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ROBUSTNESS OF PRESTRESSED REINFORCED CONCRETE STRUCTURES UNDER SPECIAL IMPACTS

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The purpose of the study was to develop the principles of the theory of robustness of reinforced concrete structural systems of buildings and structures with prestressed elements and methods of protecting them from progressive collapse under special impacts. To achieve this, the article presents the results of studies of monolithic reinforced concrete frames of multi-storey buildings and reinforced concrete frames, with prestressed elements in transcendent states caused by special effects, are given in the article. The current state of the problem of robustness of building frames under special impacts is considered. A method for calculating the reinforced concrete frame of a multi-storey building with prestressed elements has been developed and its static-dynamic deformation has been studied to determine the robustness parameter. The parameters of deformation and destruction of prestressed reinforced concrete multi-story frame frames of buildings under design and beyond design impacts are experimentally determined. The results of the experimental study of frame structures are compared with the results of studies of similar structures without prestressing. The obtained results of the study can be used in the development of methods for protecting the frames of multi-storey buildings from progressive collapse.

Keywords: reinforced concrete structure, prestressing, robustness, special impact

1 INTRODUCTION

Currently, impacts of a natural, man-made and even terrorist nature, which were previously not taken into account by standards for design, but often caused the collapse of structures or the entire building, have become noticeably more frequent. Many accidents occurring in the world of buildings and structures that are designed in accordance with current standards for design are not always caused by explainable reasons. In this regard, research has begun in a number of countries to determine the true causes of such phenomena. More and more theoretical [1] to [3] and experimental [4] to [6] works began to appear with new terminology, including the concept of protecting buildings and structures from progressive collapse, and more recently with the term “robustness” [7], [8]. Moreover, in many countries, including Russia, in order to increase the structural safety of buildings and structures, preserve the life and health of the people in them, standards for design have been developed and introduced into design practice to protect buildings and structures from progressive collapse under special impacts.

The problems of robustness of structures and methods of their protection from progressive collapse constitute a new direction in solving the general problem of safety. Here, as in works [7] to [9], the term “robustness of a structure” refers to the ability of a system to distribute the load between other elements in the event of damage or weakening of one of the elements (corrosion, sudden shutdown of unnecessary elements of statically indeterminate systems). However, the term “robustness” itself is not new and is used in other areas of engineering, for example, in shipbuilding [10]. Research in this direction has been increasingly intensively carried out by scientists from different countries over the past two to three decades. Review works have been published [11] to [13], which present issues related to the problem of protection against progressive collapse, basic terminology, classification of types of progressive collapse, analysis of existing conceptual and methodological approaches to meeting structural safety requirements, and approaches to solving robustness problems. A large number of publications in recent years have been devoted to the development of methods of protection against progressive collapse, for example, work [14] to [16].

As these studies deepen, a number of new scientific problems arise, without solving which it is difficult to ensure the protection of buildings and structures from progressive collapse, and even more so the standardization of the basic parameters for the calculation and design of buildings and structures that are resistant to special impacts. Until now, research in this direction has focused mainly on unstressed reinforced concrete structures and models of their deformation. We can name individual theoretical [17], [18] and experimental [19], [20] works, in which it was shown in a statement that prestressing largely determines the robustness of reinforced concrete structural systems and can be considered as one of the effective ways to protect buildings and structures from progressive collapse [21] to [23]. A rational solution to increase the robustness of building frames can be the installation of prestressed reinforcement in the bending and tensile elements of building frames. The solution to this problem is largely connected with the creation of a deformation model, the construction of criteria for the strength and crack resistance of prestressed reinforced concrete elements of structural systems during a sudden redistribution of force flows. A large number of theoretical and experimental studies are devoted to the conditions of strength and plasticity of concrete and reinforced concrete, which differently resist tension-compression of structural elements, for example works [24], [25]. However, all these works did not consider prestressed reinforced concrete structures.

In this regard, the purpose of this work was to develop the provisions of the theory of robustness of reinforced concrete structural systems of buildings and structures with prestressed elements and methods of protecting them from progressive collapse under special impacts. The objectives of the study included:

- determination of dynamic additional loads in a reinforced concrete frame structural system with prestressed beams under static-dynamic loading;
- construction of a model of deformation of a prestressed element in the limit and beyond the limit state under a special impact;
- determination of the robustness parameters of monolithic reinforced concrete frames with prestressed beams under the special impact under consideration to confirm the proposed design dependencies.

Modeling of the considered physically and structurally nonlinear systems to determine the parameters of static-dynamic deformation diagrams of sections of prestressed elements was carried out taking into account nonlinear deformation and cracking of load-bearing elements. The resolving equations for analyzing the deformation of the considered frame structures with prestressed elements are constructed on an energy basis without involving the apparatus of structure dynamics.

