Influence of Compliance of the Connection of Reinforced Concrete Structures in the Analysis of Progressive Collapse Hazard

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Annotation. The results of a numerical study of a fragment of a reinforced concrete frame of a multi-storey building with a special impact in the form of a sudden hypothetical removal from operation of one column are presented. For a more rigorous assessment of the stress-strain state of reinforced concrete frames of multi-storey buildings, it is proposed to take into account the elastic-plastic work of the junctions of structural elements. Two options for connecting a crossbar with a column are considered: the first is absolutely rigid, the second is taking into account nonlinear compliance in the areas: "bending moment-angle of rotation", "transverse force-deformation", "longitudinal force-deformation". According to the results of numerical analysis, a change in internal forces (up to 30%) in the elements of reinforced concrete systems is shown due to the non-linear operation of both structural materials and the geometric non-linearity of the change in the dimensions of the design model due to the compliance of nodes. The revealed differences in the nature of the change in the stress-strain state are explained by an increase in the plastic properties of the carrier system. The established phenomena require further experimental verification, taking into account various types of structural element connections.
Keywords: progressive collapse, reinforced concrete structures, dynamic reloading, survivability, special limiting state, physical nonlinearity.

Introduction

The most widely used for civil buildings are frame bearing systems. They have become widespread due to the wide possibilities of variations in space-planning solutions of the internal space, as well as due to the rapidly developing technologies of monolithic housing construction [1,2].

When solving the problems of modeling the nodal junction of a crossbar with a column, it is known from the basic design provisions [3,4] that the junction can be hinged, rigid, and with partial pinching. When calculating the risk of progressive collapse of a monolithic

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reinforced concrete building, a rigid interface is often taken for calculations, and further calculations are performed as for a rigid node (Fig. 1).

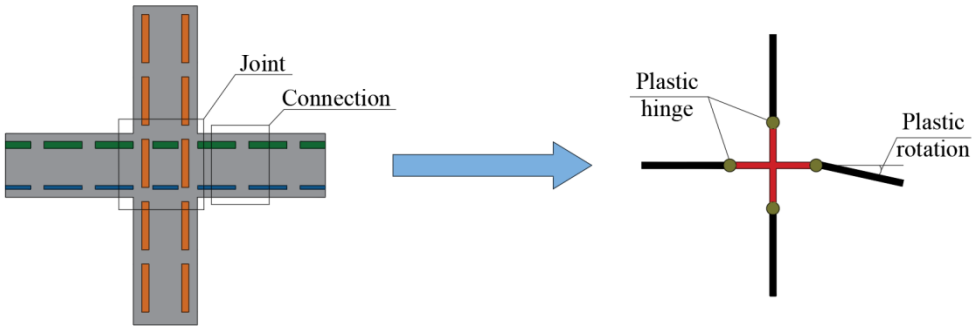


Fig. 1. Accounting for the plasticity of nodes.

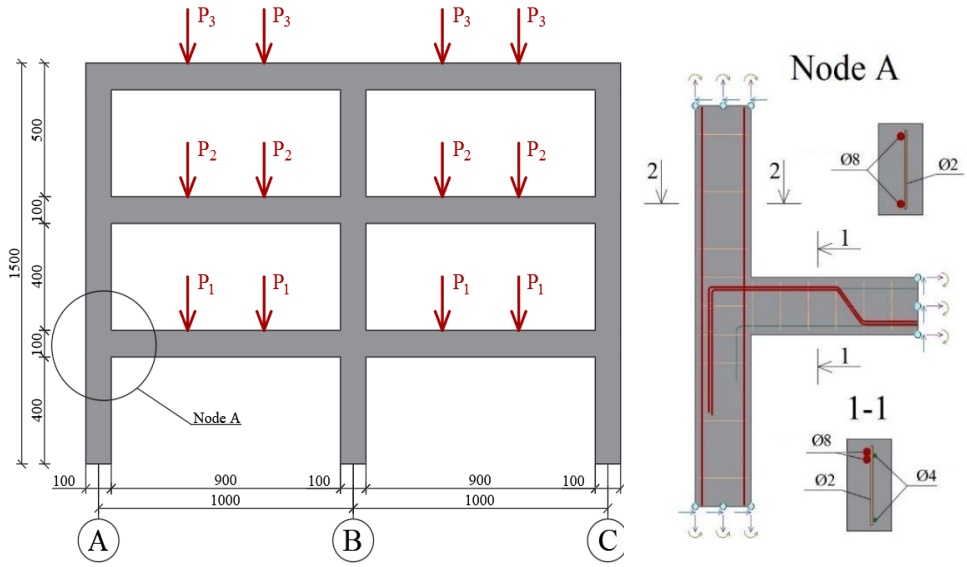
At the same time, as shown by theoretical and experimental studies aimed at increasing the survivability of load-bearing systems made of monolithic reinforced concrete [5,6,7], the issues of the behavior of load-bearing systems, taking into account the actual work of conjugation of structural elements, remain studied only fragmentarily, at the staged level.

