

RESISTANCE OF STEEL FRAMES WITH RIGID AND HINGED JOINTS TO PROGRESSIVE COLLAPSE

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Abstract. This paper addresses a significant and current issue in the field of improving the mechanical safety of buildings and structures with metal frames subjected to specific types of impact. Based on experimental tests and numerical verification, it studies the behavior of a steel frame in an emergency. The rapid removal of the central column was considered as an example of such an accidental action. To increase the frame's resistance to progressive collapse, the structure incorporates tie rods, which redistribute additional loads. Two types of frames were considered: those with hinged beam-column connections and those with similar rigid units. The experiments revealed the nature of the change in strains over time under dynamic loading and determined the characteristics of vibrational processes for frames with different joint designs. The role of tie rods in stabilizing frames against progressive collapse was determined. The displacement variation over time was also determined. The approach to modelling the accident situation was found to be in satisfactory agreement with experimental data. It was established that frames with hinged joints have a lower load-bearing capacity at the joint connections than frames with rigid joints. However, they have a predictable failure mechanism and a shorter transient dynamic process duration following an accident impact.

Keywords: dynamics, steel frames, progressive collapse, deformations, damping, mechanical safety, robustness, accidental action

ОЦЕНКА СОПРОТИВЛЕНИЯ ПРОГРЕССИРУЮЩЕМУ РАЗРУШЕНИЮ СТАЛЬНЫХ РАМ С ШАРНИРНЫМИ И ЖЕСТКИМИ СОЕДИНЕНИЯМИ ЭЛЕМЕНТОВ

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Аннотация. В работе рассматривается важный и актуальный в настоящее время аспект повышения механической безопасности зданий и сооружений с металлическими рамными каркасами при особых воздействиях. На основе экспериментальных испытаний и численной верификации изучено поведение стальной рамы при аварийном воздействии. В качестве такого аварийного действия рассматривалось быстрое удаление средней стойки из расчетной схемы. Для повышения устойчивости к прогрессирующему разрушению рамы в ее схему были включены страховочные элементы в виде тяжей, перераспределяющих дополнительные нагрузки от аварийного динамического нагружения. Рассматривалось два типа рам: с шарнирными соединениями балки и колонны, а также с аналогичными жесткими узлами. В результате экспериментов выявлен характер изменения продольных деформаций во времени при динамическом нагружении, определены характеристики колебательных процессов для рам с различными конструктивными исполнениями узлов. Определена роль тяжей в обеспечении устойчивости рам к прогрессирующему разрушению. Установлен характер изменения перемещений во времени. Достигнуто удовлетворительное соответствие экспериментальным данным подхода к моделированию аварийной ситуации. Установлено, что рама с шарнирными узлами обладает более низкой несущей способностью по узловым соединениям по сравнению с жесткими узлами, однако имеет прогнозируемый механизм разрушения и меньшую длительность переходного динамического процесса аварийного воздействия.

Ключевые слова: динамика, стальная рама, прогрессирующее разрушение, деформации, демпфирование, механическая безопасность, живучесть, аварийное воздействие

1. INTRODUCTION

Mechanical safety of buildings under accidental actions is one of the main challenges in construction science. A significant number of studies addressing this issue makes it possible to identify one of the urgent tasks of increasing the resistance of buildings to progressive collapse. This is the incorporation into the design scheme of additional structural elements, which are sometimes called safety elements. Such elements, e.g., struts, ties, prestressed ropes, rods with adjustable stress, diaphragms, wall fillings, suspenders, etc. redistribute loads, participate in the perception of dynamic loading and significantly increase the robustness of buildings and structures under accidental actions.

For industrial facilities, the robustness enhancement aspect is discussed in [1]. Based on the analysis of the stress-strain state of the structures of the existing reconstructed facility, possible accidental situations are related both to the structural features of the building and to the specifics of the technological process carried out in the considered metallurgical facility.

The concept of collapse resistance design of a steel framed system with members in which internal forces are controlled is outlined in [2]. These members are designed considering the range of forces that may appear during progressive collapse. Their presence allows to regulate the area of the structural system in which the failure of structural elements occurs.

The paper [3] presents the results of the study of robustness of damaged steel trusses, as well as the release time during which local failure occurs. Based on experimental and theoretical studies, the influence of local failure on load-bearing structures as a whole is studied. Numerical analysis shows that the shorter the failure time of a truss member, the greater the dynamic forces arising in the structure. Based on the obtained results, the failure time of the damaged rod and the redistribution of forces on the neighboring members of the truss have been calculated.

