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# Digital modeling of seismic impact on the frame of multi-storey buildings with outrigger systems

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**Abstract.** The article studies the operation of building frame structures with outrigger floors, taking into account seismic effects. The object of the study is a monolithic reinforced concrete frame of the building. The studies were carried out using the modern Lira SAPR software package, which implements the finite element method. Dynamic calculations were performed for several models with different design solutions for outrigger systems and their location. The study of the effectiveness of the decisions made was carried out based on the results of the spectrum of frequencies and periods of natural oscillations. Based on the results of dynamic calculations, two constructive solutions were chosen with higher frequencies and shorter oscillation periods compared to the original model. A study was made of the effect of outrigger floors on the stress-strain state of the building frame. Based on the results of the calculation, conclusions are drawn and recommendations are given for the design of earthquake-resistant buildings.

## 1 Introduction

With an increase in the density of urban development, the issue of rational use of free areas for construction becomes especially acute.

The most cost-effective choice is the construction of high-rise buildings. The design of such facilities requires a high level of qualification from specialists of all sections. Increased loads on the structural elements of the building and special design requirements expect the specialist to use non-standard design solutions.

An important aspect of the calculation of unique buildings and structures is to take into account emergency factors such as explosion, fire, progressive collapse, the occurrence of karst failures, as well as seismic impact.

Seismic impact poses a great danger to the building and the people inside. This is due to the randomness and unpredictability of the earthquake. However, based on many years of experience in observing earthquakes around the world, humanity has managed to accumulate a knowledge base that allows minimizing the damage caused to a building by

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seismic impact. Two approaches are used: ensuring a sufficient level of strength, as well as damping vibrations with the help of special design solutions.

The main provisions for the design of high-rise buildings and world experience on this topic are set out in the work "Design of modern high-rise buildings" written by Peifu Xu, Xueyi Fu, Cuikun Wang, Congzhen Xiao.

Prof. Ya. M. Aizenberg, Doctor of Engineering, scientific director of the school of dynamic control of seismic response at TSNIISK named after V.A. Kucherenko, posed and studied the tasks of optimal design in earthquake-resistant construction for the first time, and it was proposed to evaluate the structural solutions of building frames according to its dynamic characteristics [1].

One of the important directions in the development of the construction industry is the construction of modern buildings that meet the requirements of reliability and cost-effectiveness of design solutions. The construction of multi-storey buildings in earthquake-prone areas is a difficult task, both at the design stage and at the stage of erection of structures. The further life cycle of the

object depends on the correctness of the adopted design decisions and the accuracy of the design model of buildings and structures.

The issues of regulation of the stress-strain state and dynamic characteristics of the elements of the building frame by changing the design scheme are considered in the manual “Selected problems in structural mechanics and the theory of elasticity (regulation, synthesis, optimization), edited by N.P. Abovsky.

The aim of the work is to study the influence of design solutions to prevent progressive collapse on the dynamic characteristics of the frames of multi-storey buildings. It is proposed to investigate the influence of shrouds not only on the dynamic characteristics of buildings erected in seismically hazardous areas, but also to analyze the stress-strain state of the structures of the buildings under study with recommendations for further design of multi-storey frame buildings.

## 2 Problem statament

To improve the accuracy of engineering calculations of frame buildings in seismically hazardous areas, simulate the behavior of a multi-storey building with the optimal design solution obtained from the results of dynamic calculation [2]. When choosing the optimal structural scheme, apply modern design solutions to increase the resistance of the building frame to progressive collapse [3].

To solve the problem, it is necessary to:

- develop a finite element model of the building frame and study its dynamic characteristics;
- apply several options for structural solutions for the building frame and perform modeling of frames with solutions for studying dynamic characteristics;
- based on the results of dynamic calculations, select the optimal design solutions for studying the seismic impact on the behavior of the building frame;
- perform modeling of seismic loads on the building frame and analyze the stress-strain state of the building frame from seismic impact;
- give recommendations on the design of seismic-resistant frameworks of buildings that meet the requirements of modern standards and regulations.

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## 3 Materials and methods

The calculation scheme of the 21-storey section of the building of a multi-storey two-section residential building was built in the Lira SAPR software using the coordinates obtained from AutoCAD [4]. The structure was designed according to the frame scheme. The main load-bearing structures are: diaphragms for seismic effects, columns and beam-type ceiling. All structures are made of monolithic reinforced concrete.