The work of A.M. Belostotsky is devoted to the problem of numerical and numerical-analytical methods for calculating reinforced concrete structural systems. [8-10], including during emergency impacts Travush V.I. [8-11], Kolchunova V.I. [8,10,12-14], Fedorova N.V. [5-7,11, 12,16,18,19]. At the same time, taking into account the compliance of the conjugation of element structures under emergency dynamic impacts has not been studied enough. There are various approaches to take into account the compliance of joints under static loading, here we can note the works of N. N. Trekin [20] and A. N. Mamin [21]. In this regard, the objectives of this work are to evaluate the effect of compliance of interface nodes of structural elements of the bearing system from monolithic reinforced concrete on the resistance to progressive collapse.

Methods

To identify the nature of the effect of compliance on the stress-strain state of monolithic reinforced concrete structural systems during emergency actions associated with the instantaneous removal of one of the load-bearing elements of the system, a numerical model of a reinforced concrete frame made on a scale of 1:6 was used. The geometric dimensions and the scheme of reinforcement of the investigated reinforced concrete frame are shown in Fig. 2. Two models were considered: the first one with absolutely rigid nodes, the second one taking into account the flexibility of the connection.

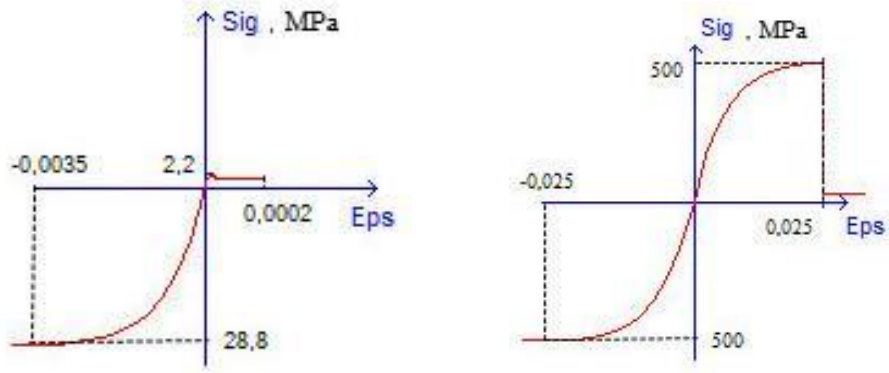
Models of frames of the first and second series are made of B40 class concrete. Reinforcement is made by flat frames with longitudinal reinforcement with a diameter of 8 mm, class A500, and a transverse diameter of 2 mm with wire reinforcement with Rs,n=300 MPa.



a) b)

Fig. 2. a) design scheme of the frame frame; b) constructive solution of node A.

The strength and deformation characteristics of concrete and reinforcement are taken taking into account the nonlinear law of deformation (Fig. 3).



a) b)

Fig. 3. a) Graph of the exponential law of concrete deformation; b) Graph of the exponential law of reinforcement deformation.

The degree of compliance was taken into account by the operation of special finite elements, using state diagrams "moment-angle of rotation", "transverse force-deformation" and "longitudinal force-deformation". To plot the state diagrams of the junctions of structural elements, the method of a nonlinear deformation model was used, in which the transition from the stress diagram in concrete and reinforcement to generalized internal forces is determined using the procedure of numerical integration of stresses over a normal section. To do this, the normal section is conditionally divided into small sections: according to the height and width of the section. Stresses within small sections are assumed to be uniformly distributed. The parameters were set for two possible types of reinforcement: crossbars or columns (Fig. 4).