Study [4] has been dedicated to the investigation of the collapse resistance of steel frames with

prestressed tie rods. The authors developed a macromodel of a typical connection for static nonlinear analysis of structural performance using finite element modeling with OpenSees. The model was validated against experimental data and applied to a six-story framed building. The scenarios of extreme and mid-column removal at the first floor have been considered. The results of the analysis showed that the steel braced frame has a fairly high resistance to collapse. The structure did not collapse if the middle column failed, and the probability of collapse if the outermost column failed was 2%. The work [5] deals with the study of the relationship between the dynamic coefficient and the collapse resistance of a structure under the column removal scenario. It was found that the influence of medium and high strain rates on the ultimate displacement of structures under column removal can be ignored. It confirmed that the static FEM analysis of structures under column removal can be used to determine the ultimate limit state of the structure under medium and high strain rates.

The paper [6] considers an approach to the calculation of steel framed structures taking into account structural nonlinearity, including the removal of supports, accidental impacts, etc. This approach is based on the direct method of integration balanced by static equivalents of reactions.

The paper [7] analyzes the performance of the steel frame during the removal of the inner column and determines the critical deformations at collapse. The analysis was performed using finite element modeling employing the ABAQUS program. It considered the influence of beam span and height, thickness and side ratio of the floor slab of the building on the magnitude of these deformations due to the removal of the internal column of the considered steel frame of the building. Comparison of deformations of steel frame showed that the presence of floor slab significantly reduces the magnitude of deformations. At the same time, increasing the side ratio of the floor slab from 1:1 to 1:2 increases their magnitude by 20%.

The finite element analysis as pointed out in [8] is a general approach to perform nonlinear dynamic analysis of steel frame collapse with semi-rigid joints. The numerical results showed that the real performance of the assemblies has a significant effect on the dynamic reactions and subsequently on the failure process of the framed structures. It was marked that the failure of members and their joints, as well as the nonlinearities of material and joint behavior, should be accounted for in the analysis of structural failure. It was found that at the ends of beams in rigid and linear semi-rigid frames only element failures have been observed, while in nonlinear semi-rigid frame only joint failure has been identified.

The paper [9] presents a method for quantitative assessment of dynamic effects on a steel frame structure as a result of instantaneous removal of an internal column. This method allows us to calculate the value of the dynamic factor at the moment of reaching the limit state of structural failure and to predict its deformations under such a scenario. Similar to [7], a comprehensive parametric analysis was carried out in [9] to study the influence of various structural parameters such as beam span and depth, slab thickness and side ratio on the dynamic factor, including at the moment of structural collapse.

The paper [10] presents the results of experimental and theoretical studies of steel frames with reinforced concrete slab against progressive collapse. Finite element modeling of the structure was verified according test data for joints. The developed models were verified by the results of displacement tests, forces in the members. The failure regimes were established. Particular attention was paid to the development of resistance mechanisms of the floor slabs and the influence of beam-column assembly types on the behavior of the structure. In addition, the influence of the spacer system in the structure on the resistance to progressive collapse was investigated.

The results of the study of a modular steel structure are presented in [11]. Based on experimental data and numerical simulation, the failure mechanisms and force redistribution were studied for a four-story, nine-span modular

steel structure under different failure scenarios. It was emphasized that the redistribution of forces occurs only within the span of the failed member or block and has little effect on the other part of the structure.

A comprehensive analysis of the influence parameters on the failure mechanism and failure resistance action of a typical bolted beam-to-column connection on angles in steel frames subjected to fire is given in [12]. The results of numerical analysis showed that all steel frame structures with different types of beam-to-column connections exhibits the arch action after the heating phase due to the thermal expansion of the beams. Based on the results, a theoretical method was proposed to predict the failure mechanism of steel frames with bolted beam-to-column connections subjected to fire under progressive collapse conditions.

The paper [13] investigates the influence of dynamics in progressive collapse by analyzing the dynamic factor for steel structures considering the increase in the number of floors. A numerical algorithm including static and dynamic analysis was proposed. This algorithm is applied to evaluate five framed structures with seismic design. An accurate finite element model was developed, taking into account imperfections and geometric nonlinearity, using the OpenSees software.

In order to increase the resistance to progressive collapse of steel frames, the authors of [14] have developed and investigated the beam-column interface, strengthened with a folding plate welded to the inner side of the I-beam flange and to the column. The load-carrying capacity of such a connection for progressive collapse was evaluated based on the results of tests and numerical analysis using the ABAQUS program. A comparative analysis of the performance of two types of assemblies: standard and reinforced with welded plates showed that the load-bearing capacity of the plate-strengthened specimen is 21.1% higher, indicating that such assemblies have the ability to increase the resistance to failure of steel framed structures.

