# BUILDING CONSTRUCTIONS, BUILDINGS AND ENGINEERING STRUCTURES
# СТРОИТЕЛЬНЫЕ КОНСТРУКЦИИ, ЗДАНИЯ И СООРУЖЕНИЯ



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*Original Empirical Research*

## Ensuring the Strength, Rigidity and Stability of Load-Bearing Structures of a Multi-Story Building of Complex Shape under Seismic Impacts

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**Abstract**

***Introduction.*** In order to ensure earthquake resistance and to reduce seismic loads, a spatial calculation of the load-bearing structures of a multi-storey building of complex shape was performed. This article analyzes the design system, computational and dynamic model taking the main and special combinations of loads into account.

***Materials and Methods.*** The calculations were performed by means of the analytical method and the finite element method (FEM) in the STARK ES software package.

***Research Results.*** The results of dynamic calculation are obtained for basic and special combinations of loads and corresponding combinations of internal forces in the calculated structures of a multi-storey building of complex shape. A total of 53 loadings were used.

***Discussion and Conclusion.*** The results of the calculation of a multi-storey building of complex shape have shown that the required strength, rigidity and stability of load-bearing structures are ensured in the design situation in question.

**Keywords:** building, seismic impact, calculation, load, structural system, seismic resistance, calculation dynamic model, strength, rigidity, stability

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*Оригинальное эмпирическое исследование*

## Обеспечение прочности, жёсткости и устойчивости несущих конструкций многоэтажного здания сложной формы при сейсмических воздействиях

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**Аннотация**

***Введение.*** С целью обеспечения сейсмостойкости и снижения сейсмических нагрузок выполнен пространственный расчет несущих конструкций многоэтажного здания сложной формы. В настоящей статье анализируются конструктивная система и расчетно-динамическая модель с учетом основных и особых сочетаний нагрузок.

***Материалы и методы***. Расчеты проводились аналитическим методом и методом конечных элементов (МКЭ) в программном комплексе STARK ES.
***Результаты исследования.*** Получены результаты динамического расчета при основных и особых сочетаниях нагрузок и соответствующих сочетаниях внутренних усилий в рассчитываемых конструкциях многоэтажного здания сложной формы. Всего было использовано 53 загружения.
***Обсуждение и заключение.*** Результаты расчета многоэтажного здания сложной формы показали, что обеспечивается требуемая прочность, жёсткость и устойчивость несущих конструкций при рассматриваемой расчетной ситуации.

**Ключевые слова:** здание, сейсмическое воздействие, расчет, нагрузка, конструктивная система, сейсмостойкость, расчетно-динамическая модель, прочность, жёсткость, устойчивость
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**Introduction.** The design of high-rise buildings involves complexities of assessing the stress-strain of the main load-bearing structures during seismic impacts.

In order to analyze the reliability, strength, rigidity and stability of load-bearing building structures under basic and special combinations of design loads, a spatial calculation of a multi-storey building of complex shape was performed. The building is under construction on a site where intense seismic impacts are likely [1–6, 15].

A scientific and technical assessment of the compliance of design solutions to ensure the safety of buildings with the requirements of regulatory documents of the Republic of Azerbaijan where the building is under construction is provided.

**Materials and Methods.** The structural system is a 29-storey complex-shaped building with a height of 150.70 m with a 4-storey structure in the stylobate part and two underground levels. The multi-storey building is located on the drained lands of the Caspian Sea on a 160×80 m construction site and is connected to the coastline via a bridge and a tunnel.

The building is designed according to the scheme of a frame-link frame. The main supporting structures (columns and beams of floors, cores of rigidity, slabs and basement structures) are designed from monolithic reinforced concrete; steel columns and beams — for the top of the building.

The structural stability system is made up of rigidity cores extending from the foundation plate to the top of the building. There are eight elevators in the rigidity cores. The cores also provide access to the stairs. The cores are made up of walls that transfer vertical and horizontal forces to the foundation [1–6, 15]. Apart from the walls, the floors are supported by vertical and inclined columns. The main cores have a plan size of 17.40×14.40 m and form a rectangular shape. The thickness of the outer walls is 800 mm, the inner walls are 300 mm.

The foundation of the building is a solid monolithic slab resting on a pile base. The thickness of the slab is 2650 mm, 2900 mm under the towers and 750 mm, 1000 mm and 2350 mm for the rest of the building. Piles with a diameter of 1.5 m under the foundation of the towers and 2.0 m under the foundation of the stylobate/basement.

The roof of the stylobate is made up of a steel structure and its cladding - a glass facade.

Two reinforced concrete cores of rigidity on each side of the building at the 27$^{th}$ floor level are connected by a steel frame structure — a 90 m long mega-truss forming the shape of a crescent. At the junction, the height of the mega-farm is 7.6 m, in the center — 20.45 m. The roof above the upper level has a rounded shape. The connecting beams are mostly steel profiles encased in concrete. The connection of the truss to the reinforced concrete cores is provided by steel plates. These reinforced concrete cores of rigidity are the main elements ensuring the stability, strength and rigidity of the building. The truss elements were designed to handle vertical and horizontal loads. It should be noted that the main steel beams of the mega-farm will be subjected to significant axial forces due to the general deformation of the building and due to horizontal and vertical loads acting on it [7–12].

It is assumed that some of the mega-truss will be assembled on the stylobate floor slab and then installed in the design position. The lifting scheme assumes that parts of the mega-truss and the walls of reinforced concrete cores of rigidity will be built first resulting in a rigidly connected frame. This cantilever frame will support a lifting platform and hydraulic jacks for mounting the middle section of the truss.

The suggested construction sequence is divided into the following stages:

– Construction of the underground part and the stylobate. The first stage entails the construction of the base structures. The walls of the rigidity cores are then mounted followed by the basement columns. After the stylobate and the basement roof have been constructed, it is planned to install the main structures of the steel roof.

– Construction of the towers. The main walls, columns and slabs are up to the level of the 27th floor.

– Installation and lifting of the truss. It is assumed that some of the steel truss will be assembled at ground level and then installed in the design position.

– The upper part of the building. After the completion of the reinforced concrete cores of rigidity and the elements around the mega-farm will be raised to the design position and connected to the cores of rigidity at the level of the 27th floor. After that, jacks will be installed between the levels of floors 21-26. Small steel parts on the 18th, 19th and 20th floors will be constructed using a tower crane. The other floors of the farm (floors 28 and 29) can then be constructed using a tower crane.

In order to assess the reliability of the design solutions employed in the project, the spatial model of the building was calculated for the design loads and impacts. The calculation was carried out by means of the STARK ES software package [12–16].

A spatial shell-rod model was employed as a computational model where the supporting columns, crossbars and truss elements are represented by rod elements of a general type, the coating shell, floor slabs and walls are represented by elements of a flat shell (Fig. 1).

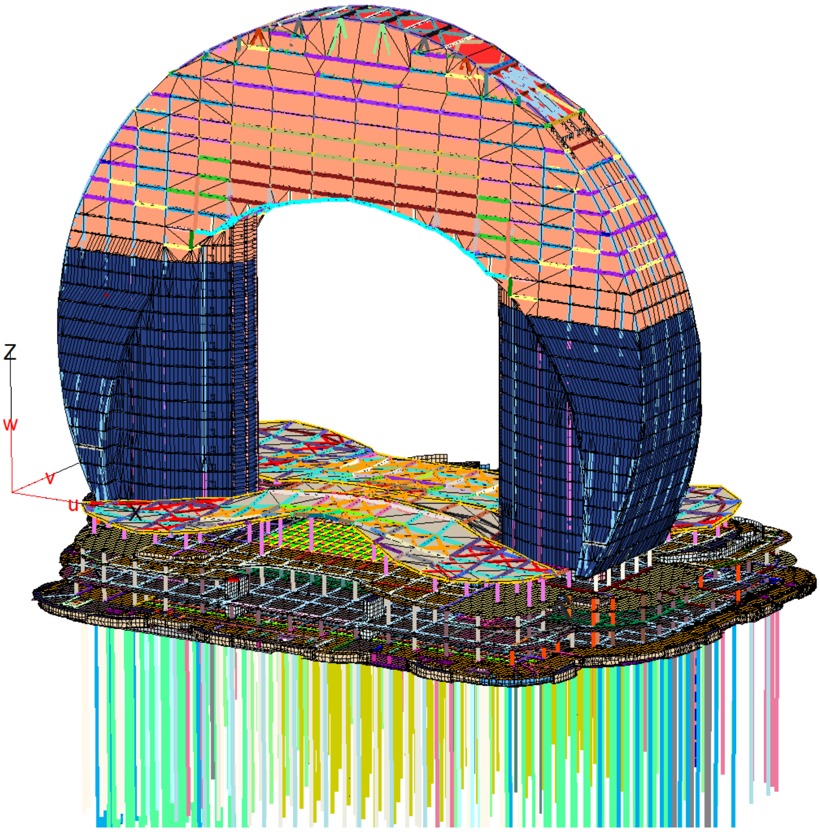


Fig. 1. A finite element model of a multi-storey building of complex shape [15]

The level of responsibility of the building in compliance with GOST 27751-88 "Reliability of Building Structures and Foundations. Main Provisions of the Calculation" is high. The value of the reliability coefficient of responsibility in compliance with GOST 27751-88:

- while calculating forces and stresses (according to the first group of limiting conditions) in building structures, bases and foundations of a building is assumed to be equal to $\gamma_n = 1.1$;

-while identifying displacements (according to the second group of limit states) of structures and base deformations, it is assumed to be equal to $\gamma_n = 1.0$;

- while calculating for emergency impacts ("progressive" destruction) and seismic impacts — equal to $\gamma_n = 1.0$.

Evenly distributed temporary loads on the floor slabs are accepted in compliance with the purpose of the premises. Load reliability coefficients $\gamma_f$ and load combination coefficients $\Psi_i$ are adopted in compliance with the requirements of AzDTN 2.1-1.