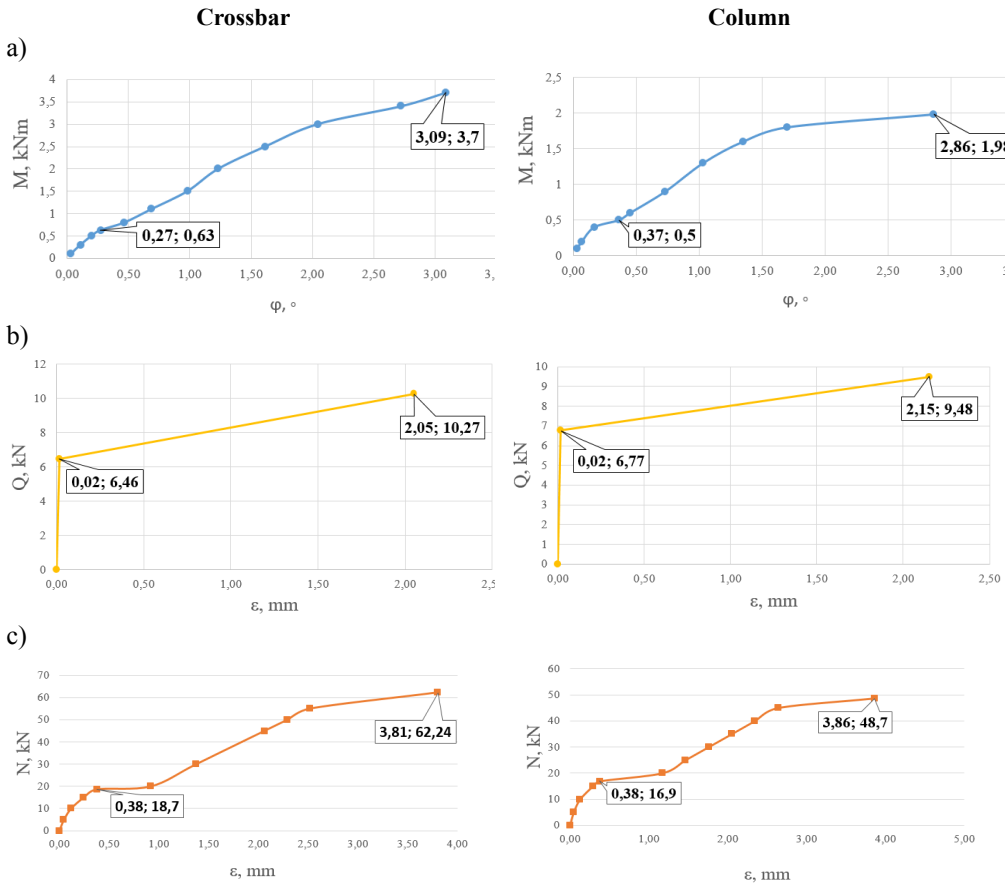


Fig. 4. a) Dependence of the angle of rotation on the bending moment; b) Dependence of transverse strain on transverse force; c) Longitudinal strain versus longitudinal tensile force.

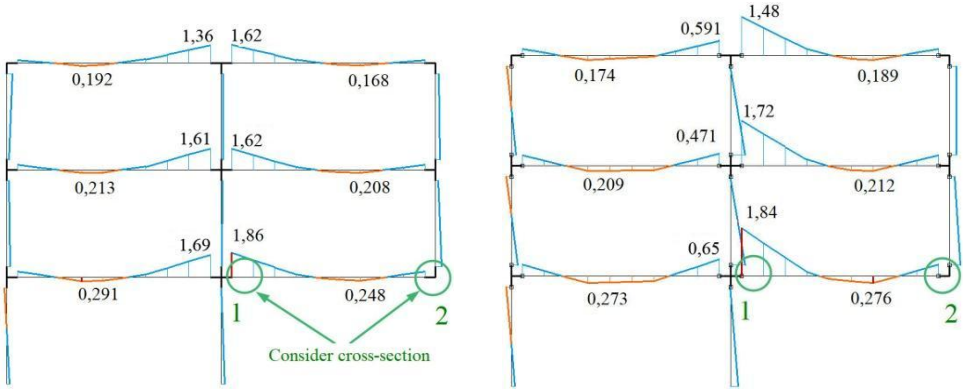
To assess the nature of the dynamic redistribution of power flows between the structural elements of the considered models of reinforced concrete frames, a dynamic calculation was performed for the sudden removal of the first floor column. The load in the form of concentrated forces was applied in 1/3 of the calculated span on the crossbars of the first, second and third, respectively. The load parameters are as follows - P1 = 4.56 kN, P2 = 3.65 kN, P3 = 2.28 kN. In the process of computational analysis, damping factors were taken into account using Rayleigh coefficients.