The paper [15] presents the results of experimental and numerical analysis of the

mechanism of progressive collapse of a steel frame with beam-column connections made of L-profiles. According to the results of the research, the deformations of the connecting elements allow a better assessment of the process of failure and deformation of structures during the progressive collapse of the frame, as well as the performance mechanism of the damaged frame and the redistribution of forces between the load-bearing structures occurring at damage.

In [16], the effect of vertical ties on the load-bearing capacity of steel frames under progressive collapse was investigated. The test results showed that ties can increase the ultimate load-bearing capacity of frames by 102.3%.

The study [17] of steel frames with masonry infilling walls in the plane of the frames with smaller beam cross-sections demonstrate an increase in the load-bearing capacity of such structures compared to frames without such infilling. The supporting effect of the double strut that is formed inside the infilled diaphragm wall during the collapse phase, steel frame structures with infilled walls better resist to large displacements in accidental design situation than the corresponding frames without infilling.

The article [18] presents the results of static and dynamic tests of frames with bolted beam-column assemblies equipped with additional structural details to prevent progressive collapse. The results of tests of such assemblies showed that their load-bearing capacity is ensured even at rotations of the beam support part of more than 0.2 rad.

The paper [19] is dedicated to experimental and theoretical studies of beam-column assemblies of steel frames with lightweight frame-clad walls for progressive collapse at the removal of the inner column. Based on parametric analysis, the influence of key design variables on the resistance to progressive collapse of the structure was examined. The results emphasize that the influence contributed by the wall cladding of the frame on the load carrying capacity of the steel frame is significant.

The objective of this study is to investigate the load-bearing capacity of a steel frame with tie rods against progressive collapse.

2. METHODS

2.1 General provisions. As part of the problem statement, the resistance to progressive collapse of an experimental specimen of a framed structure with rigid and hinge joints of beams and columns and safety suspender elements was investigated experimentally. The purpose of the research was to identify the deformation regimes of the frame and determine the characteristics of its stress-strain state (STS). The initiation of progressive collapse was performed by removing the middle column. The release time was assumed to be small. Physically the removal was performed by horizontal impact. The experimental results were used to verify the accuracy of modeling the progressive collapse of steel frames.

2.2 Experimental designs and experimental plan. The specimens are frames whose beams and columns consist of 10B I-beams (GOST 26020-83) (Figure 1). Two variants of joints were considered. In the first variant the joints of beams with columns at supports and between each other in the spans were rigid, and in the second variant it was hinged. The connection of the columns to the power floor was rigid in all cases. To ensure that the frame deformed predominantly in its plane, a structure including additional columns and beams was used. Beams made of 51x3 round pipes (GOST 10704-91) connected the outermost joints of the frame to the force floor.

The frame was loaded with concrete blocks fastened to the beams by a steel cage consisting of plates tightened with studs. The mass of each of the blocks was 195 kg. The models and types of assemblies in rigid and hinged versions are shown in Figure 2. The general view of the experimental specimens is shown in Figure 3.

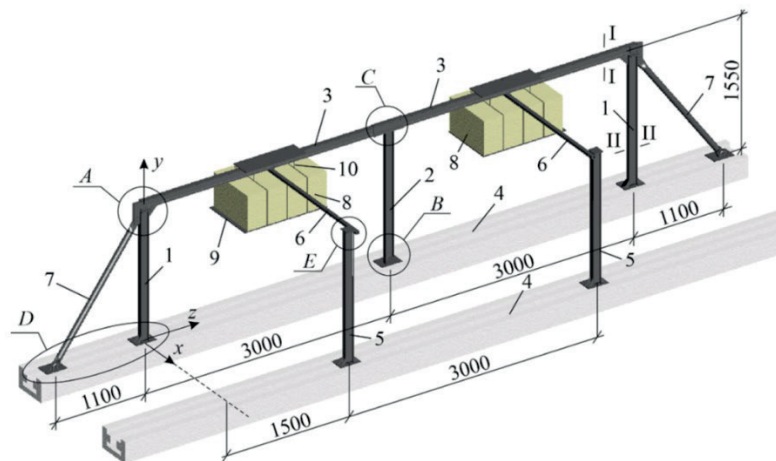


Figure 1. Specimen of the framed structure with rigid joints: 1 - end columns, 2 - middle (removable) column, 3 - beams, 4 - power floor, 5 - additional columns, 6 - beams, 7 - tie rods, 8 - load blocks, 9 - support plates, 10 - studs; A-E marking of joints; I-I, II-II - cross-sections for measuring values of stress-strain state