2 METHOD

Consider a prestressed beam reinforced concrete element of a structural system and determine the design parameters of its deformation under force loading - at the first stage and subsequent dynamic (impact) additional loading - at the second stage. This loading mode simulates a special effect in the form of an instantaneous removal of one of the bearing elements from the structural system loaded with the operational load, which is used in the calculation analysis of the robustness of structural systems under conditions of special emergency effects [26]. The diagram method was used to determine these calculated parameters. The design parameters of the deformation diagrams of the "moment-curvature" sections are obtained on an energy basis from the conditions of conservation of potential energy after a structural restructuring of a structurally nonlinear system. The curvature in an arbitrary cross section of a prestressed reinforced concrete element was determined by the diagram method using a simplified “moment-curvature” relationship [27] (Figure 1):

$$æ = \frac{M - M_1}{B_1}, \tag{1}$$

M_1 is a segment cut off on the axis of the moments of the “M-æ” diagram, at a load higher than the cracking load ($M > M_{crc}$). In a prestressed element, this segment is denoted by $\overline{M_1}$. Parameter. B_1 characterizes the stiffness of a reinforced concrete element, the physical meaning of which is shown in the diagram: $B_1 = tg\alpha$.

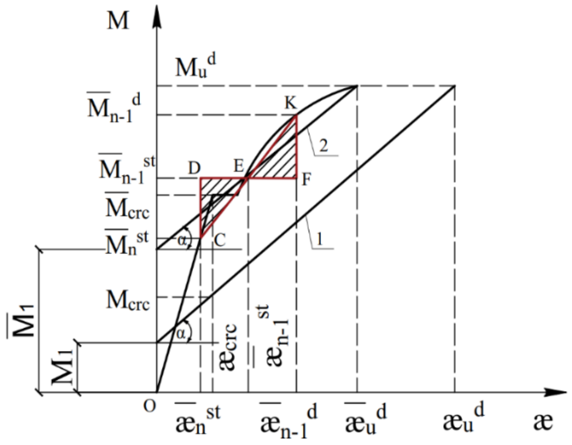


Fig. 1. Diagram "curvature moment (M-æ)" of static-dynamic deformation of the section of a reinforced concrete element: 1 - unstressed system, 2 - prestressed system

To determine $\overline{M_1}$ in prestressed bending and eccentrically compressed reinforced concrete elements, we use the notation adopted in the general formula for determining the curvature of a reinforced concrete element, and, by analogy with M_{crc}, the moment $\overline{M_1}$ is represented as:

$$\overline{M_1} = \varphi_2 b h^2 R_{bt,ser} + \varphi_3 N_{tot}(y_{so} + r). \tag{2}$$

As a result, the final expression for the curvature of a prestressed reinforced concrete element is obtained in the form:

$$æ = \frac{M_s - \varphi_2 bh^2 R_{bt,ser} + \varphi_3 N_{tot}(y_{so} + r)}{\varphi_1 E_s A_s h_0^2}. \tag{3}$$

The level of potential energy in a prestressed reinforced concrete element of a structural system after a sudden structural rearrangement with the accepted deformation diagrams of the elements "M-æ" (see curves 1, 2) is determined by the expression:

$$\Phi(æ)dæ = \int_0^{æ} M(æ)dæ = \int_0^{æ}(M_1 + æB_1)dæ = \frac{B_1}{2}æ^2 + M_1 æ. \tag{4}$$

The condition of constancy of the total energy for the considered section of the prestressed element leads to the expression:

$$\Phi(æ_{n-1}^{d}) - \Phi(æ_{n-1}^{st}) = \bar{M}_{n-1}^{st}(æ_{n-1}^{st} - æ_{n}^{st}). \tag{5}$$

After substituting (5) into (4), a quadratic equation is obtained with respect to the desired dynamic curvature $æ_{n-1}^{d}$, the solution of which is written as:

$$æ_{n-1}^{d} = \frac{\bar{M}_{n-1}^{st} - M_1 + \sqrt{(\bar{M}_{n-1}^{st} - M_1)^2 + \bar{B}_1^2 \cdot (æ_n^{st})^2 - 2\bar{B}_1^2 \cdot æ_n^{st} \cdot (\bar{M}_{n-1}^{st} - M_1)}}{\overline{\bar{B}_1^2}}. \tag{6}$$

Similarly, an expression was obtained for determining the dynamic moment in an arbitrary section of an n-times statically indeterminate frame:

$$M_{n-1}^{d} == \frac{M_{n-1}^{st} - M_1 + M_1 \cdot B_1 + \sqrt{(M_{n-1}^{st} - M_1)^2 + B_1^2((æ)_n^{st})^2 - 2B_1 \cdot (æ)_n^{st} \cdot (M_{n-1}^{st} - M_1)}}{B_1}. \tag{7}$$

The robustness parameter of a reinforced concrete statically indeterminate frame-rod structural system with prestressed elements is determined from the calculation of this system loaded by the forces λP_i applied in each third of the crossbar span at distances αl αl from the supports, and by the prestressing forces in the crossbars (Figure 2). The loads on the crossbars are assumed to be parametric and their change is proportional to a certain parameter λ, which is called the robustness parameter in the work.