While calculating the building, the following loads and impacts are considered:

- vertical constant loads from the own weight of the load-bearing and enclosing structures of the building;
- long-term loads from engineering equipment;
- temperature loads;
- snow load;
- average and pulsation components of the wind load (terrain type A);
- seismic impact for an 8-point area.

Snow area — I. The estimated weight of the snow cover per 1 m$^2$ of horizontal surface is 0.8 kPa. In the calculation model the snow load is applied uniformly over the entire surface of the building cover. Snow bags are also considered.

The wind area — VI. Type of terrain A. Standard value of wind pressure $\omega_0$ = 0.73 kN/m$^2$.

The seismicity of the construction site is assumed to be 8 points (repeatability of 1000 years). The soil class according to seismic properties is III. Fig. 2–3 show the dynamicity coefficient and values of the parameters for calculating the seismic impact.

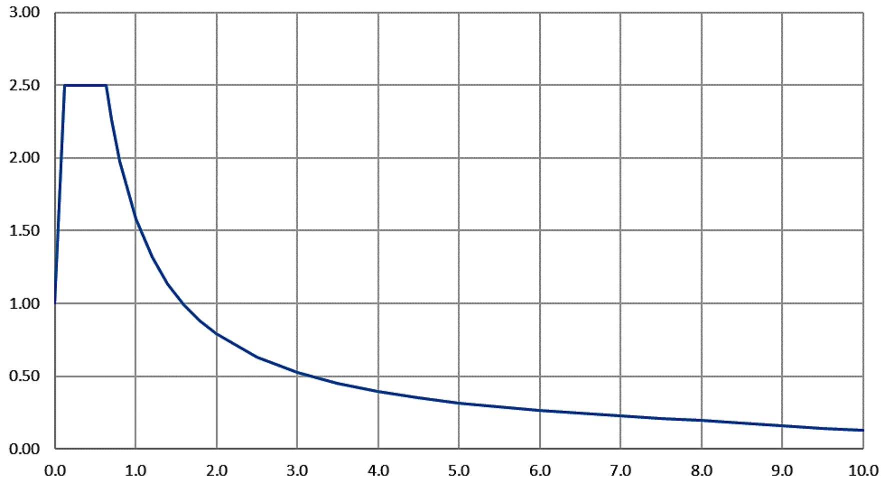


Fig. 2. Dynamic coefficient β(T)

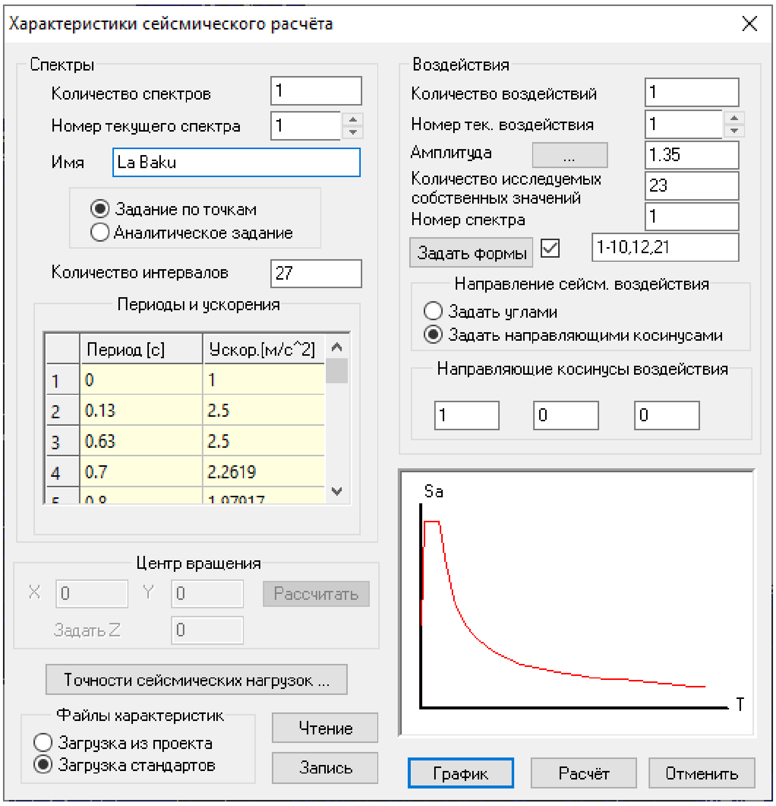


Fig. 3. Characteristics of the seismic calculation

The loads on the design scheme were assumed in compliance with AzDTN 2.1-1 and according to the initial data. A total of 53 loads were used in the calculation model of a multi-storey building of complex shape to account for all of the loads. Diagrams of the application of some of the loads are shown in Fig. 4–7.

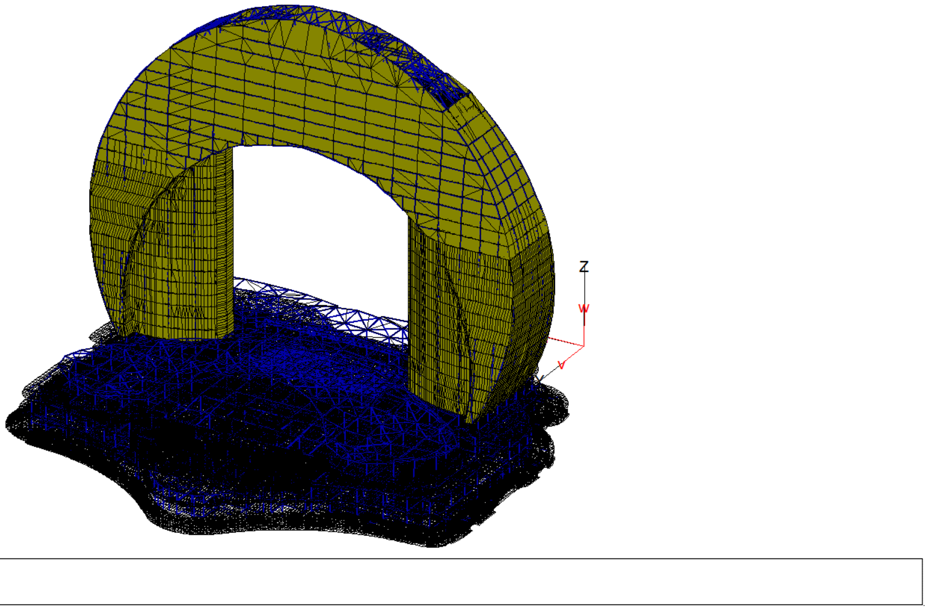


Fig. 4. Scheme of applying the load from the weight of facade structures, kN/m$^2$ [15]

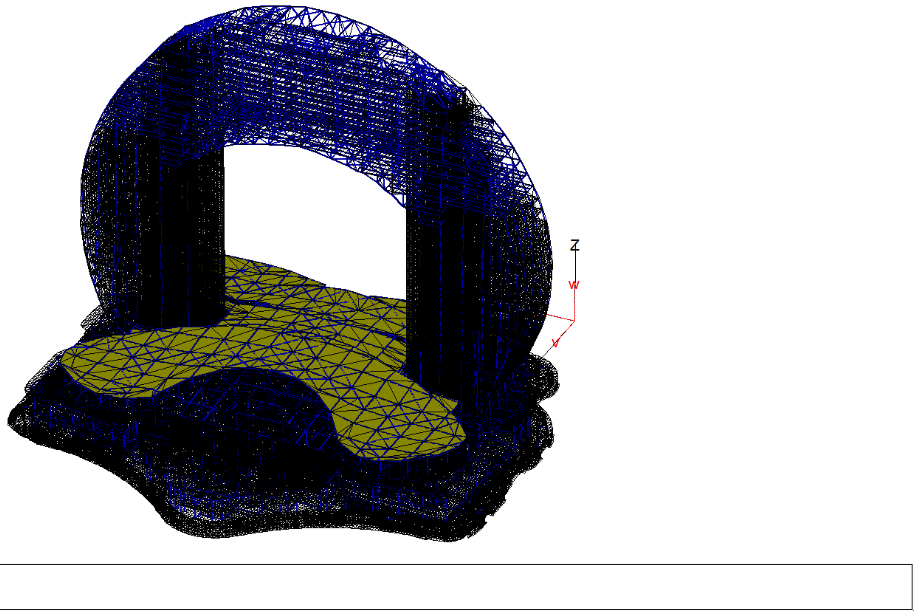


Fig. 5. Scheme of application of the load from the weight of the roof structures of the stylobate, kN/m$^2$ [15]

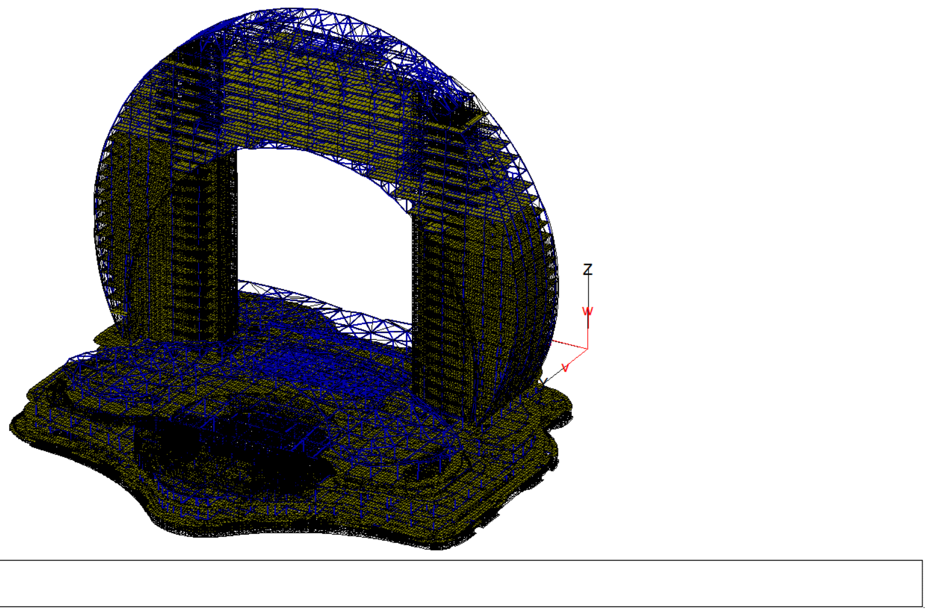


Fig. 6. Scheme of applying the load from the weight of the partitions, kN/m$^2$ [15]