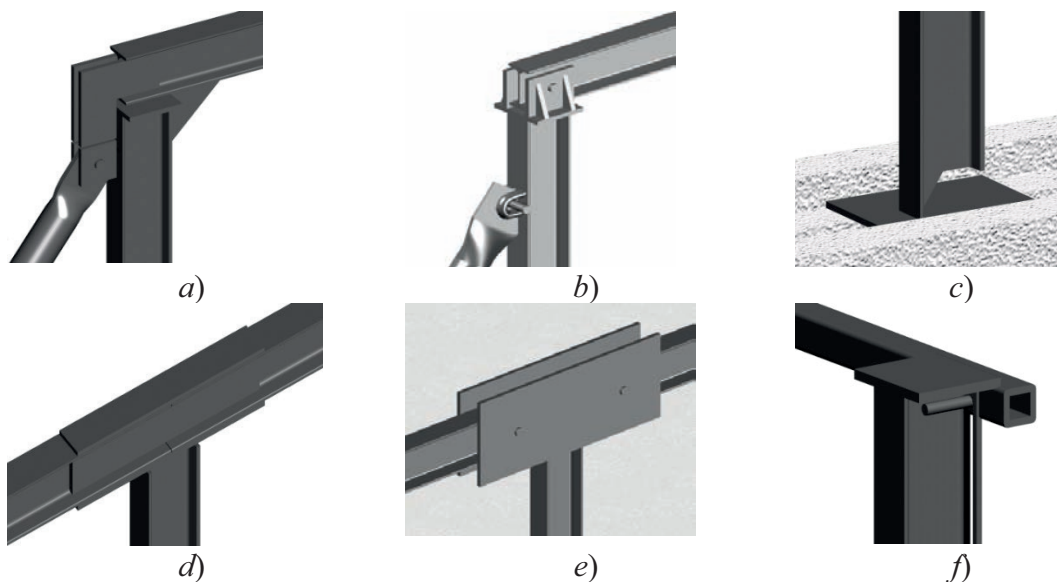


Figure 2. Joints of the experimental frames (labeled in Figure 1): (a) joint A; (b) hinged joint A; (c) hinged joint B; (d) hinged joint C; (e) hinged joint C; (f) hinged joint D



Figure 3. General view of experimental specimens: (a) with rigid assemblies; (b) with hinged assemblies (showing the erecting supports used before installing the middle column)

The experimental investigations were planned according to the following scenario. For a frame structure with rigid and hinged joints, 3 loading stages were performed. In the first stage, one load was placed in each span of the frame. In the second stage, one more load was added and in the third stage yet another load was added. At each of the stages, the middle column RC was removed using a rod striker T (Figure 3, a). During the removal, the displacements and deformations of the frame were measured. Here, the tie rods are safety elements that increase the robustness of the frame at an accidental action. If the removal of the column resulted in plastic deformations, the frame specimen was replaced with a new one for the subsequent test. The recorded displacements and deformations were compared with each other and with the simulation results.

2.3. Displacement and deformation measurement in time. KF 5P1-3-200B12 strain gauges were glued for the beam and column in the cross sections shown in Figure 1 and Figure 4. Cold-curing cyanoacrylate was used for gluing. There were measured longitudinal strains in the beam and column flanges. To transfer data to the computer, an analog-to-digital converter LTR-212 with a sampling frequency of up to 3kHz was used. The frequency of 1.5 kHz was considered as sufficient for the experiment. An electronic recorder Lgraph was used for plotting deformation histories. Linear displacements of the frame beam in the vertical direction were measured at point D (Figure 4).