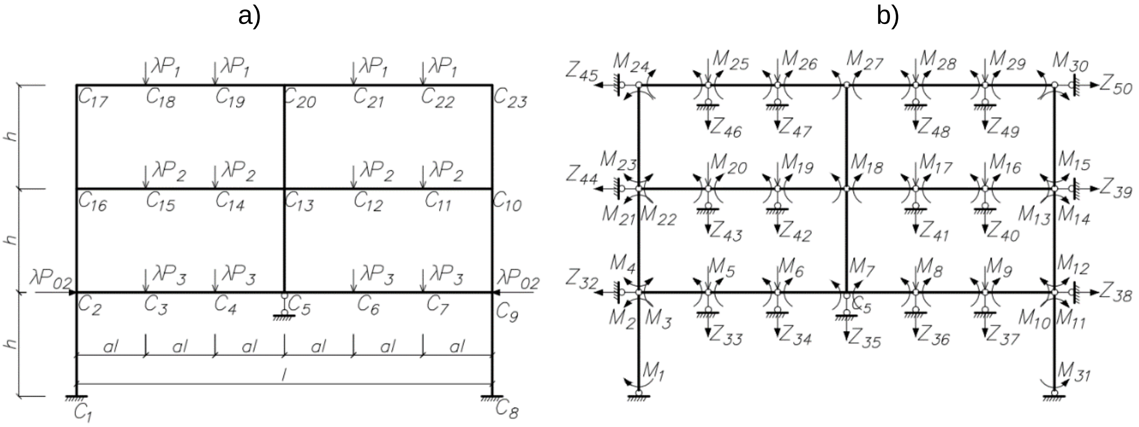


Fig. 2. Given (a) and based (b) mixed method system for determining the parametric load (robustness parameter)

The calculation of such a structurally nonlinear system was carried out using a variant of the non-ordinary mixed method [19].

The system of canonical equations of the mixed method for the considered frame structural system (Figure 1) has the form:

$$\left.\begin{aligned} &\sum_{j=1}^{31}\delta_{ij}\cdot M_j + \sum_{j=1}^{31}\delta'_{ij}\cdot Z_j + \sum_{j=1}^{31}\Delta_{ip} + \sum_{j=1}^{31}\delta_{ip}\cdot\lambda = 0(j = 1,2,\dots,n = 31)\,; \\ &\sum_{i=7}^{50} r'_{ij}\cdot M_j + \sum_{i=7}^{50} r_{ij}\cdot Z_j + R_{ip} + r_{ip}\cdot\lambda = 0, (i = k+1,\dots,k = 50). \end{aligned}\right\} \tag{8}$$

In matrix form, equation (8) is written as a system:

$$\left.\begin{aligned} A\cdot\vec{M}+B\cdot\vec{Z}+\overrightarrow{\Delta_p}+\overrightarrow{\delta_p}\cdot\lambda=0;\\ C\cdot\vec{M}+D\cdot\vec{Z}+\overrightarrow{R_p}+\overrightarrow{r_p}\cdot\lambda=0.\end{aligned}\right\} \tag{9}$$

The value of the forces in the switching off connections of the structural system from the total action of the given and parametric loads are calculated by the formula:

$$M_j=M_{jp}+m_{jp}\cdot\lambda\;(j=1,2,\dots,k), \tag{10}$$

where $M_{jp},\ m_{jp}$ are column matrix elements $\overrightarrow{M_p}$ и $\overrightarrow{m_p}$.

Turning off the moment or linear connection after the removal of one of the racks of the frame will occur when the limit value of the force in this connection is reached (with the yield of the reinforcement or the brittle fracture of the compressed concrete). Then, for all efforts in switching off moment constraints, the following system of inequalities must be satisfied:

$$\left|M_j\right|=\left|M_{jp}+m_{jp}\cdot\lambda\right|\le M_{j,\text{пр}}^{d}\;(j=1,2,\dots,k), \tag{11}$$

where $M_{j,\text{пр}}^{d}$ is the limiting value of the dynamic force in the disconnected link, which for a prestressed crossbar is determined in accordance with the current regulatory documents. From the solution of inequality (11), the minimum value of the parameter λ_m is found, at which the limit value is reached in the most loaded connection. The value ofλ_m is determined by the formula:

$$\lambda_m=\min\left(\frac{M_{j,\text{пр}}^{d}\pm\left|M_{jp}\right|}{m_{jp}}\right)\;(j=1,2,\dots,k). \tag{12}$$

3 EXPERIMENTAL STUDIES

For experimental confirmation of the proposed deformation dependences of the static-dynamic deformation of reinforced concrete structural systems, experimental tests of the robustness of monolithic reinforced concrete frames with prestressed crossbars were carried out under the considered special impact. The tests were carried out on reinforced concrete structures of flat frames of two series: RZh-1 - a frame with a suddenly turning off central post; RZh -2 - a frame with a suddenly turning off extreme rack (Figure 3).