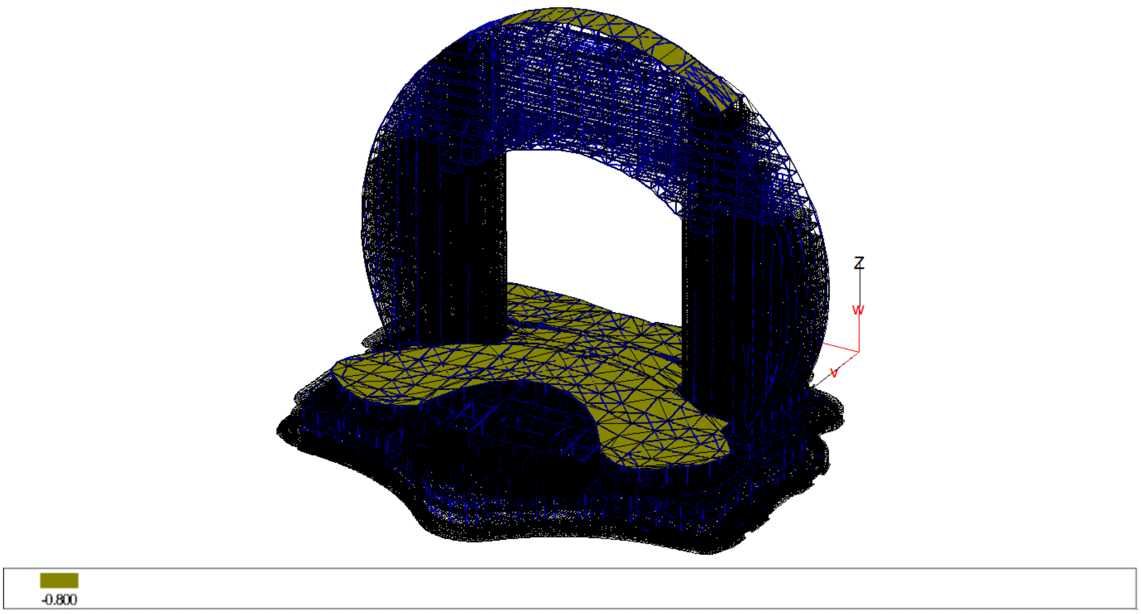


Fig. 7. Snow load application scheme, kN/m$^2$ [15]

**Research Results**. The foundation draft was evaluated for the main combinations of the full values of the standard loads. The pattern of the foundation sediment is shown in Fig. 8. The maximum sediment was 50.2 mm.

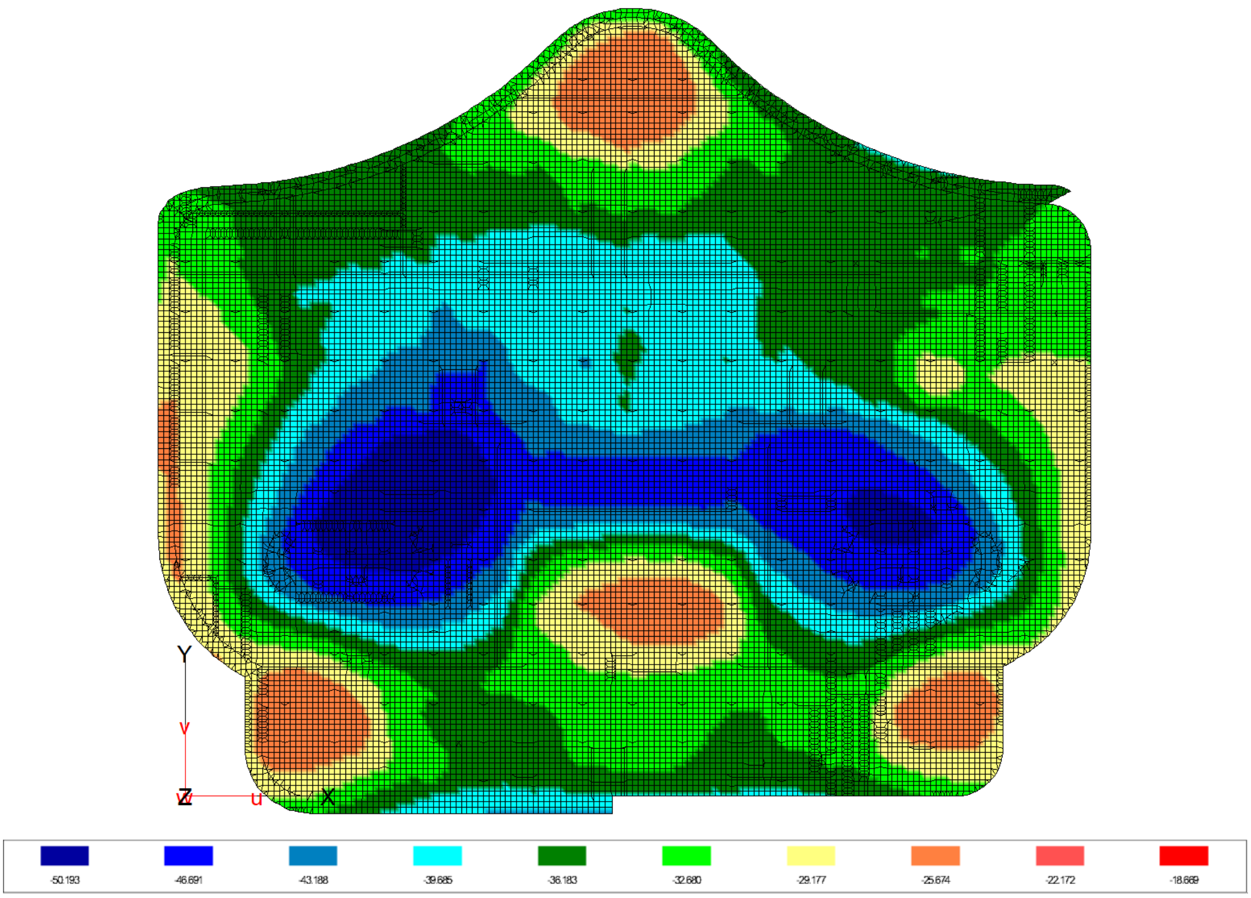


Fig. 8. Pattern of the foundation sediment, *Uz* [15]

The maximum value of the relative difference in the drafts from the main load combinations is $s/L$ = 0.00016, which is not beyond the limit value of 0.005.

The horizontal deviations of the top of the building were evaluated for the main combinations of the total values of the standard loads (Fig. 9).

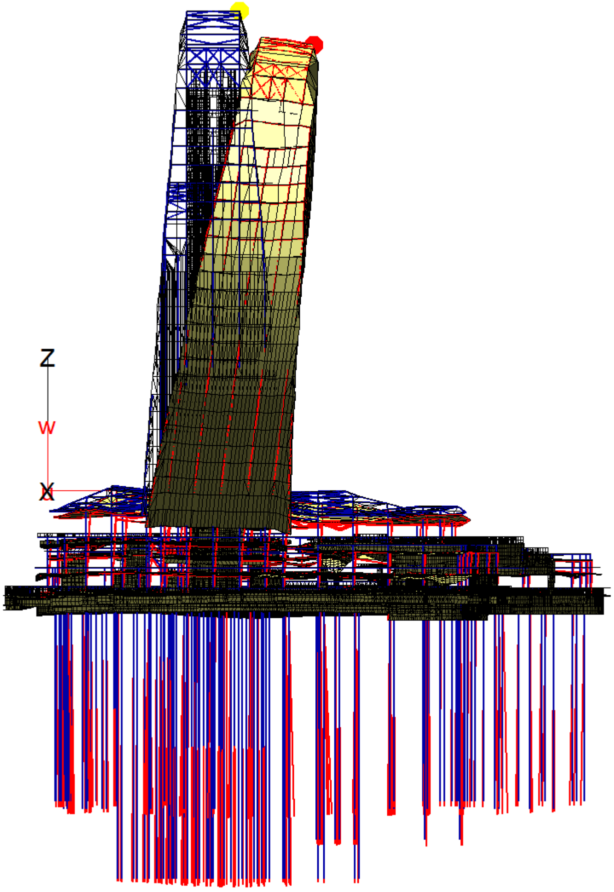


Fig. 9. Horizontal displacement of the top of the building [15]

The maximum horizontal displacement of the top of the building from the standard load values is 163.4 mm, which is not beyond the maximum permissible value of 300 mm.

The results of the calculation of the first form of stability loss are shown in Fig. 10.

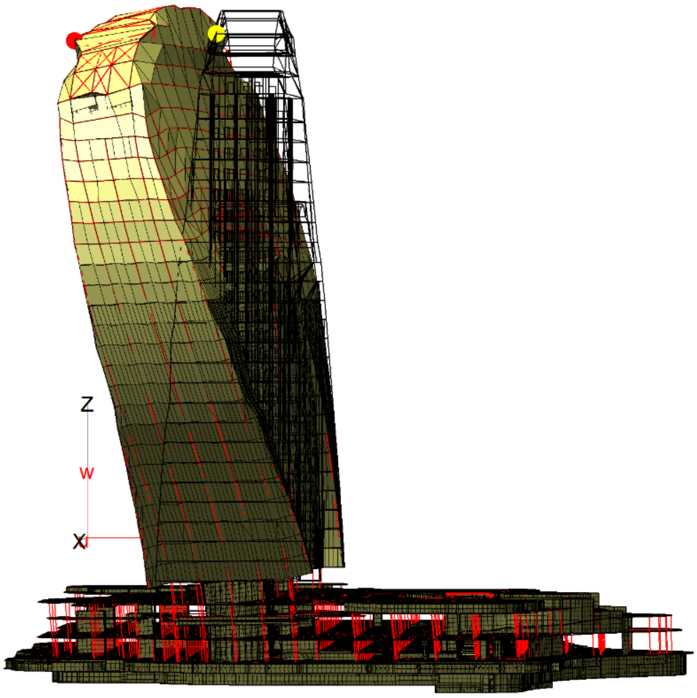


Fig. 10. Form 1 of stability loss [15]

The lowest critical load parameter (stability margin) considering the reliability coefficient of responsibility is 10.4. The overall stability of the load-bearing structures of the building is ensured.