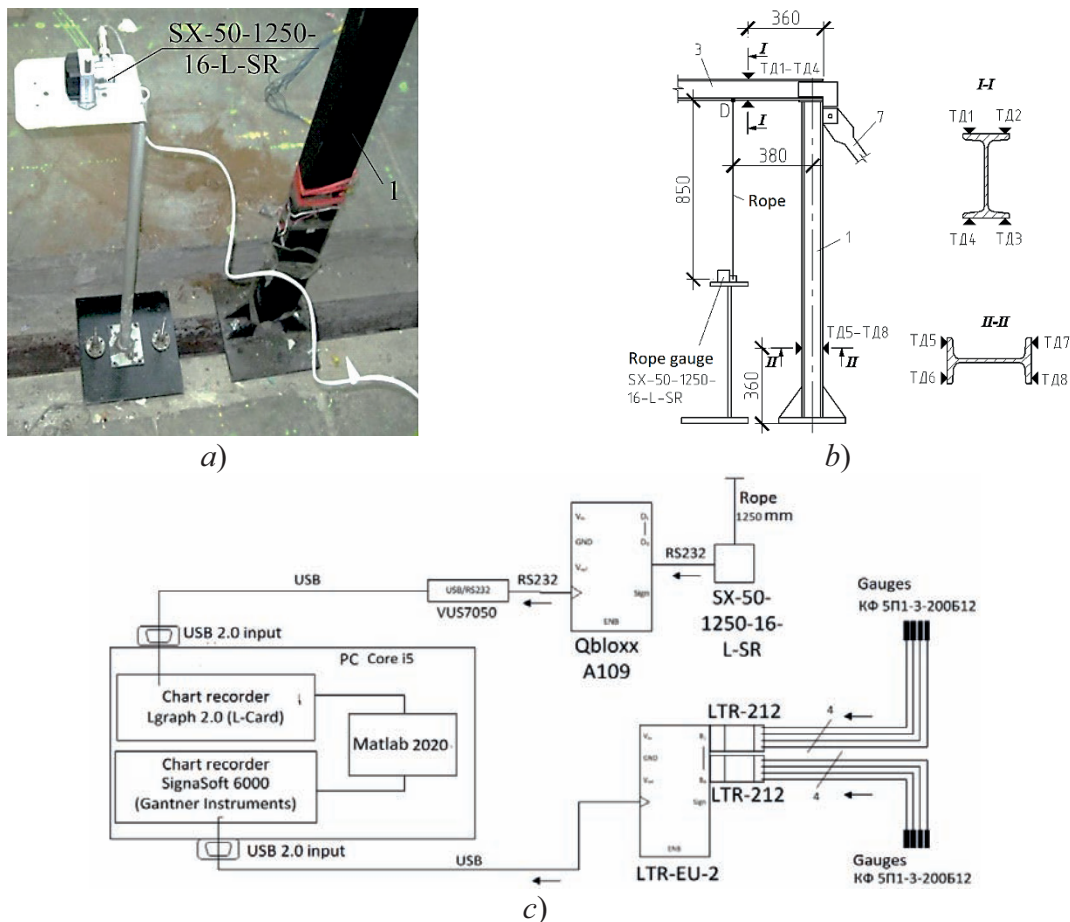


Figure 4. Measurement of stresses and strains in time: general view of the rope gauge (a), diagram of installation of the rope gauge and strain gauges (b); 1 - column, 3 - beam, 7 -rod; schematic diagram of data acquisition and processing in the experiment (c)

After stabilization of the system subjected to an accidental impact, the displacements of other points were measured with a laser rangefinder. The data obtained during the tests had to be cleaned from noise. For this purpose the data were exported to MATLAB software, where the values of strains and displacements were subjected to one-dimensional Meyer wavelet transformation by polynomials of 6 and 7 orders. The general scheme of information processing is shown in Figure 4, c.

2.4 Preparation for the experiment. Before the dynamic tests, the properties of the steel of the frame I-beams were determined experimentally. Plane specimens were cut from the I-beam wall and tested for uniaxial tension in compliance with the standard methodology. As a result of statistical processing of the data it was found that the I-beams were made of steel with physical yield strength of $349 \pm 13 \text{ MPa}$ and ultimate tensile strength of $522 \pm 15 \text{ MPa}$. Strain of the specimens corresponding to the yield strength was, and corresponding to the tensile strength was $0,0018 \pm 0,0002$, and the strain of the specimens corresponding to the tensile strength was $0,233 \pm 0,026$.

2.5 Numerical analysis. The frame was calculated using the finite element method in a physically, geometrically, and structurally nonlinear formulation based on the stepwise direct integration method described in [6, 20]. The peculiarity of this method is that the tangent coefficients of the general stiffness matrix are constructed at each step of time integration for the deformed state of the system. In this case, the associated law of flow theory is used to determine the values of elastic and shear moduli. At the same time, to estimate the strength, the dynamic yield strength σ_m^d , determined by reference data as $\sigma_m^d = 1,1 \cdot \omega^{1/17} \cdot \sigma_m$, where ω is the frequency

of the lowest tone of vibration, σ_m is the yield strength obtained in static tensile tests, is introduced into the calculation. The calculation diagram of material performance was taken as a linear approximation of the actual steel deformation diagram obtained experimentally

3. RESULTS AND DISCUSSION

3.1 Deformation measurement. The results of the experimental tests of rigid and hinged frames and the evaluation of their robustness are shown in Table 1. Figure 5 shows the resulting state of the experimental specimens..