Results and discussion

As a result of the performed computational analysis, the nature of the change in time of internal forces for the most loaded element of the structural system was revealed (Fig. 5, 7, 9). The most indicative are the following elements of the structural system: 1 - the supporting section of the crossbar; 2 - support section of the crossbar above the removed column; 3 - compressed column.

When analyzing the nature of the change in bending moments, it was found that when taking into account the compliance of the joint, the moments are redistributed at all three

levels and in the central column due to the formation of plastic hinges, in particular: for the first level crossbar, the moment value changed by 1,77 times, for the second - by 3,43, the third - by 2,6 times, in the column the bending moment increased by 0,58 times (Fig. 5).

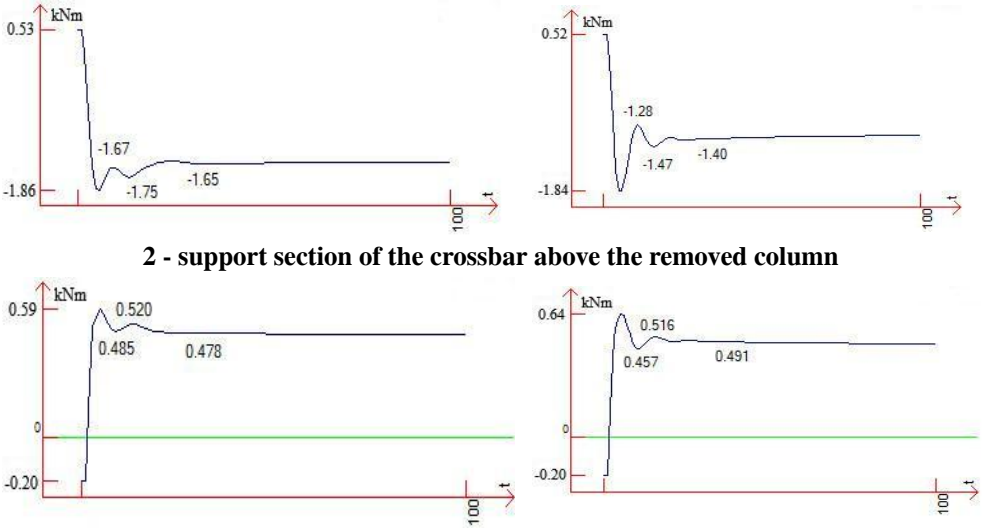


a) b)

Fig. 5. Diagram Of Bending Moments: a) fora frame with rigid nodes; b) taking into account the compliance of the nodes.

Analyzing the nature of the change in time of the bending moments in time (Fig. 6) at point 1, it can be noted that the maximum value is reached at the moment of time: td=0.04 seconds. At the same time, significant changes in the oscillatory process are observed. The discrepancies in the amplitude values are 30%, which is explained by the greater plasticity of the system with pliable nodes. Analyzing the section of the crossbar adjacent to the removed column (point 2), there is a different entry point into the oscillatory process, which differs by 8%. The parameters of the change in time of the oscillatory process differ slightly due to the lack of the possibility of redistributing forces to neighboring structures.

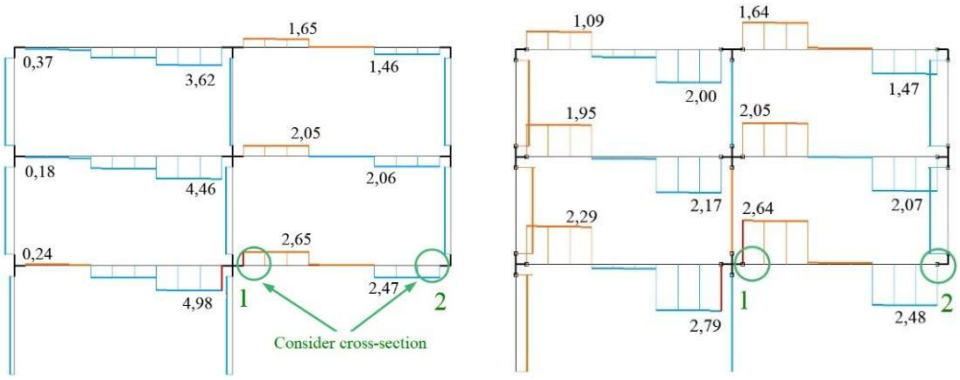
1 - the supporting section of the crossbar



a) b)

Fig. 6. Time change of bending moments:a) fora frame with rigid nodes; b) taking into account the compliance of the nodes.