Fig. 11–13 show the first forms of natural vibrations of a multi-storey building of complex shape.

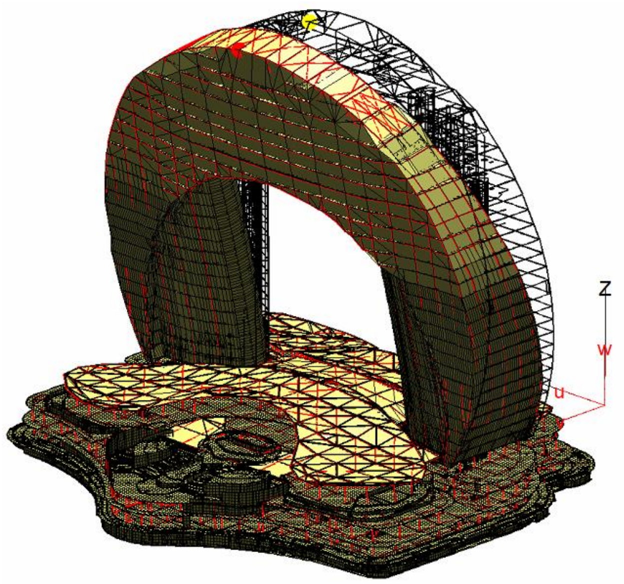


Fig. 11. First form of own oscillations, $f_1$ = 0.340 Hz [15]

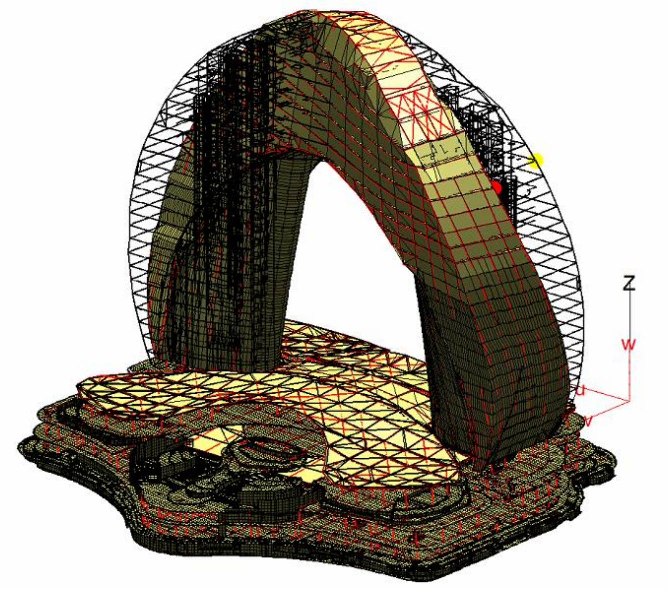


Fig. 12. Second form of own oscillations, $f_2$ = 0.459 Hz [15]

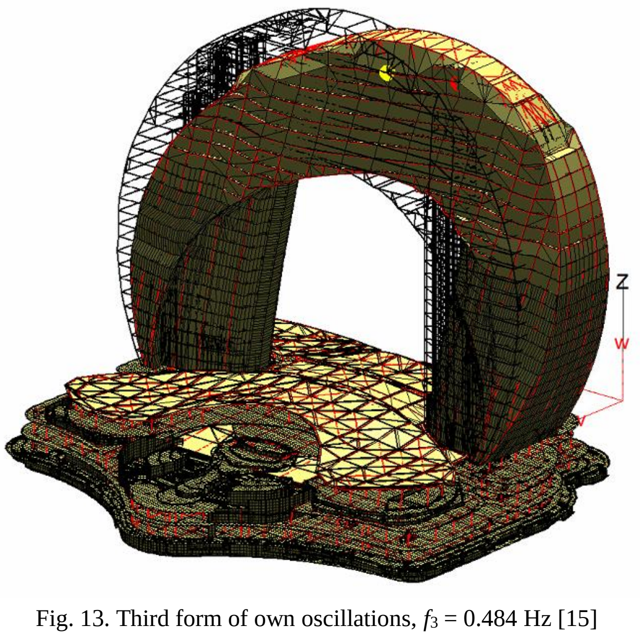


Fig. 13. Third form of own oscillations, $f_3$ = 0.484 Hz [15]

The vertical deflections of the floor slabs of the western and eastern towers of a multi-storey building of complex shape at different elevations are shown in Fig. 14–17.

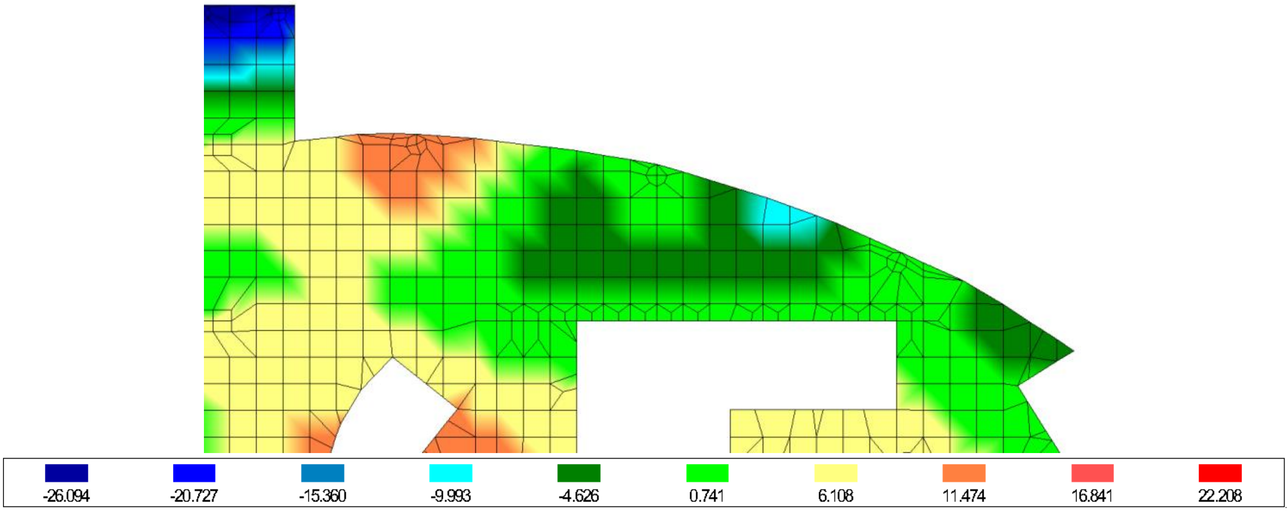


Fig. 14. Maximum relative vertical displacements of the western tower at –6.7 m [15]

The maximum vertical deflection of the floor slab from constant and prolonged loads was 11.47 mm with a console reach of 4.9 m, which is nit beyond the limit value of $l$/200 = 49 mm.

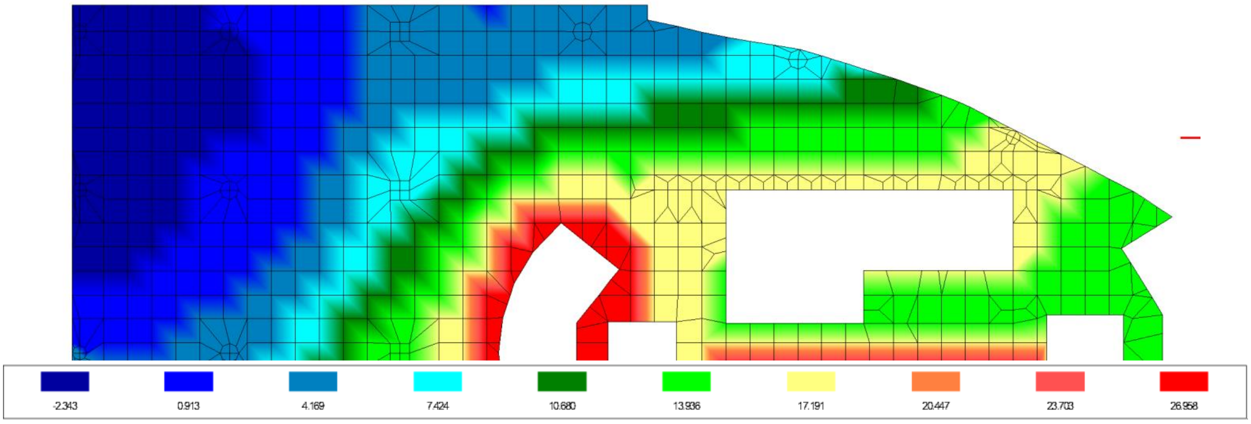


Fig. 15. Maximum relative vertical movements of the western tower at +42.8 m [15]

The maximum vertical deflection of the floor slab from constant and prolonged loads was 1.30 mm with a span of 6.6 m, which is not beyond the limit value of $l$/200 = 33 mm.