Table 1. Estimation of the resistance of frames to progressive collapse at the removal of the middle column

Rigid connection of elements, loading stage, result		Hinge connection of elements loading stage, result	
I	The robustness is assured	I	The robustness is assured
II	The robustness is assured	II	Failure (tie rod and frame connection)
III	The robustness is assured	III	Failure (tie rod support assembly)

Plots of strain histories for the frame with hinged beam-column joints according to the strain gauge arrangement (Figure 4, b) are shown in Figure 6, a-d. Similar plots for the frame with rigid joints are shown in Figure 6, e-h. To compare the deformation patterns of the frame correctly, only the first stage of loading was considered, at which the robustness is ensured for both frames.



a)



b)

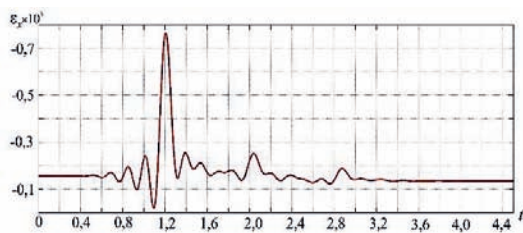
Figure 5. Experimental specimens after testing: frame with hinge assemblies at loading stage II (a); frame with rigid assemblies at loading stage III (b)

The displacement histories for the first stage of loading is shown in Figure 7.

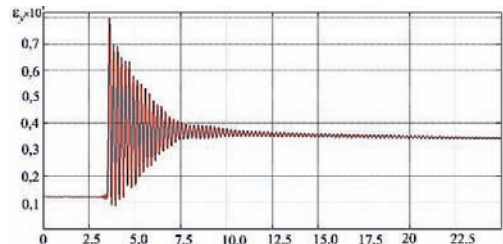
Analysis of the data presented in Table 1 and Figure 6 allows us to draw conclusions:

- The frame specimens with hinged joints failed at the loading level corresponding to 33.3 % of the planned one in the experiment, equal to 1170 kg, at which the frame with rigid joints has the property of robustness. This result is

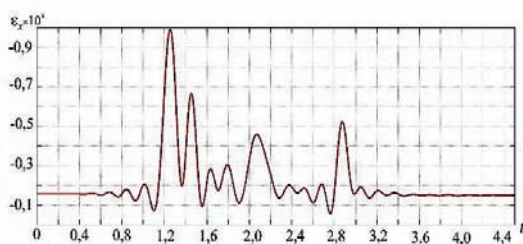
observed in the presence of safety suspender elements. Preliminary calculations have shown that without the presence of safety elements at hinge joints, both the experimental specimen and any other frame of the building at the initiation of the accident associated with the removal of the middle column does not have the property of robustness. This means that the local failure propagates to a complete collapse;