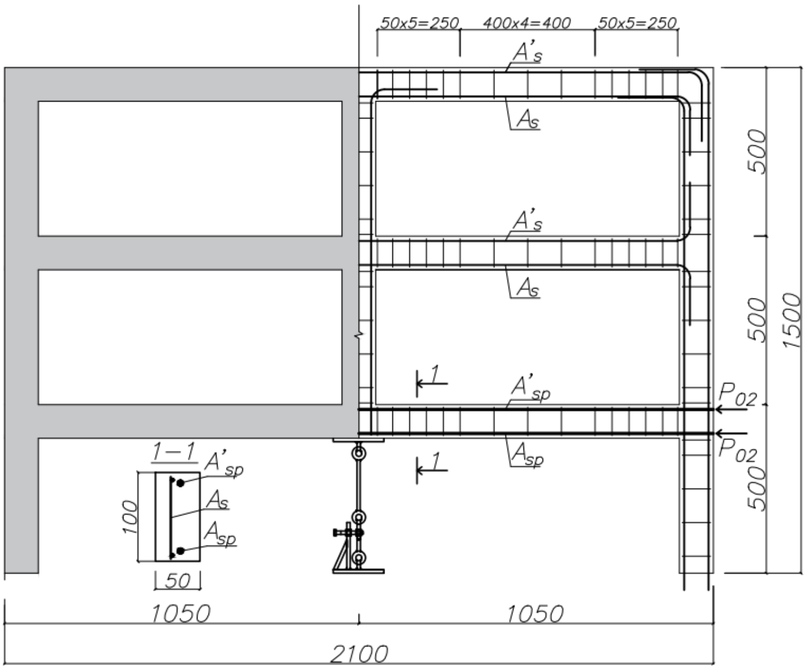


Fig. 3. Scheme of formwork (a) and reinforcement (b) of the frame structure of the first series

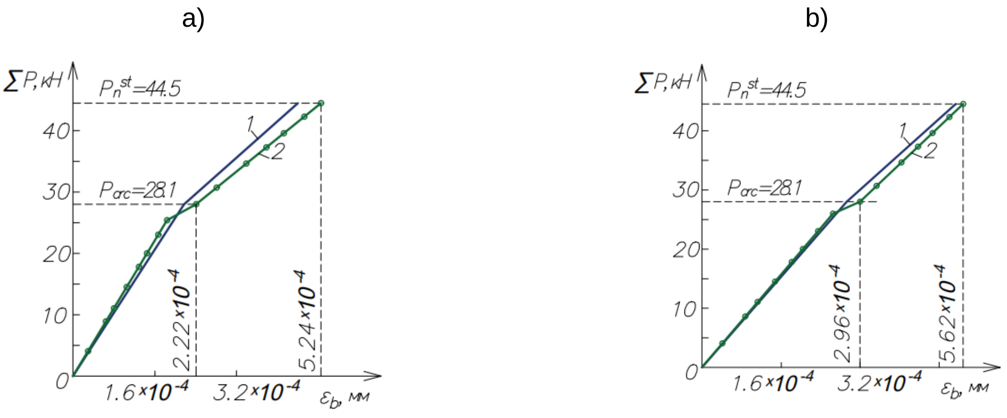
The experimental structures were designed and manufactured in the form of two-span prestressed reinforced concrete frames made of class C40 concrete. Cross-sections of beams and columns of frames are taken 50x100 mm. The value of the initial controlled stress is $\sigma_{sp}=514\,MPa$. The concrete compression force, taking into account all losses, was $P_{02}=17\text{k}N$ for each reinforcing bar. The crossbars of the frames of the second and third floors were reinforced in the upper and lower zones along the height of the section with working reinforcement in the form of a single rod with a diameter of 8 mm, class A500. The crossbar above the first floor of the frame, in order to protect it from progressive collapse, was made prestressed. Prestressed reinforcement was installed in the upper and lower zones from a rod with a diameter of 8 mm class A600. The transverse reinforcement of the crossbars is made of wire with a diameter of 2 mm, a pitch of 50 mm and 100 mm. Such reinforcement was assigned based on the results of the calculation of experimental frame structures for the design test load in the form of concentrated forces Pi applied in pairs to each crossbar symmetrically at a distance of 300 mm from the columns and the design impact in the form of a sudden removal of the central post for the RZh-1 frame and the end post for the RZh frame -2.

The experimental structures were loaded in two stages. At the first stage, according to the primary design scheme, the application of the operational load on the frame was modeled in the form of two concentrated forces in each girder span. At the second stage, a special effect was applied to the frame in the form of a sudden removal of the central or extreme pillar. The application of a special impact was carried out using a specially made folding (switching off) rack.