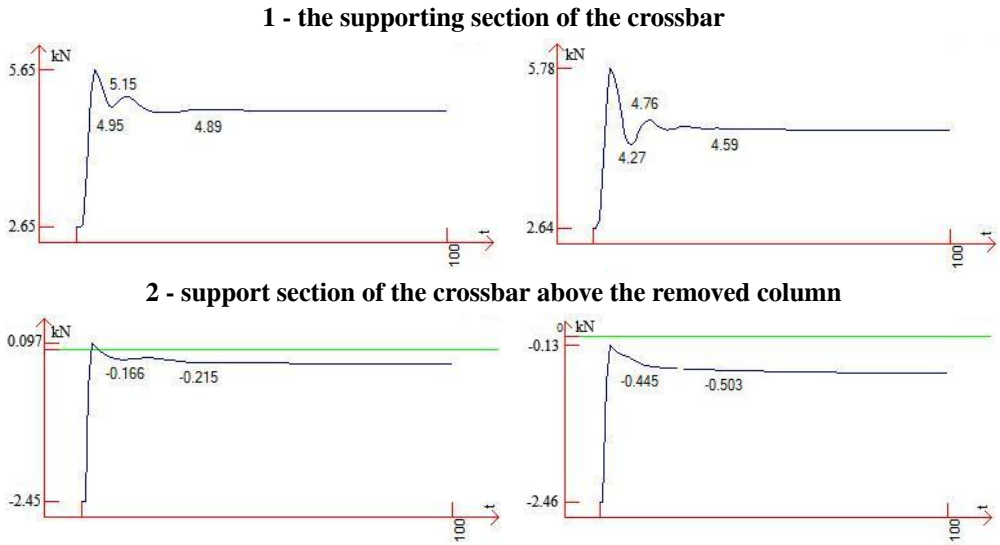
Indicative is the gradual increase in transverse forces along the crossbar of all three levels of the undamaged span, due to dynamic additional loading of the central column for the model with rigid nodes, with uneven values of the transverse force on the supports, which is not observed when compliance is taken into account (Fig. 7).



a) b)

Fig. 7. Diagram of transverse forces: a) fora frame with rigid nodes; b) taking into account the compliance of the nodes.

Similarly, there is a change in the values of the transverse force (Fig. 8) in time. The maximum amplitude value at point 1 differs slightly, about 2%, while minor discrepancies are observed in the process of oscillation damping from 10% to 15%.

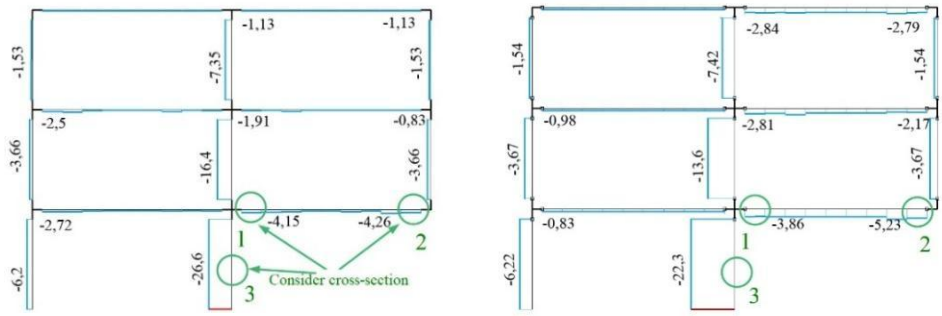


a) b)

Fig. 8. Time change of shear forces: a) fora frame with rigid nodes; b) taking into account the compliance of the nodes.

When analyzing the change in the transverse force at point 2, the amplitude value of the transverse force in the first period of the oscillatory process (about 30%) with a small numerical value (about 0.1 kN) attracts attention. It is also necessary to note a smooth, unchanged decrease in the longitudinal force in the cross section of the crossbar adjacent to the removed column. What is not observed in the model with rigid nodes.