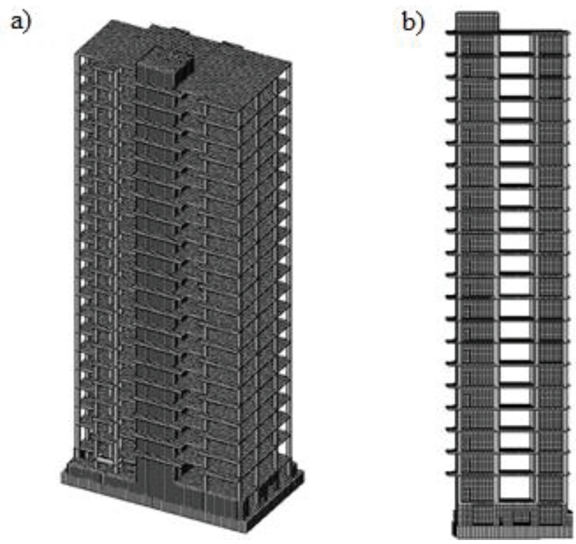


**Fig. 1.** Calculation model of the building: a) 3D view; b) side view.

Slab grillage, floor and roof slabs, walls and diaphragms for seismic effects were modeled by triangular shell elements with 18 degrees of freedom and quadrangular shell elements with 24 degrees of freedom [5]. The columns were modeled by spatial rods with 12 degrees of freedom. The calculation scheme was developed taking into account the rigid embedding of columns, diaphragms for seismic effects and walls into a monolithic slab grillage. The main step of the finite element mesh of the design model is 500x500 m (Fig. 1).

The following sections and materials are assigned to the structures: foundation slab 1800 mm thick; floor slabs 210 mm thick; sections of columns 400x400 mm, 500x500 mm, 600x600 mm; stiffening diaphragms 300 mm thick; basement walls 300 mm thick.

Sections are assigned to all elements of the building frame in accordance with the adopted design solutions [6]. To form a load case from its own weight, the volumetric weight of materials is specified. The concrete deformation modulus corresponds to class B25.

The calculation model takes into account 7 dynamic loadings: wind pulsation in four directions; seismic loads are taken into account in the direction of the main axes of the building. Modeling of seismic impacts is performed by a linear-spectral method.

In the calculation of seismic loads, the second category of soil is taken into account in terms of seismic properties and the seismicity of the site is 8 points.

The calculation of the frame of the building was performed, the frequencies and forms of natural vibrations were obtained [7]. The first and second forms are translational, the third is torsional, the next forms are bending and bending-torsional (Fig. 2).

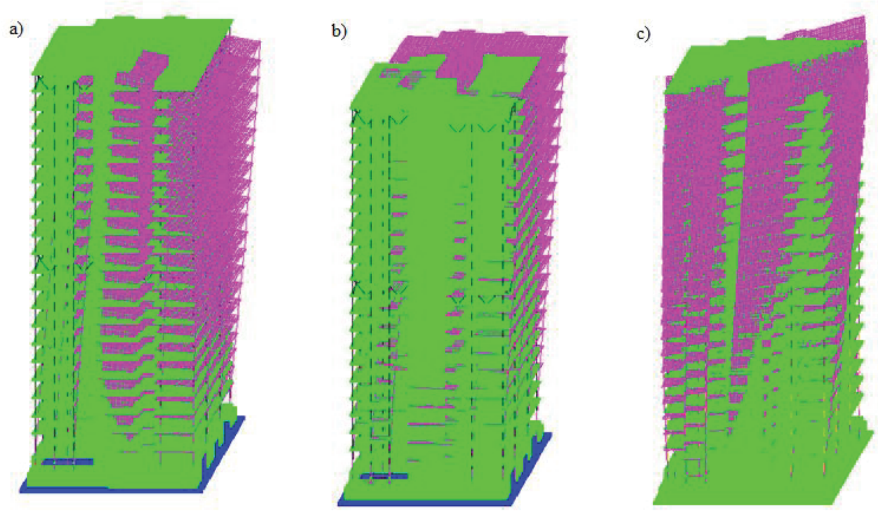


**Fig. 2.** Vibration modes: a) first mode; b) second mode; c) third mode.

For the investigated building frame, it is proposed to consider the arrangement of outrigger floors according to the obtained dynamic characteristics of the building frame. Four constructive solutions are considered:

- outrigger floor on the 21st floor made of metal structures (Model 1);
- outrigger floor on the 21st floor made of reinforced concrete structures (Model 2);
- outrigger floors on the 11th and 21st floors made of metal structures (Model 3);
- outrigger floors on the 11th and 21st floors made of reinforced concrete structures (Model 4).