In the process of testing in experimental frame structures, the following were measured: the load of cracking and the load of exhaustion of the bearing capacity, deflections of the frame crossbars, deformations of concrete and reinforcement, the width of the opening and development of cracks at all loading levels, the time of dynamic additional loading of the frame elements.

The analysis of the data obtained during the experimental study of monolithic reinforced concrete frames with prestressed crossbars showed that the nature of deformation, cracking and destruction of structures has a number of features.

Experimental diagrams of deformation of concrete in the compressed zone of the support section of the crossbar above the first floor of the frame of the first series (RZh-1) and the central section of the crossbar above the first floor of the frame of the second series (RZh-2) at the first stage of loading were close to bilinear in nature (Figure 4). The maximum value of concrete deformations up to the moment of cracking in the frame of the first series was 1.46•10-4, in the frame of the second series 1.66•10-4. In the second section of deformation after application of the maximum design load, the experimental values of concrete deformation were 5.2•10-4 and 5.6•10-4 for the RZh-1 and RZh-2 series frame, respectively.



1- experimental values, 2- theoretical values

Fig. 4. Diagrams of concrete deformation in the supporting section of the crossbar of the frames of the first series (a) and the central section of the frame of the second series (b)

Analyzing the nature of the formation, opening and development of cracks obtained in the frame structures, the following can be noted.

At the first stage of loading in the prestressed RZh-1 frame structure, when loaded with the total design load, the first cracks were found in the support zones of the first floor crossbar near the outermost columns with a total load of ∑Pi=28.1 kN. Accordingly, the moments of formation of these cracks were 0.59 and 0.66 kNm. As the load increased to the level ∑ Pi=42.0 kN, new cracks appeared in the support section of the crossbars above the first floor and above the second floor near the outermost columns. At the considered stage of loading with the design load, normal cracks formed in the middle part of the span of the frame crossbars.

After the beyond-design impact caused by the sudden removal of the central post, in the RZh-1 frame, due to the structural restructuring of the structural system, cracks that had previously formed due to dynamic additional loading of the elements of the structural system opened up and new cracks formed in the support sections of the crossbar of the third floor of the frame. In addition, normal cracks were formed in the crossbars of all floors of the experimental structure. The largest crack opening width after the application of a special impact was reached in the support sections and amounted to 2.00 mm and 2.09 mm. However, significant damage did not occur in the experimental frame structure (Figure 5).

In the prestressed frame structures of the RZh-2 series, at the first stage of testing under loading with the total design load, the first cracks were found in the support zones of the crossbars of the second floor near the central column with a similar total load, as in the RZh-1 frame, equal to ∑Pi=28, 1kN (picture 6). Accordingly, the moment of formation of these cracks was 0.59 kNm. As the load increased to the level of ∑Pi=42.0 kN, new cracks appeared in the support section of the crossbars above the first floor near the outermost columns. At the stage of loading with the design load before the sudden shutdown of the end column, normal cracks did not form in the spans of the frame crossbars.

After the beyond-design impact from the sudden removal of the left post, in the RZh-2 frame, due to the structural restructuring of the structural system, an additional opening of previously formed cracks occurred. New cracks were also formed in the supporting sections of the crossbar of the third floor of the frame, as well as normal cracks in the crossbars of all floors of the experimental structure. The largest crack opening width after applying a special impact was 0.70 mm and 0.65 mm in the support section of the central and right columns. At the same time, the experimental frame design did not receive visible damage (Figure 7).

To evaluate the parameters of the diagrams of static-dynamic deformation of reinforced concrete prestressed elements, a numerical analysis of the design diagrams "moment-curvature" was performed and the results of the calculated values of these diagrams were compared with the results of experimental studies of reinforced concrete frames in the event of a sudden shutdown of the central or outer column (frame series RZh-1 and RZh-2, respectively). Curvatures during static-dynamic deformation in the reference section 1-1 of the RZh-1 frame and the span section of the crossbar of the RZh-2 frame above the first floor were calculated using the method proposed in previous paragraph and volumetric FE module in SP LIRA SAPR, taking into account concrete and reinforcement deformations.

The experimental values of the static-dynamic curvatures of the frame were determined from the values of the deformations of the compressed concrete and tension reinforcement. The limiting deformations of reinforcement in the dynamic section of deformation εnd-1 were calculated from the measured increments of the crack opening width in the considered section under dynamic additional loading of the frame.