When analyzing the change in longitudinal forces in the elements of the frames under study, a significant (20%) difference was found in the middle column of the first and second floors. The decrease of which is explained by an increase of 2 times or more of the longitudinal force in the second level crossbar.

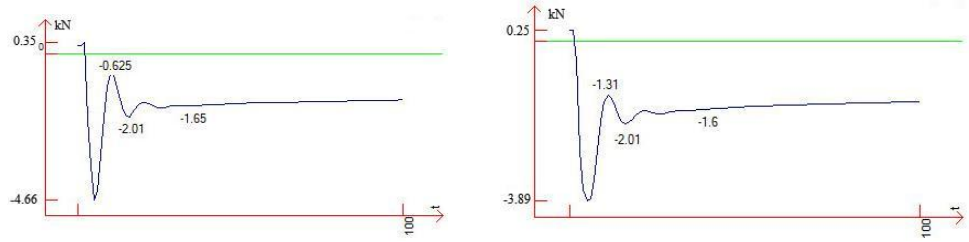


a) b)

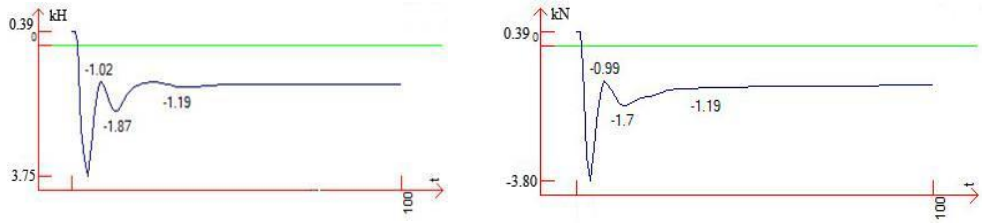
Fig. 9. Diagram of longitudinal forces: a) fora frame with rigid nodes; b) taking into account the compliance of the nodes.

The change in time of the longitudinal forces at point 1 (Fig. 10) differed in the value of the longitudinal force at the beginning of the oscillatory process, in a system with rigid nodes, it is 30% larger.

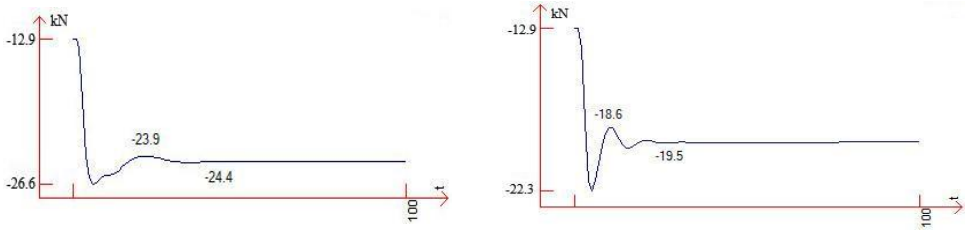
1 - the supporting section of the crossbar



2 - support section of the crossbar above the removed column



3 - compressed column



a) b)

Fig. 10. Change of longitudinal forces in time:a) fora frame with rigid nodes; b) taking into account the compliance of the nodes.

The amplitude value in the system with pliable nodes in the first period was 3.89 kN, which is 17% less than in the case of rigid conjugation of the system elements. The maximum longitudinal force in 1 section decreased by 16.5%, and during attenuation it changed by an insignificant amount. In section 2, the longitudinal force remained almost the same. In section 3, the maximum longitudinal force decreased by 16%, and with damping by 20% (Fig. 10). The longitudinal forces in the column, at the moment of exclusion of the outer column, are the same and amount to 12.9 kN, however, during the oscillatory process in the horizontal elements of the system they change, damping in the case of rigid nodes on one vibration, and when taking into account the compliance of the joints of two. At the same time, upward deviations remain in the range from 25% to 30%.

Conclusions

The performed dynamic analysis of the simulation of an emergency impact in the form of an instantaneous removal of its corner column from a reinforced concrete frame made it possible to establish that the achievement of a special limit state in the structural system of a prefabricated monolithic frame is localized in the area adjacent to the removed column.

According to the results of numerical analysis, a significant change in internal forces (up to 30%) in the structural elements of reinforced concrete systems is shown due to the non-linear operation of both structural materials and the geometric non-linearity of the change in the dimensions of the design scheme due to the compliance of the joints of the structural elements. The established phenomena require further experimental verification, taking into account various types of structural element connections.

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