefficient ψ take an average of 0.45, characterizing the hysteresis dissipation of energy, to determine the decrements of fluctuations in calculations for seismic effects.

3. It is recommended to adopt in the standards the value of the reduction coefficient R_μ=3.3 for reinforced concrete bending elements and R_μ=3.9 for frame nodes when determining seismic loads.

4. The results of the presented experimental studies can be used to refine or adopt reduction coefficients for frame structural systems in the current standards for earthquake-resistant construction, since they need reasonable revision or clarification, as well as practical calculations. The values of the reduction coefficients (behavior) in determining seismic loads according to the norms for reinforced concrete bent elements of frame systems with an average plasticity class should be taken equal to 3.3, for nodes – 3.9.

Conflict of interest

The authors declare that they have no conflict of interest about this research, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

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The manuscript has no associated data.

Use of artificial intelligence.

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

References

1. EN 1998-1 (2004). (English): Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings [Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC]. Available at: https://www.phd.eng.br/wp-content/uploads/2015/02/en.1998.1.2004.pdf
2. Newmark, N., Rosenbluet, E. (1980). Fundamentals of Earthquake-Resistant Construction. Moscow: Stroyizdat, 344.
3. Borges, J. F., Ravara, A. (1978). Design of reinforced concrete structures for seismic areas. Moscow: Stroyizdat, 135.
4. Polyakov, S. V. (1983). Earthquake-resistant structures of buildings. (Fundamentals of the theory of seismic resistance). Moscow: Higher School, 305.
5. Baryshnikov, A. Ya., Shevchenko, B. N., Valovoy, A. I. (1985). Low cycle fatigue of concrete during compression. Beton and reinforced concrete, 4, 27–28.
6. Stavrov, G. N., Rudenko, V. V., Fedoseev, A. A. (1985). Strength and deformation of concrete at repeated static loads. Concrete and reinforced concrete, 01, 133–134.

7. Rudenko, V. V. (1980). Out-of-center loading of concrete and reinforced concrete elements with a small number of repeated loads. Proceedings of Higher Educational Institutions. Construction and Architecture, 4, 12–13.
8. Rudenko, V. V. (1981). Operation of non-centrally compressed elements. Concrete and reinforced concrete, 11, 5–6.
9. Babich, E. M., Pogorelyak, A. P., Zalesov, A. S. (1981). Work of elements on transverse force with a few repeated loads. Concrete and reinforced concrete, 6, 8–9.
10. Effects of repeated loading of materials and structures (1966). Proc. RILEM. Vol. I-IV. Mexico,
11. Abakanov, M. S. (2013). Strength of reinforced concrete structures under low-cycle loads of seismic type. Earthquake-resistant construction. Safety of building structures, 05, 30–34.
12. Abakanov, M. S. (2008). Low-cycle strength of nodes of two-branch reinforced concrete columns of one-story industrial buildings under loads of seismic type. Khabarshy-Bulletin of the Kazakh Head Academy of Architecture and Civil Engineering, 2 (28), 99–109.
13. Gvozdev, A. A., Dmitriev, S. A., Gushcha, Yu. P., Zalesov, A. S., Mulin, N. M., Chistyakov, E. A. (1978). New in the design of concrete and reinforced concrete structures. Moscow: Stroyizdat, 204.
14. Akbiev, R. T., Abakanov, M. S. (2023). Operational assessment of the consequences of the devastating earthquake in Turkey (according to the official published data of the media and the global network). Geology and Environment, 3, 35–51. https://doi.org/10.26516/2541-9641.2023.1.35
15. Chopra, A. K. (2005). Earthquake dynamics of structures: a primer. Oakland: Earthquake Engineering Research Institute. Available at: https://archive.org/details/earthquakedynami0000chop_ed02
16. Newmark, N. M., Hall, W. J. (1982). Earthquake spectra and design. California. Available at: https://tuxdoc.com/download/1982-newmark-amp-hall-eeri-earthquake-spectra-and-design-5_pdf
17. Xie, L., Wu, J., Huang, Q. (2017). Experimental Study on Low-Cycle Fatigue Performance of Weld-Free Buckling-Restrained Braces. Journal of Earthquake Engineering, 22 (8), 1392–1414. https://doi.org/10.1080/13632469.2017.1286622
18. Tong, C., Wu, J., Hua, K., Xie, L. (2020). Low-Cycle Fatigue Life Estimation Curve for Buckling-Restrained Braces Based on Cumulative Plastic Deformation. Journal of Earthquake Engineering, 26 (6), 2773–2801. https://doi.org/10.1080/13632469.2020.1772152
19. Bas, E. E., Moustafa, M. A., Pekcan, G. (2020). Compact Hybrid Simulation System: Validation and Applications for Braced Frames Seismic Testing. Journal of Earthquake Engineering, 26 (3), 1565–1594. https://doi.org/10.1080/13632469.2020.1733138
20. Sechi, G. J., Lopane, F. D., Hendriks, E. (2022). Mapping seismic risk awareness among construction stakeholders: The case of Iringa (Tanzania). International Journal of Disaster Risk Reduction, 82, 103299. https://doi.org/10.1016/j.ijdrr.2022.103299
21. Dong, H., Qin, J., Cao, W., Zhao, L. (2022). Seismic behavior of circular CFST columns with different internal constructions. Engineering Structures, 260, 114262. https://doi.org/10.1016/j.engstruct.2022.114262