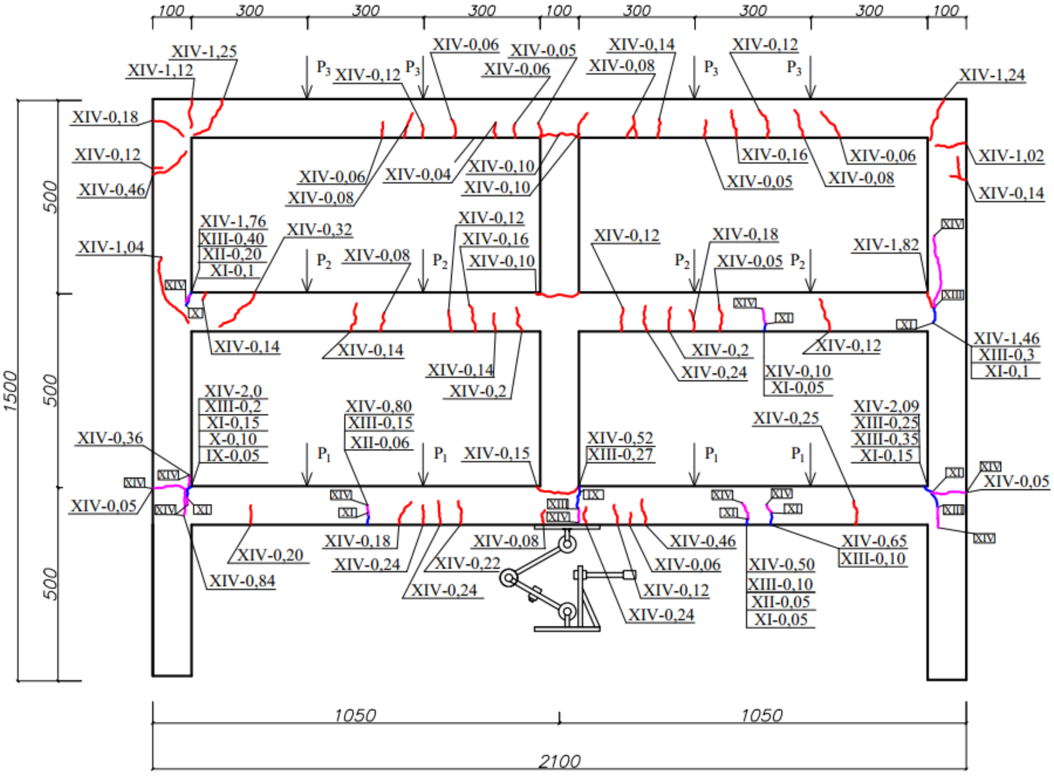


Fig. 5. Scheme of formation and width of cracks of all types in the design of the RZh-1 frame after applying a special load

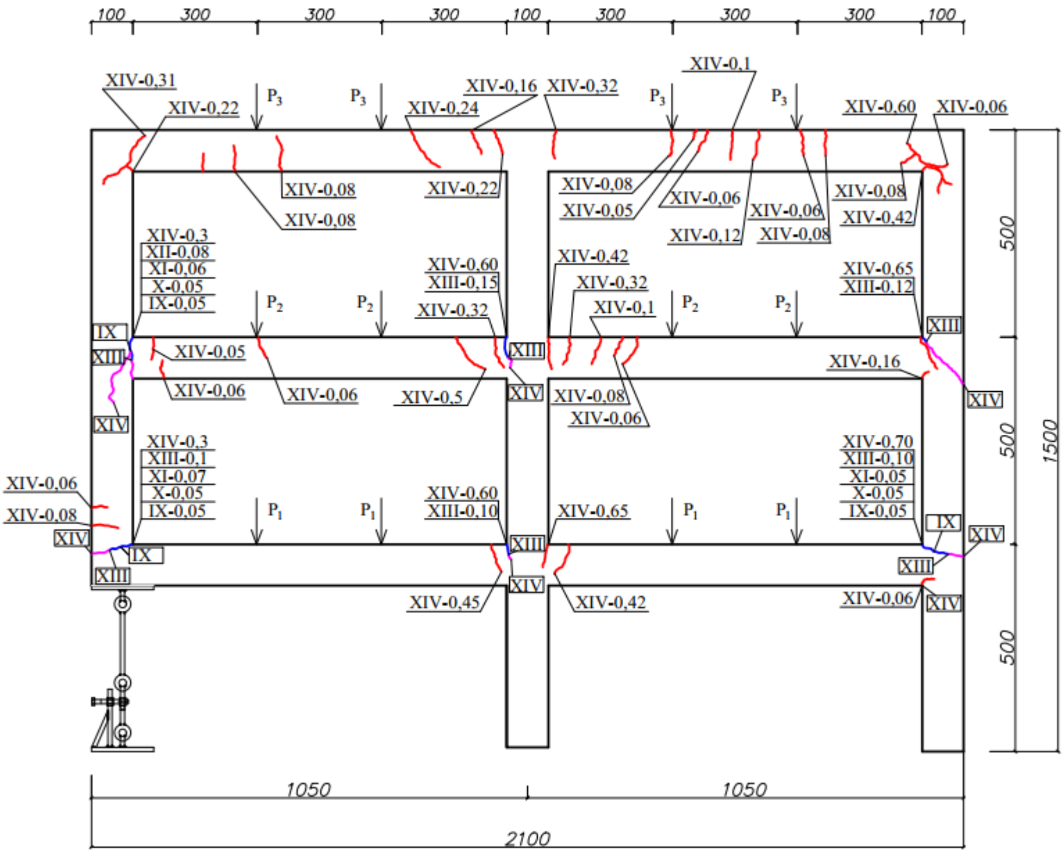
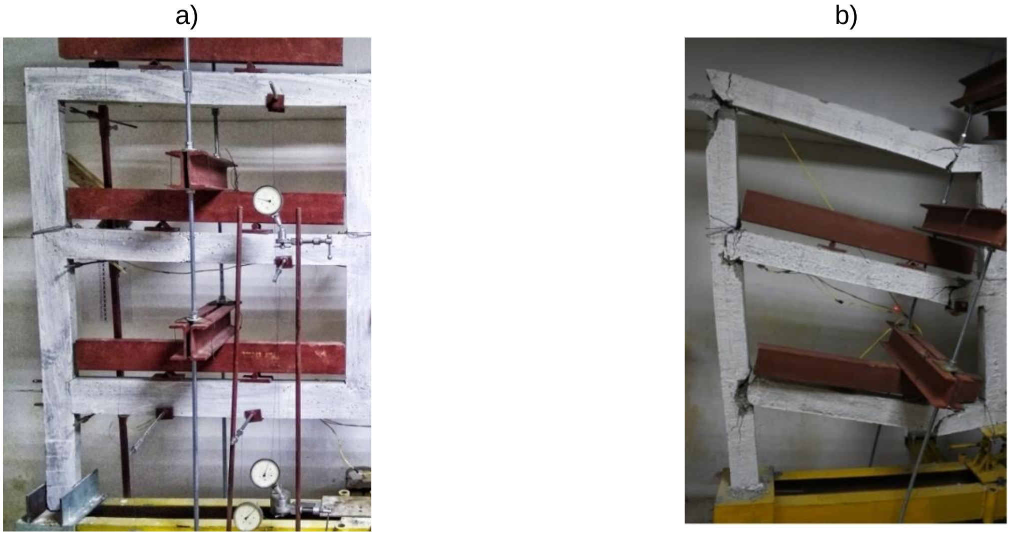