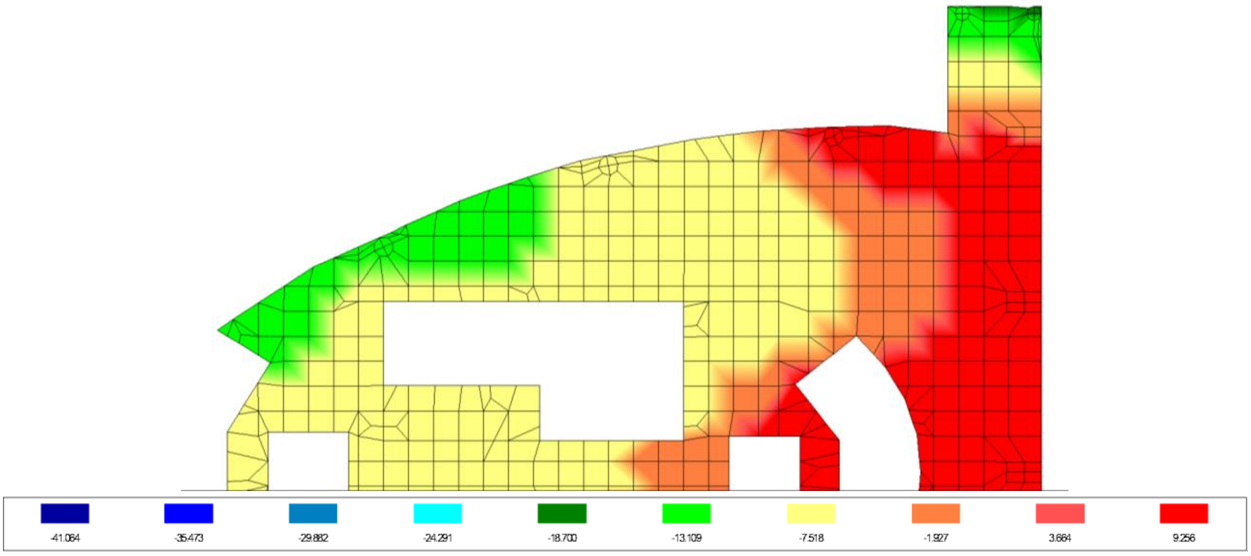


Fig. 16. Maximum relative vertical displacements of the eastern tower at –6,7 m [15]

The maximum vertical deflection of the floor slab from constant and prolonged loads was 13.8 mm with a console reach of 4.9 m, which is not beyond the limit value of *l*/200 = 49 mm.

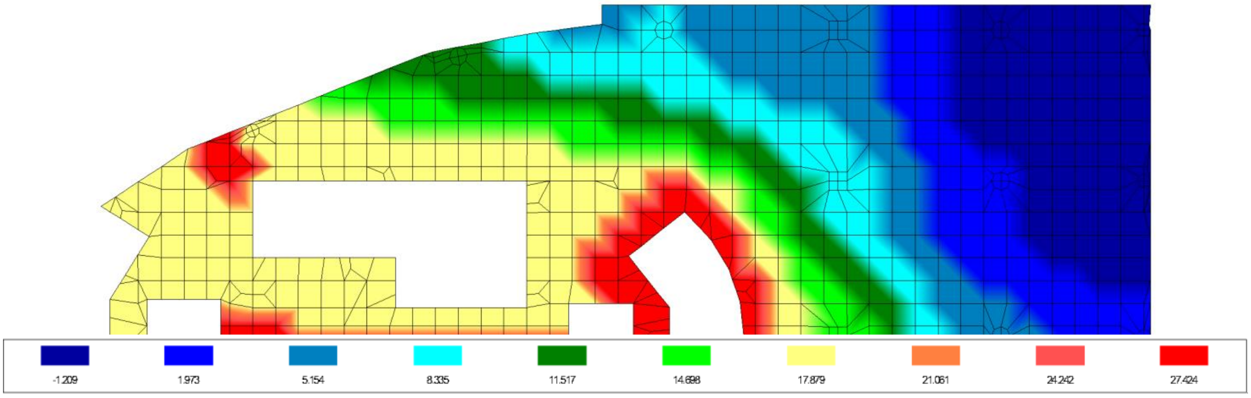


Fig. 17. Maximum relative vertical displacements of the eastern tower at +42.8 m [15]

The maximum vertical deflection of the floor slab from constant and prolonged loads was 1.21 mm with a span of 6.6 m, which is not beyond the limit value of *l*/200 = 33 mm.

The calculation of the amount of reinforcement was performed under basic and special load combinations, including seismic effects considering the conditions of strength and crack resistance. The material characteristics of reinforced concrete structures are shown in Table 1.

Table 1

Characteristics of structural materials

| **Structure** | **Concrete type** | **Longitudinal reinforcement class** | **Transverse reinforcement class** | **Thickness of the protective layer** | | | |
|---|---|---|---|---|---|---|---|
| | | | | **SO, mm** | **SU, mm** | **RO, mm** | **RU, mm** |
| Foundation, 750 mm | B45 | A500C | A500C | 60 | 90 | 160 | 200 |
| Floor slabs | B45 | A500C | A500C | 35 | 45 | 35 | 45 |
| Walls | B70 | A500C | A500C | 35 | 45 | 35 | 45 |
| Columns | B70 | A500C | A500C | 50 | 50 | 50 | 50 |

Fig. 18-29 shows the results of selecting the necessary reinforcement for a special combination of loads for some structures - parts of the foundation slab of a multi-storey building of complex shape with a thickness of 750 mm, floor slabs of the western and eastern towers at +42.80 m.

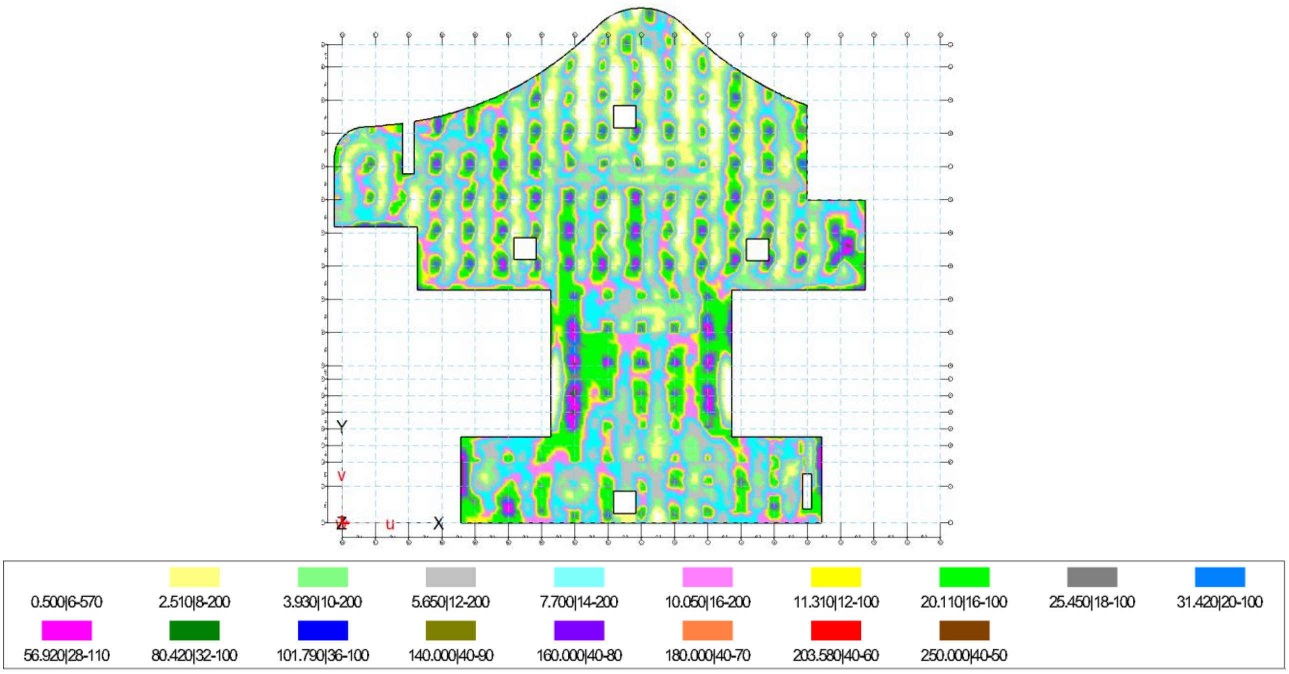


Fig. 18. Reinforcement of the foundation plate. Upper longitudinal reinforcement in the direction of the axis *R*, $cm^2/m$ [15]