For outrigger floor structures made of metal structures, the following sections are accepted: the floor lattice is a rectangular pipe 300 x 200 x 9; the belt of the floor is a rectangular pipe 300 x 6 (Fig. 3).

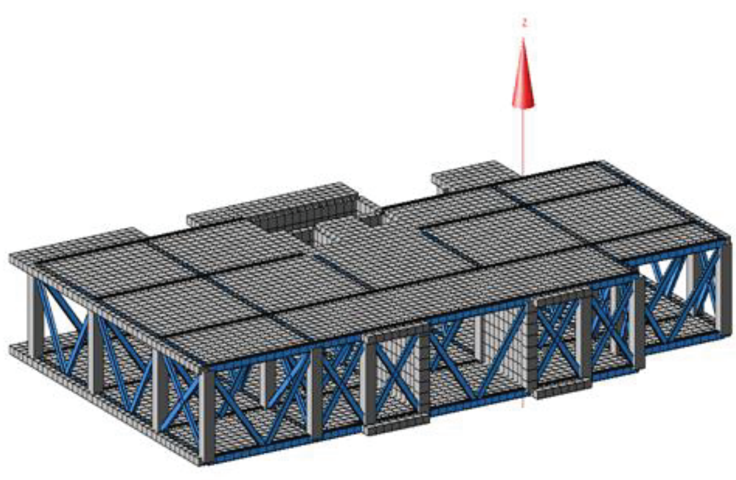

**Fig. 3.** Outrigger floor.

For outrigger floor structures made of reinforced concrete structures, beams with a section of 400x600 mm made of B25 class concrete were adopted. Fig. 4 shows Model 3

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with two outriggers in metal structures and Model 4 with two outriggers in reinforced concrete structures.

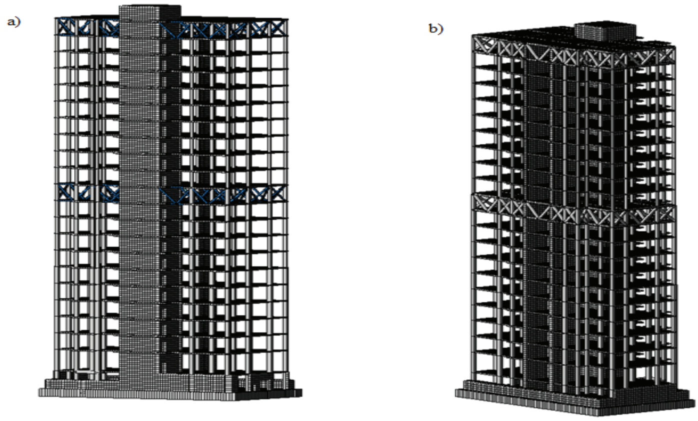

**Fig. 4.** Calculation models with two outriggers: a) in metal structures; b) in reinforced concrete structures.

A dynamic calculation of four variants of building frames on a rigid foundation was performed. As a result of the calculation of Models 1-4, the frequencies and forms of natural oscillations were obtained. When comparing the nature of vibration modes, it was found that the first three modes do not change their nature and direction, compared with the results obtained from the original model of the building frame, form 4 changed the nature of vibrations from bending-torsional to translational. An analysis of the obtained frequencies and periods showed an increase in frequencies and a decrease in periods compared to the results of the dynamic calculation of the original circuit without outrigger floors (Fig. 5).

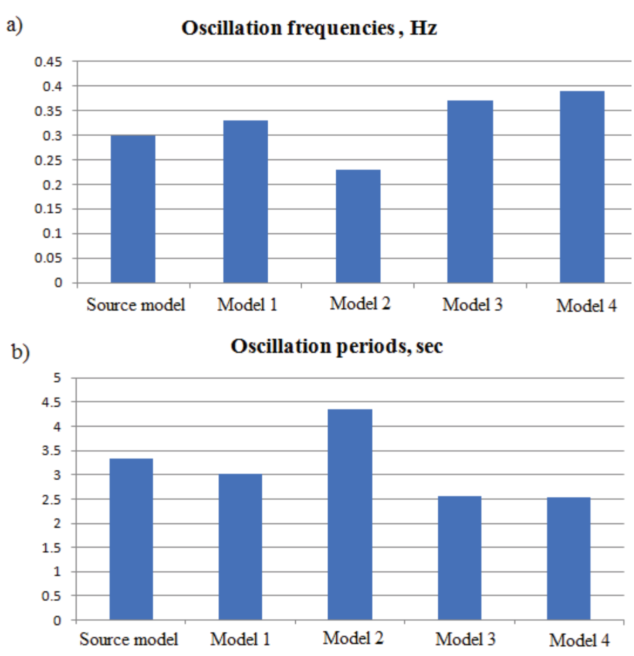

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**Fig. 5.** Comparison of the dynamic characteristics of the frame: a) oscillation frequencies; b) oscillation periods.