Fig. 6. Scheme of formation and width of cracks of all types in the RZh-2 frame structure after applying a special load


a)

b)

Fig. 7. The pattern of destruction in the experimental reinforced concrete frame-rod structural system after removing the central post with a prestressed crossbar above the first floor (a) and without a prestressed crossbar above the first floor (b)

In both frame structures (Figure 8) until the moment of cracking, the dependence "M-æ" had a character close to linear, determined by the initial stiffness of the section of frame structures B0. After the formation of normal cracks in the zone of the moment $\overline{M}_{crc}(M_{crc})$, a significant increase in curvature was observed with an almost insignificant change in load. After the proposal of the beyond-design impact and the instantaneous transformation of the original n-system into the n-1 system from turning off the central column, a significant high-speed increase in curvature was observed in the reference section under consideration (shown by a dashed line). Comparison of the experimental diagram (curve 2) with the theoretical one (curve 1) shows that the constructed calculated dependences for determining the dynamic curvatures quite satisfactorily describe the experimental strain curves. Figure 8 also shows the design parameters of the static-dynamic diagram "moment-curvature" of a similar design of a monolithic reinforced concrete frame without prestressing the crossbar (curve 3).

Analyzing the design diagrams, we can conclude that the accepted analytical dependencies for calculating the curvatures of reinforced concrete elements of frame-rod structures are in satisfactory agreement with the experimental moment-curvature diagrams obtained under the static-dynamic loading mode of such structures. So, with a total operational load ∑ Pi=42.0 kN with a calculated curvature according to the method [27] in the support section of the crossbar above the first floor æ=0.003 (1/m), the calculated deflection value was f=0.35 mm, and with the calculated curvature in section 1-1 of the crossbar of the frame of the first series æ=0.006 (1/m), the calculated deflection value was f=0.7mm, and the experimental deflection value was f=0.8mm, which indicates good convergence.