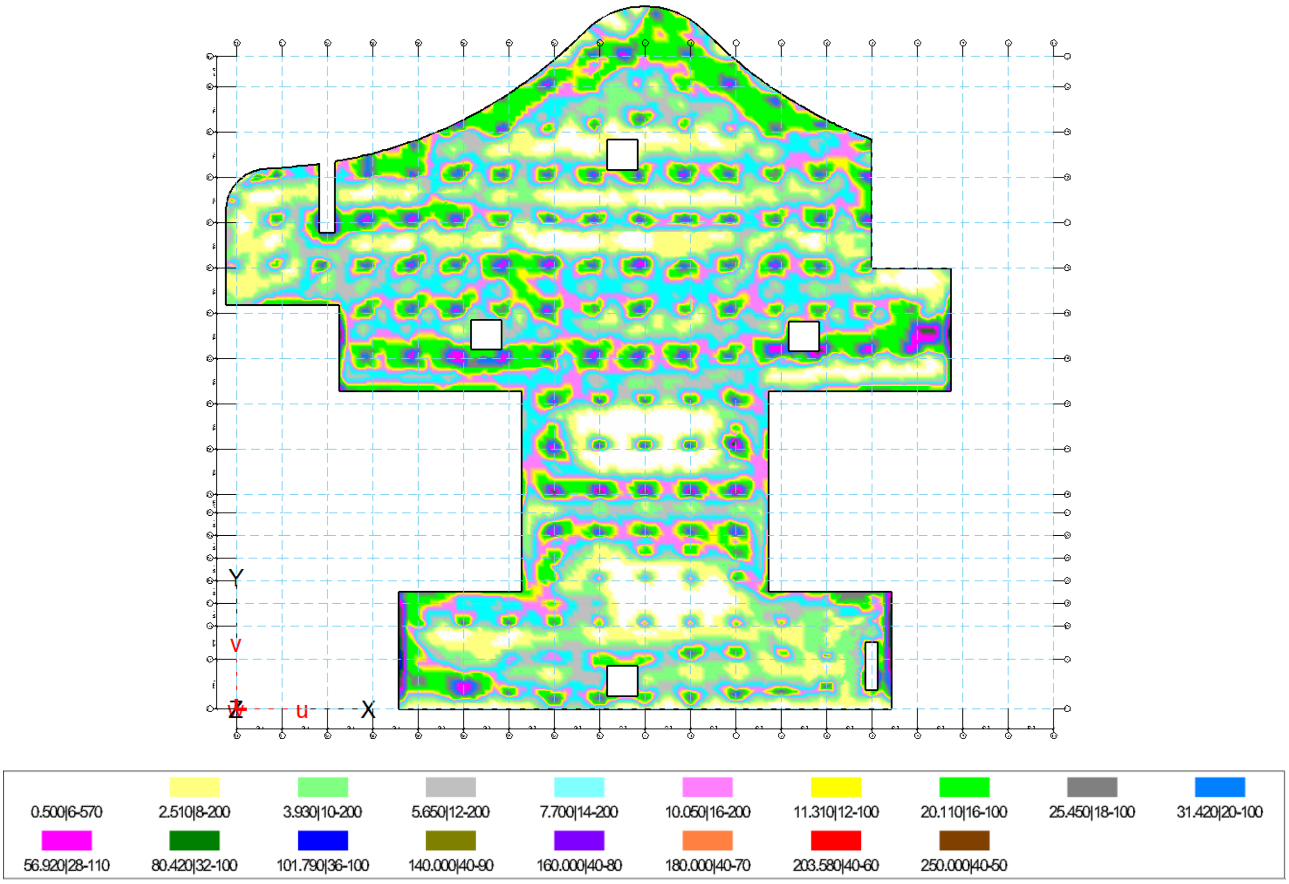


Fig. 19. Reinforcement of the foundation plate. Upper longitudinal reinforcement in the direction of the axis *S*, cm$^2$/m [15]

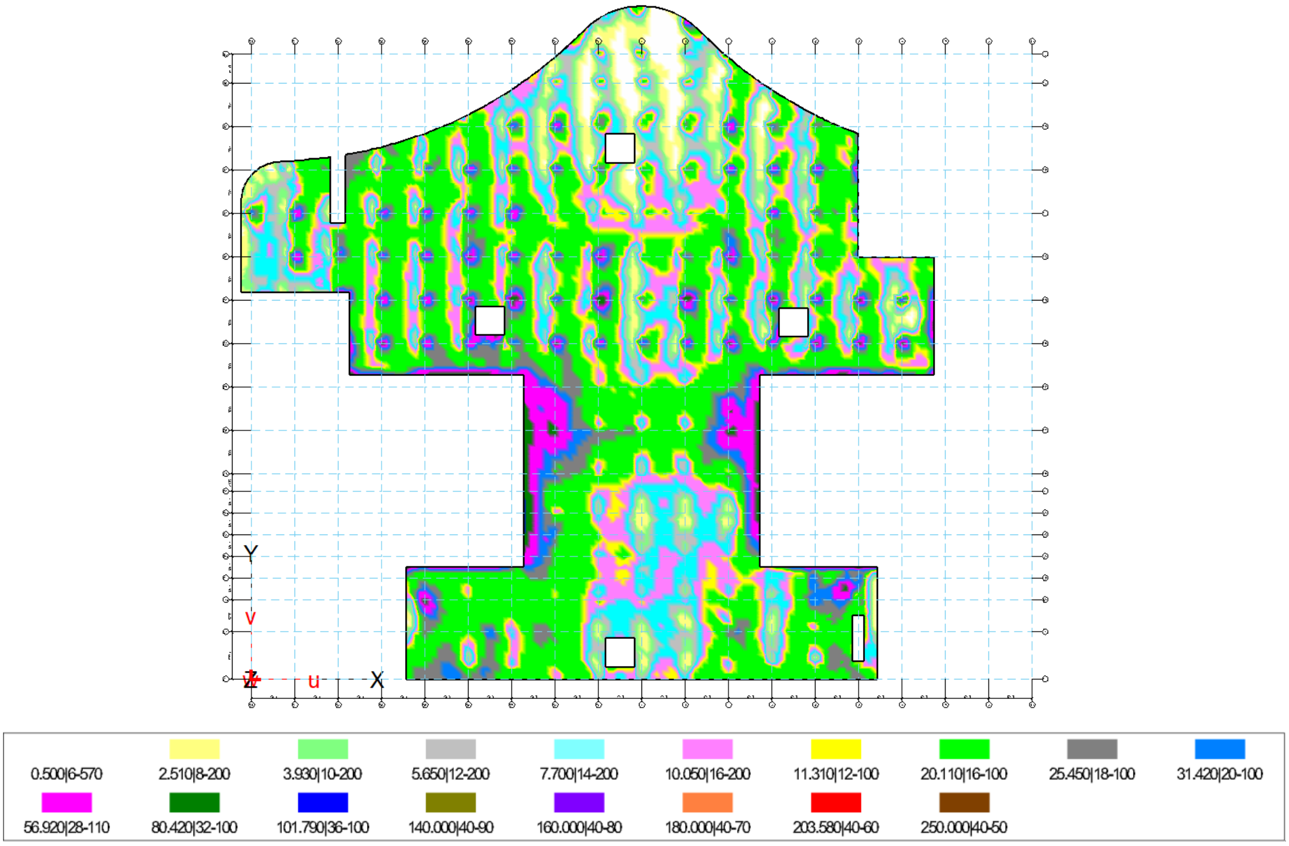


Fig. 20. Reinforcement of the foundation plate. Lower longitudinal reinforcement in the direction of the axis *R*, cm$^2$/m [15]

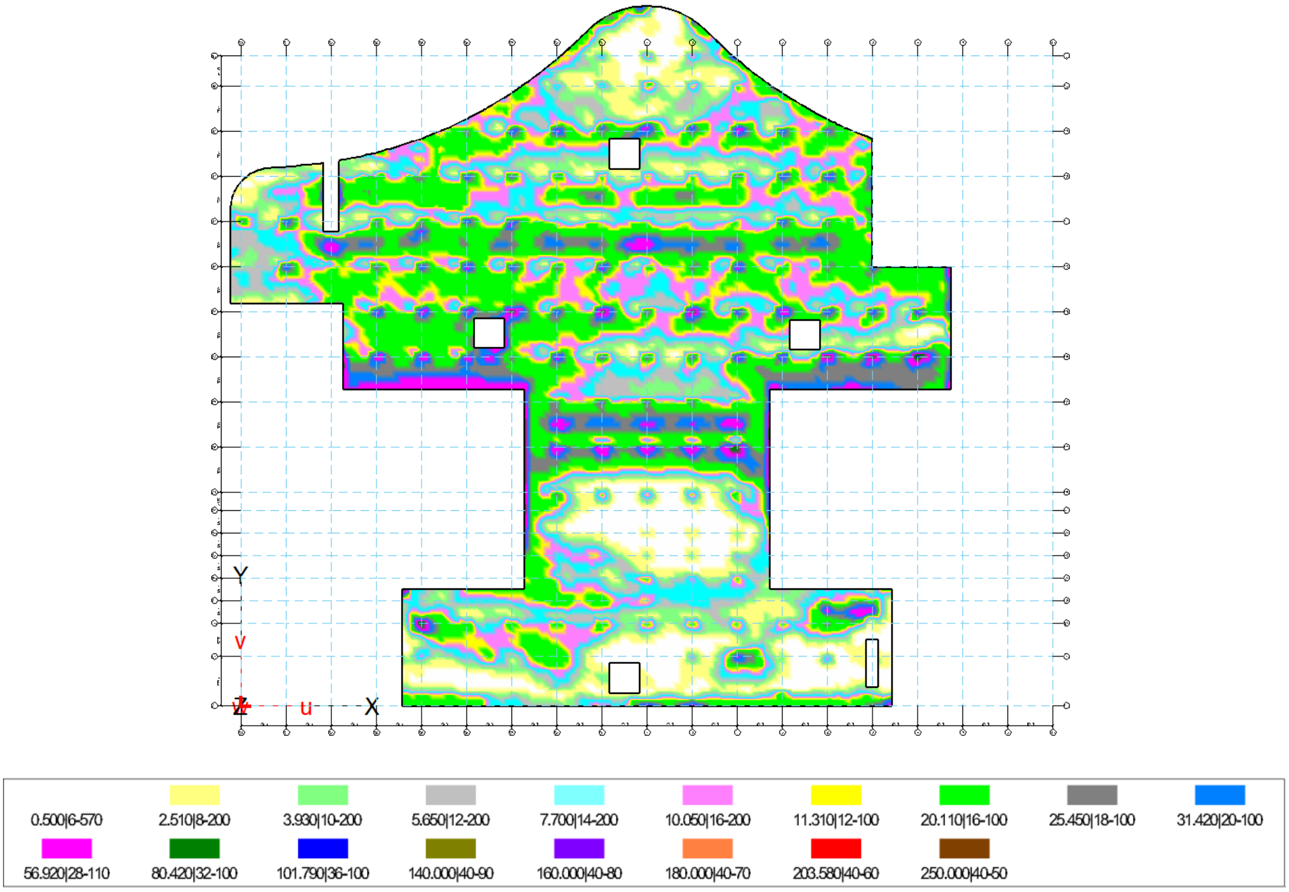


Fig. 21. Reinforcement of the foundation plate. Lower longitudinal reinforcement in the direction of the axis *S*, cm$^2$/m [15]