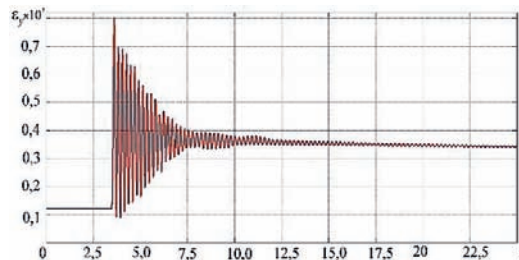
a) readings of strain gauge SG 1



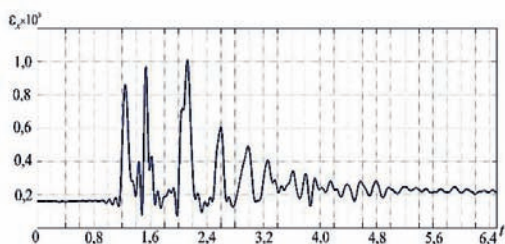
e) readings of strain gauge SG 1



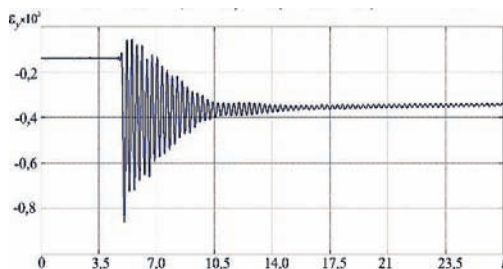
b) readings of strain gauge SG 2



f) readings of strain gauge SG 2



c) readings of strain gauge SG 3



g) readings of strain gauge SG 3

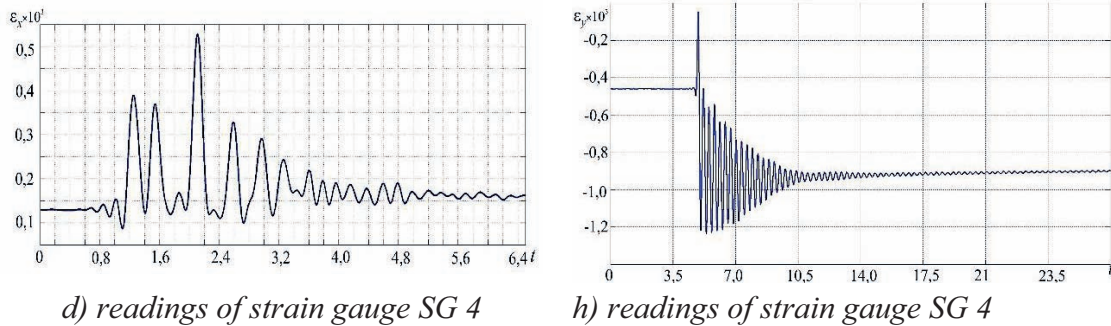


Figure 6. The strain histories for gauges mounted on the frame beam: a-d - with hinged nodes; e-h - with rigid nodes

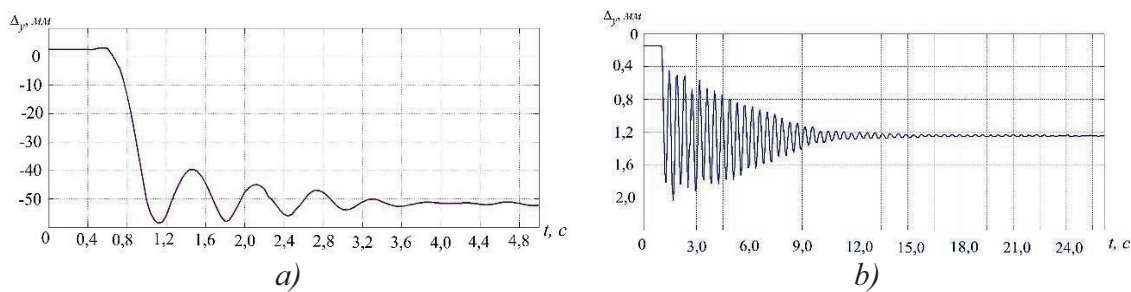


Figure 7. Displacement history of point D (Figure 4, b) of the frames: (a) with hinged joints; (b) with rigid joints

- the type of frame assembly: rigid or hinged establishes a fundamentally different pattern of localization of structural failure. For hinge assemblies, it is a kinematic chain, the reliability of which is completely determined by the reliability of the hinge design. For rigid joints, the fracture pattern is a frame with a set of plastic joints, and the invariability of this system, according to the static theorem of A.A. Gvozdev, is determined by the limit conditions in one of the cross-sections;

- the pattern of deformation under dynamic loading of frames with safety elements (increasing the robustness property) has the following features. At hinged joints the system has a structural damping coefficient of 0.01, while for rigid joints this coefficient is 0.00074, i.e., it is 13.5 times higher. The coefficient was calculated based on the processing of experimental strain data using the peak method known in the literature;

- analysis of diagrams and measurements allowed to reveal that the frame with hinged joints has a lower frequency of the main vibration mode $f_1 \approx 1.42$ Hz, while the frame with rigid joints has a frequency of $f_2 \approx 4.3$ Hz, i.e. lower by 3 times;

- peak strain values for the frame with both hinged and rigid nodes are observed in the first half-period of vibrations, while in the compressed zone of elements these values may come in the second and even in the third period of vibrations, which can be explained by the redistribution of force flows between the main frame system and safety elements (ties);

The analysis of Figure 7 shows that the peak (maximum) deflections for frames with safety elements are observed in the first half of the vibration period, which agrees with the results given in the literature for a similar accidental situation for beam systems. It should also be noted that the transient dynamic process for the

frame with rigid joints has a value of 24 s on average, which is 4.8 times longer than the same value for the frame with hinged joints. This allows us to conclude that hinge joints are preferable for materials and design solutions sensitive to vibrations.

3.2 Results of the calculation. To experimentally verify the calculation methodology for the accidental impact outlined in [6], a rod finite element model (Figure 8) was developed. The material properties were taken from the tests, and the kinematic constraints corresponded to the connections and supports made in the experimental setup.