As a result of the study, the influence of outrigger floors on the frequency spectrum of natural vibrations is shown. The addition of one outrigger on the upper technical floors did not significantly improve, and for Model 2 even worsened the frequencies and periods of natural oscillations. Model 3 and Model 4 are the optimal design solutions.

## 4 Discussion of the results

Comparison of the calculation results taking into account the seismic impact for the selected Models 3 and Model 4 was carried out with each other and with the results of the Initial Model [7-8]. The horizontal displacements of the building frame structures were analyzed taking into account the wind pulsation (Fig. 6).

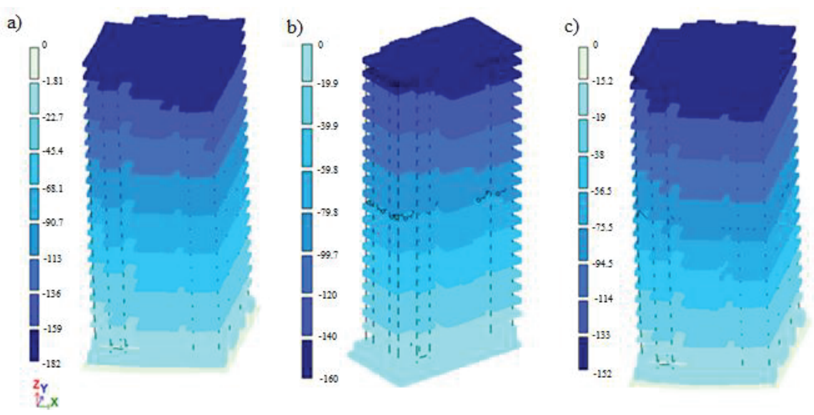


**Fig. 6.** Horizontal movements: a) Initial model; b) Model 3; c) Model 4.

As a result of the calculation, the horizontal displacements according to Model 3 decreased by 12%, according to Model 4 - by 17%.

Comparison of forces in columns from seismic impacts is made. The change in maximum effort depending on the seismic load is shown in the graph (Fig. 7).

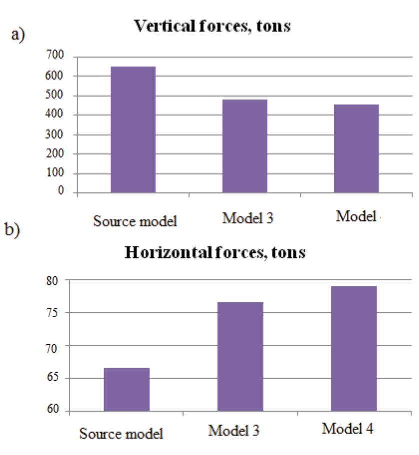


**Fig. 7.** Diagrams of changes in maximum effort: a) longitudinal; b) transverse.

The investigated component was selected based on the results of the collection of masses from static loads. From seismic action in the vertical direction when using outrigger systems, the reduction of longitudinal forces in Model 3 is by 26%, in Model 4 - by 30%. From seismic action in the horizontal direction, the reduction of longitudinal forces in Model 3 by 20%, in Model 4 by 27%.

The increase in longitudinal forces compared to the original scheme was 15-19%.

## 5 Conclusion

A finite element model of the building frame was developed and its dynamic characteristics were studied. The first and second forms have a translational direction, the third one has a torsional one, which indicates the efficiency of the decisions made.

Several options for constructive solutions for the building frame are considered: two options for outrigger systems and four options for the location of these systems along the building frame.

Based on the results of dynamic calculations, two options for constructive solutions were chosen to study the seismic impact on the behavior of the building frame.

The stress-strain state of the building frame structures is determined. The analysis of the influence of constructive solutions of outrigger floors and their location on the forces in the load-bearing structures of the building was carried out. It is shown that the rational arrangement of outrigger floors leads to an improvement in the dynamic characteristics of the building frame and a decrease in the forces from seismic loads in the supporting structures.

Based on the results of the study, constructive solutions were proposed to improve the seismic resistance of buildings and structures.

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