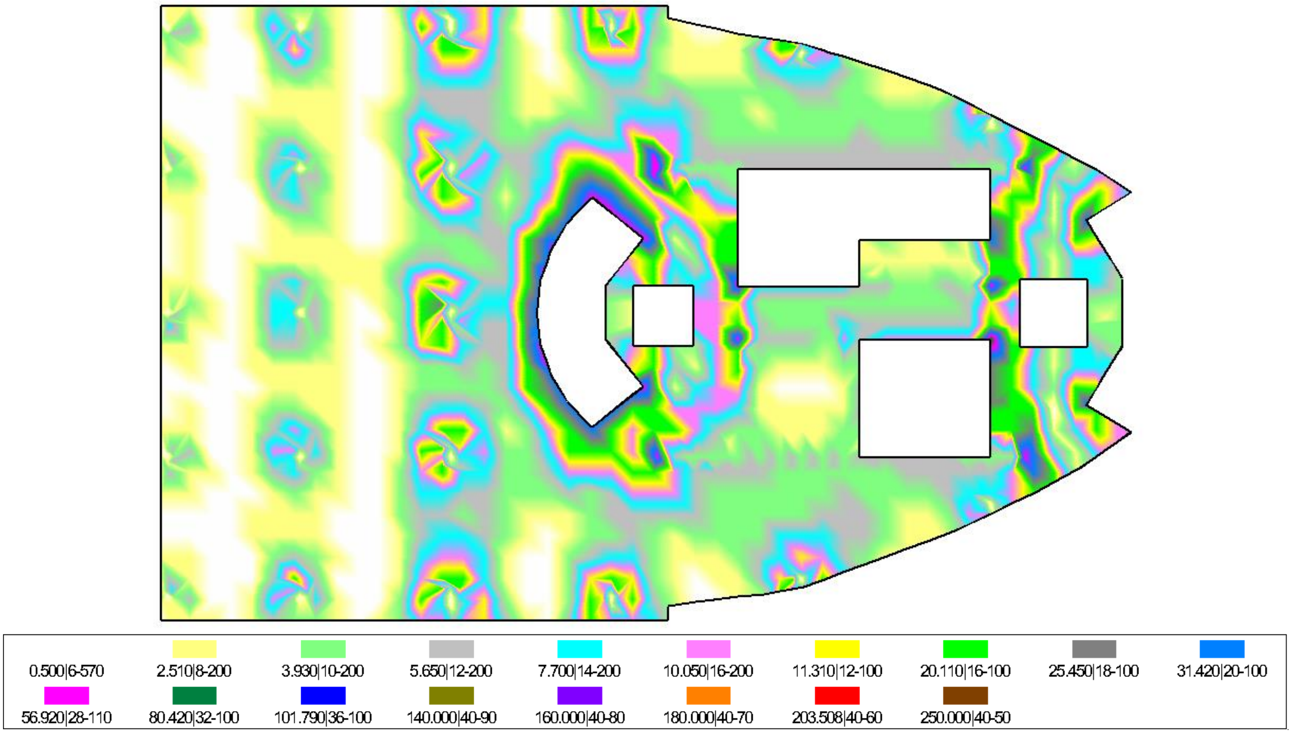


Fig. 22. Reinforcement of the floor slab of the western tower at +42.80 m. Upper longitudinal reinforcement in the direction of the axis *R*, cm$^2$/m [15]

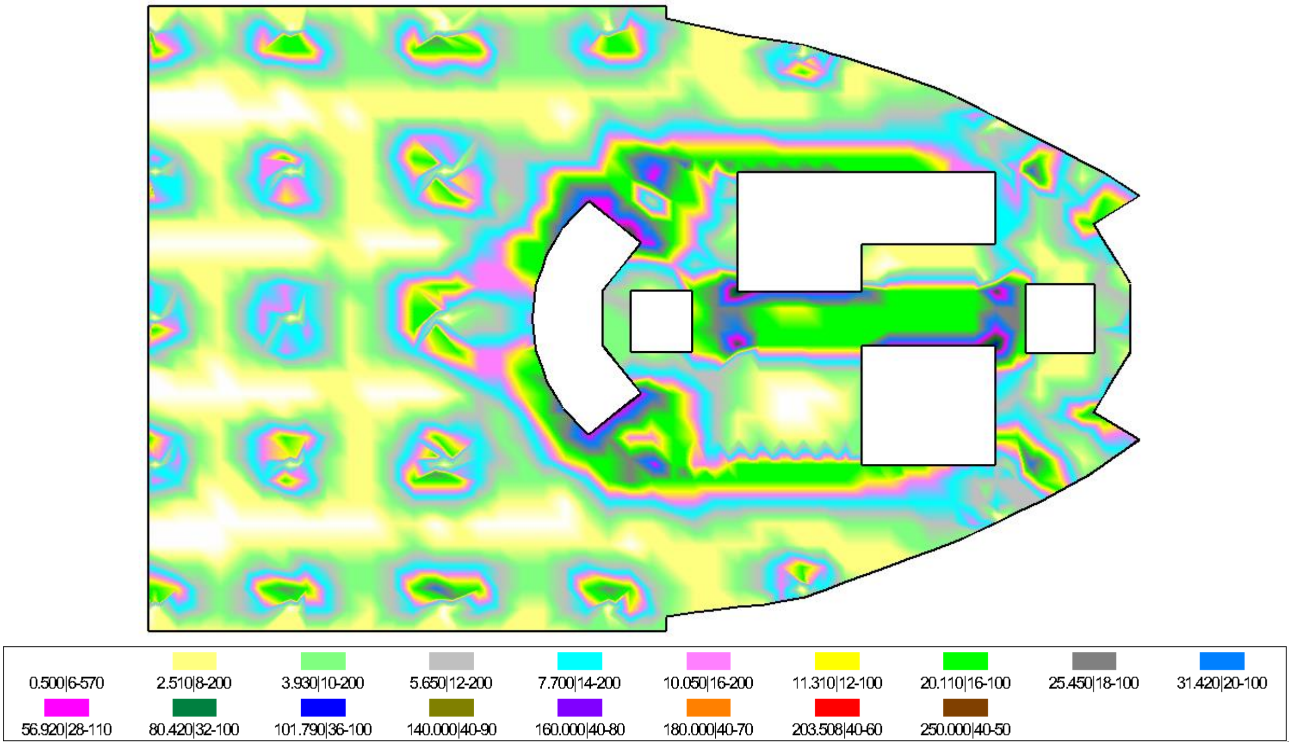


Fig. 23. Reinforcement of the floor slab of the western tower at +42.80 m. Upper longitudinal reinforcement in the direction of the axis *S*, cm$^2$/m [15]

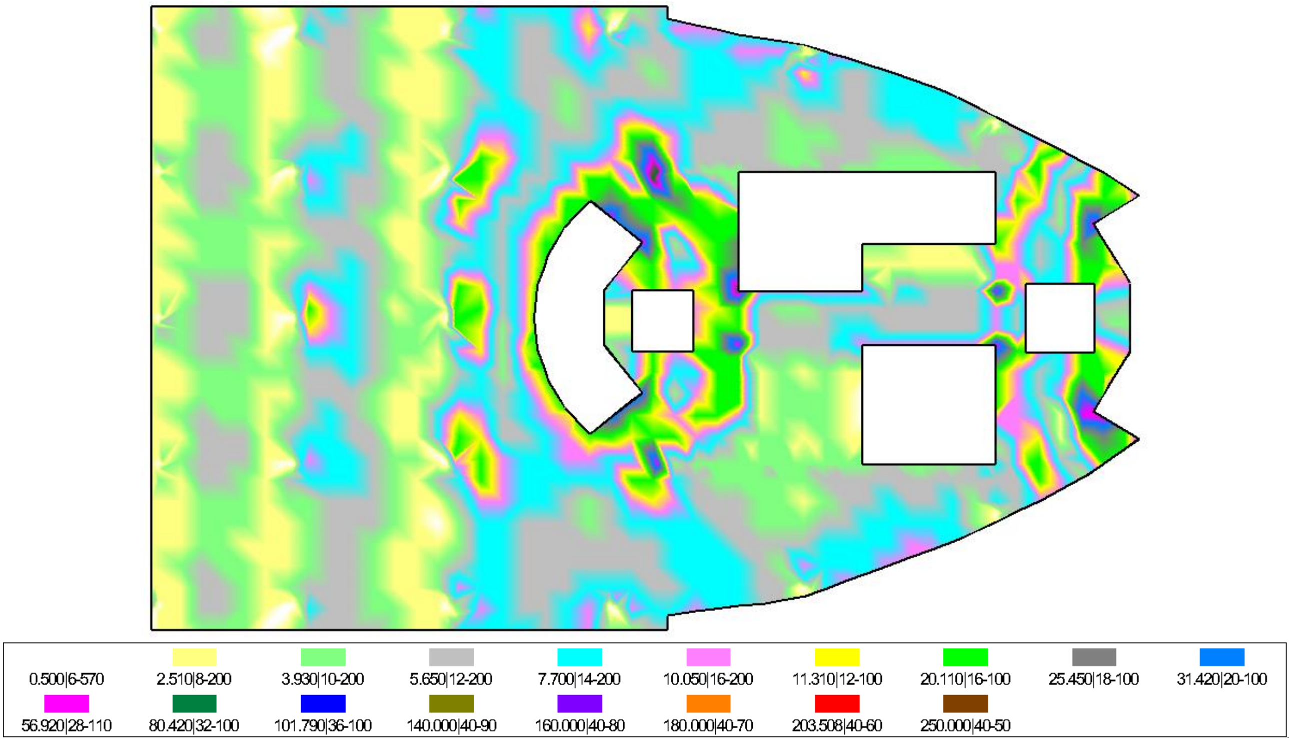


Fig. 24. Reinforcement of the floor slab of the western tower at +42.80 m. Lower longitudinal reinforcement in the direction of the axis *R*, cm$^2$/m [15]