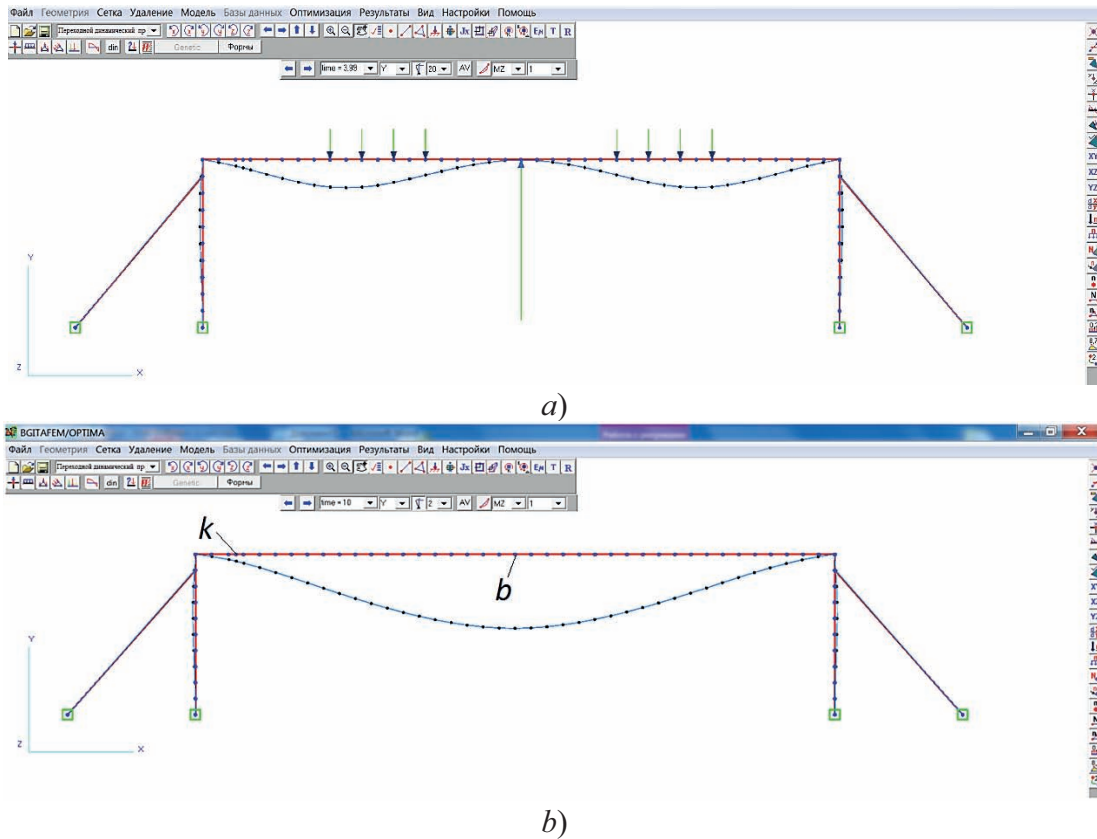


Figure 8. Deformed schemes of the experimental setup model: state of the system after dynamic relaxation before removal of the middle column (a), after vibration damping without the middle column (b)

According to the dynamic analysis procedure, initially the static equivalent of the support reaction was applied to the model. After that, the integration process continues and the system, passing the state of dynamic relaxation comes to the equivalent static state. The reaction is then quickly removed from the system, which begins to experience free vibrations under accidental loading. This process is shown in Figure 8 in the interface of the author's software

package. The results of the comparison are presented in Table 2. It should be noted that the experimentally obtained displacements agree satisfactorily with the calculated ones (they differ on average by 15%). These differences are explained by the peculiarities of the nodes fixing the installation to the power floor. These nodes do not have absolute stiffness as in the design scheme, but a small ductility to tear-off, associated with the bolt fixing.

Table 2. Comparison of frame displacement calculation results

Loading stage	Frame specimen	Maximum value, mm (dynamic)		Static value, mm (after vibration damping)			
		Experiment (rope gauge)	According to [6]	Experiment		Calculation [6]	
		y_k (fig. 8)		y_k	y_b	y_k	y_b
1	PM-1	2,05	1,91	1,2	13	0,96	9,29
2	PM-2	4,5	3,84	2,3	25	1,67	18,96
3	PM-3	7,3	6,56	3,8	45	3,42	35,90

4. CONCLUSIONS

1. It has been established that safety elements such as tie rods absorb dynamic loads and redistribute forces. This increases the resistance to progressive collapse and, consequently, the mechanical safety of buildings and structures, especially those prefabricated elements with hinged joints.
2. The load-bearing capacity of frames with tie rods is 33.3% lower than for frames with rigid assemblies under an accidental impact associated with the support removal. However, the transient time during which the vibrations cease is 4.8 times shorter. This allows making reasonable decisions when designing structures with specified safety criteria, such as placement of equipment for which vibrations are dangerous or inadmissible.
3. The damping coefficients under accidental action have been determined experimentally. It is established that frames with hinged nodes have 13.5 times lower structural damping coefficient than frames with rigid nodes.
4. Comparison with experimental data established satisfactory accuracy of the approach to numerical modeling of the accidental situation.

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