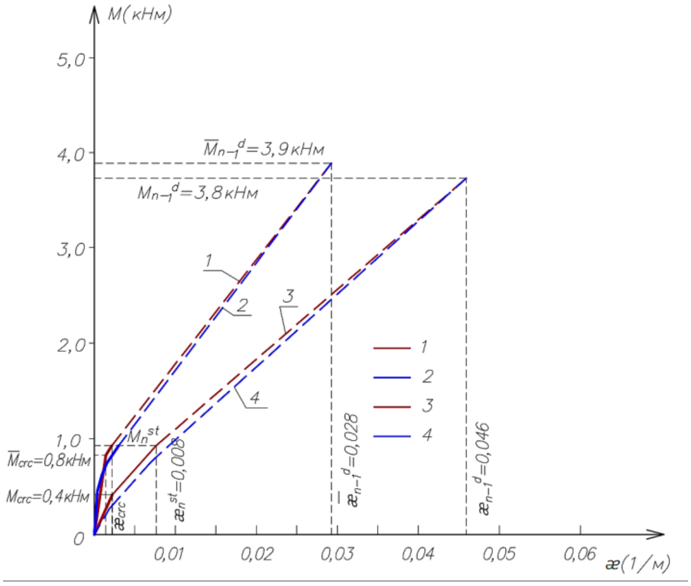


Fig. 8. Static-dynamic diagram "moment-curvature" in section 1-1 for the RZh-1 frame with prestressing: 1 - calculated according to the method for a prestressed frame; 2 - experienced for a prestressed frame; 3 - calculated according to the method for the frame without prestressing; 4 - experimental for a frame without prestressing

Experimental data on displacements were obtained by processing deflection meters installed on prototype frames for analysis and evaluation of the deformation criterion of a special limit state, which limits the maximum allowable relative deflection.

Analyzing these data, it can be noted that, according to this criterion of a special limit state, in both frames there was no exhaustion of the bearing capacity. The maximum deflection in the RZh-1 frame was 1/68 of the span length, in the RZh-2 frame 1/55 of the span length. This does not exceed the criterion of a special limit state, established by the regulatory document SP 385.1325800.2018. To compare the data on the movements of a reinforced concrete frame with a prestressed crossbar with the data on movements in an unstressed frame [29], [30], a comparative table of deflections was compiled (Table 1).

Table 1. Deflections in experimental designs of reinforced concrete frames

Frame type	Relative deflection before design impact $(f/l)_{st}$	Relative deflection after design impact $(f/l)_d$
Fame without prestressing	1/2611	1/18,8
	1/1736	1/17,1
	1/910	1/32,4
	1/1002	1/16,4
Prestressed frame	1/1326	1/78
	1/1294	1/68
	1/942	1/120
	1/1057	1/81

Comparing these results, it can be noted that for an unstressed frame with a relative deflection of 1/16-1/18 in quarters of the span of the crossbar, the bearing capacity is exhausted in the transcendent state caused by its destruction along the compressed concrete in the most stressed section.

From the comparison of the obtained pictures of the destruction of frames identical in reinforcement and tested according to the same schemes, it can be seen that the prestressing of the frame crossbars above the first floor ensures its protection under the considered special impact.

In conclusion, it can be noted that the experimental verification of the main analytical dependencies for determining the dynamic additional loads in the frame structure and its robustness parameter in the study under consideration was carried out on models of full-scale frame structures on a scale of 1:5. As was shown in [31], the scale factor influences the pattern of crack formation and damage propagation in individual elements of reinforced concrete structures. However, the mechanisms of destruction of the elements of the model and the real object are quite similar. It follows from this that the use of scale models of objects is acceptable for analyzing the mechanisms of their destruction and assessing the applicability of load-bearing capacity criteria. A more detailed extrapolation of the main results and conclusions to the design of full-scale structures will be the subject of future research.

4 CONCLUSIONS

Conducted experimental and theoretical studies of deformation, cracking and destruction of monolithic prestressed reinforced concrete structures under special effects in the form of a sudden removal of one of the bearing elements, the following new scientific and practical results were obtained:

1. Deformation dependencies are proposed to determine the parameters of static-dynamic deformation diagrams of elements of prestressed reinforced concrete structural systems during their structural restructuring caused by two-stage loading with a static load at the first stage and dynamic additional loading (special impact) at the second stage of loading.
2. Based on the results of the analysis of calculated and experimental deformation diagrams, it was established that the proposed analytical dependencies for calculating the curvatures of prestressed reinforced concrete structural elements are in satisfactory agreement with the experimental “moment-curvature” diagrams. Thus, with the total operational load on the beams of the experimental frames $\sum P_i=42.0$ kN, the calculated deflection value was f=0.7mm, and its experimental value was f=0.8mm. The discrepancy in the experimental and theoretical values of concrete deformations in the frame structures of both series did not exceed 8%.
3. The value of the dynamic additional load coefficient in prestressed frame structures was experimentally determined and calculated as the ratio of the crack opening width after a special impact to the crack opening width before the special impact. For the most stressed span sections of the experimental frames of both series, this coefficient was 6.5 and 5.0, respectively. In similar unstressed structures, this coefficient was 4.2 and 2.9, respectively. This indicates a noticeable influence of prestress on the damping properties of the structures under consideration. It has also been established that, with a sudden change in force flows in frame structures, prestressing significantly increases the rigidity of frame structural elements. The maximum deflection in the prestressed frame was 1/68 of the span, which does not exceed the special limit state criterion established by Russian and US standards. In a similar frame without prestressing, the deflection was 1/17, and its load-bearing capacity was exhausted.

5 ACKNOWLEDGMENT

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https://rscf.ru//project/24–49-10010/

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