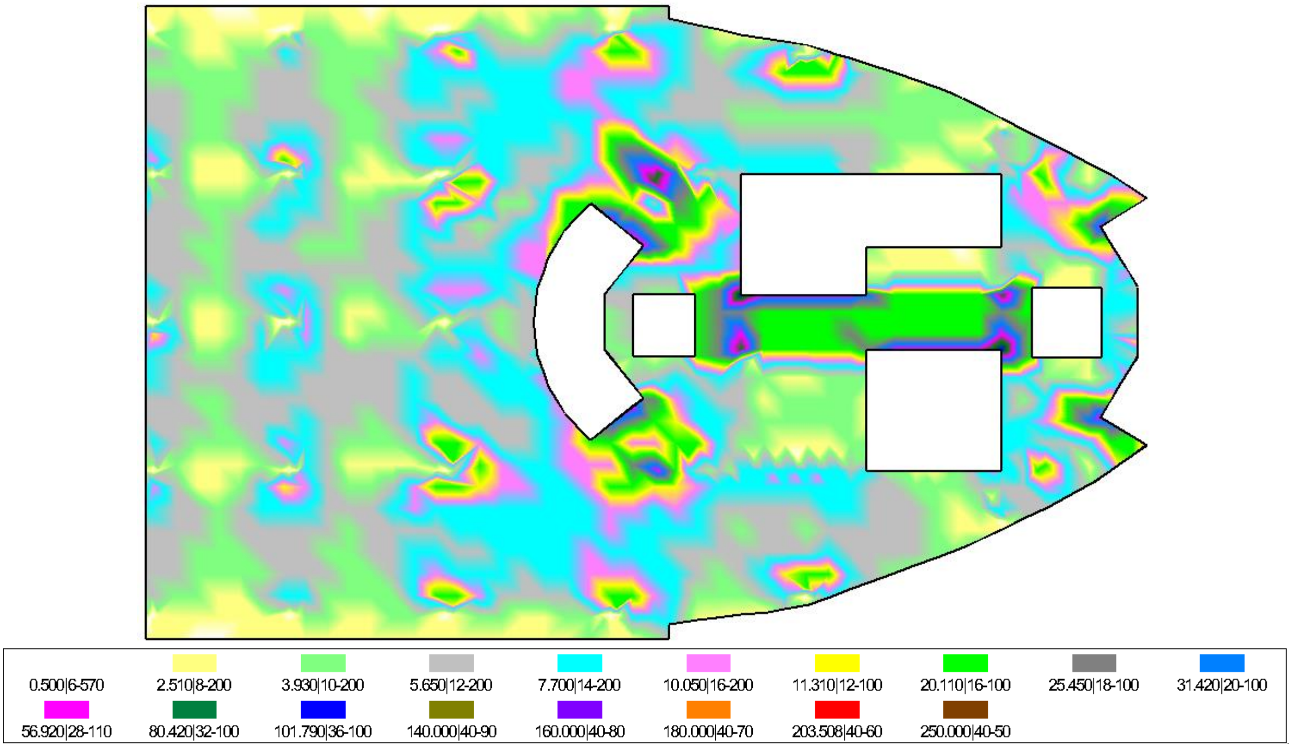


Fig. 25. Reinforcement of the floor slab of the western tower at +42.80 m. Lower longitudinal reinforcement in the direction of the axis *S*, cm$^2$/m [15]

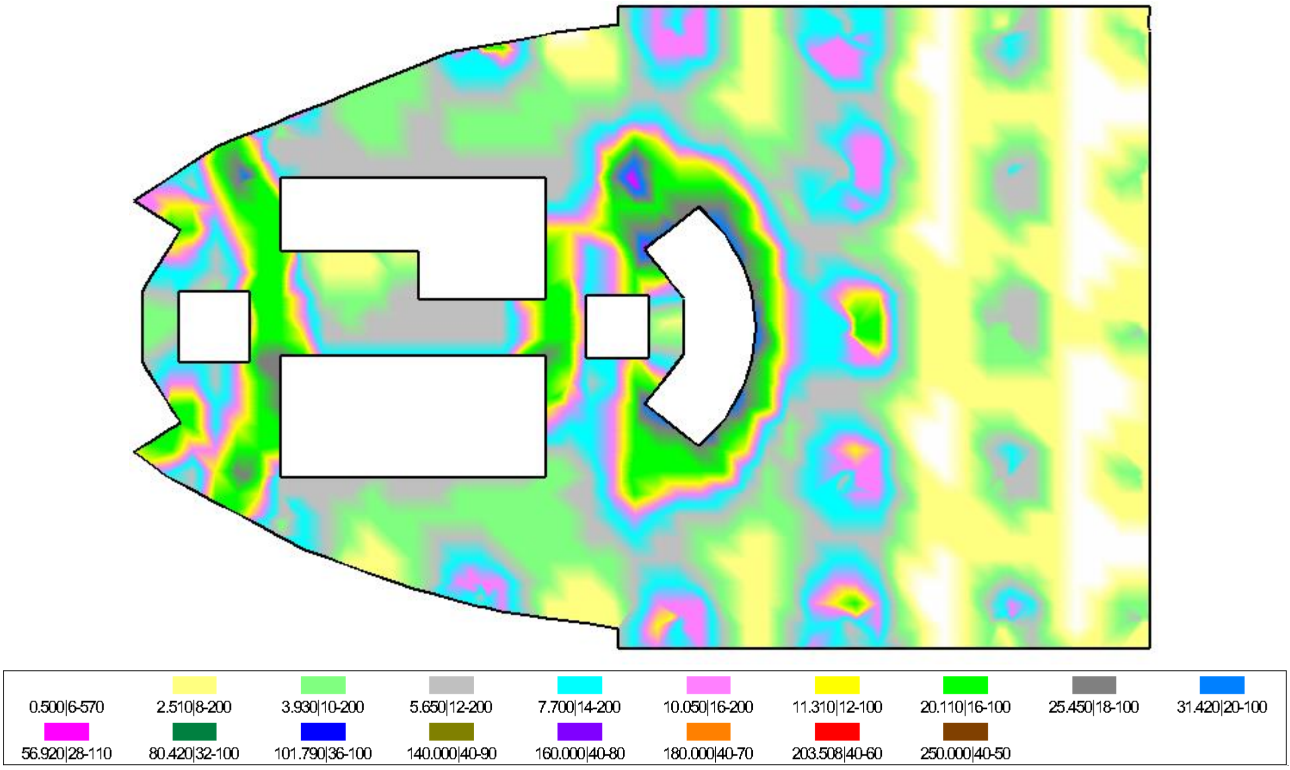


Fig. 26. Reinforcement of the floor slab of the eastern tower at +42.80 m. Upper longitudinal reinforcement in the direction of the axis *R*, cm$^2$/m [15]

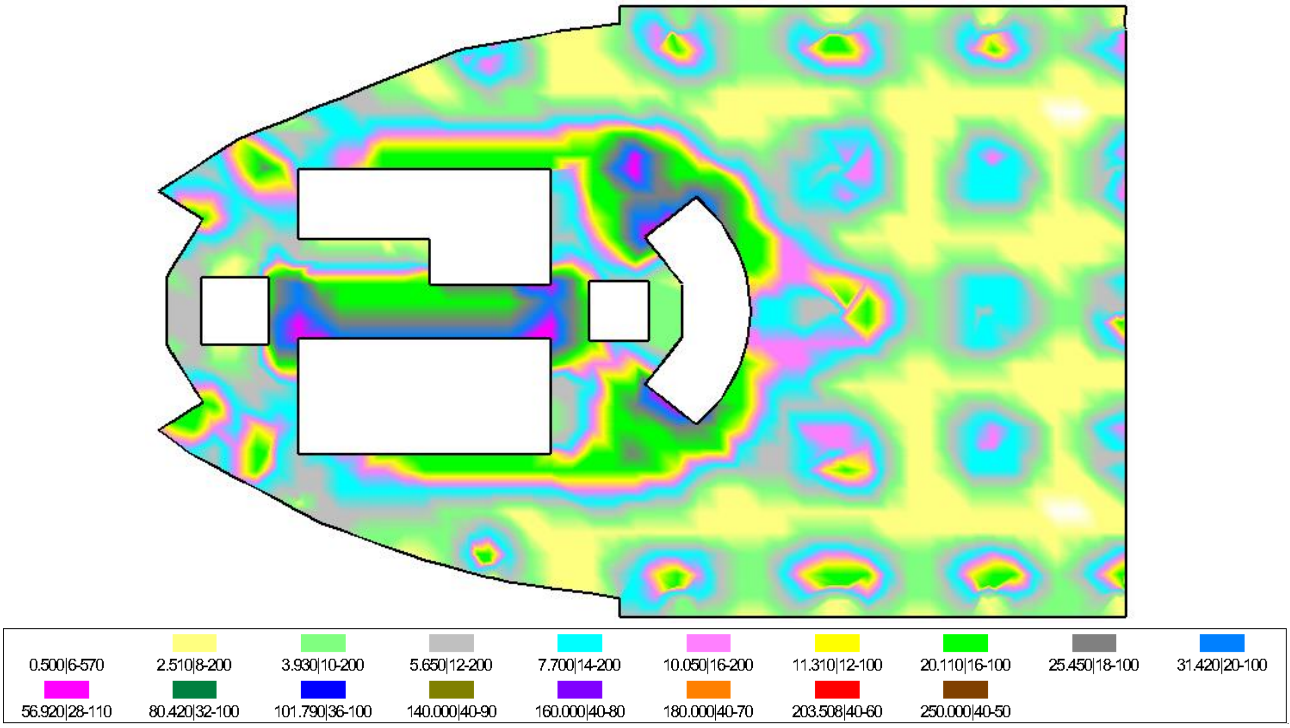


Fig. 27. Reinforcement of the floor slab of the eastern tower at +42.80 m. Upper longitudinal reinforcement in the direction of the axis *S*, cm$^2$/m [15]

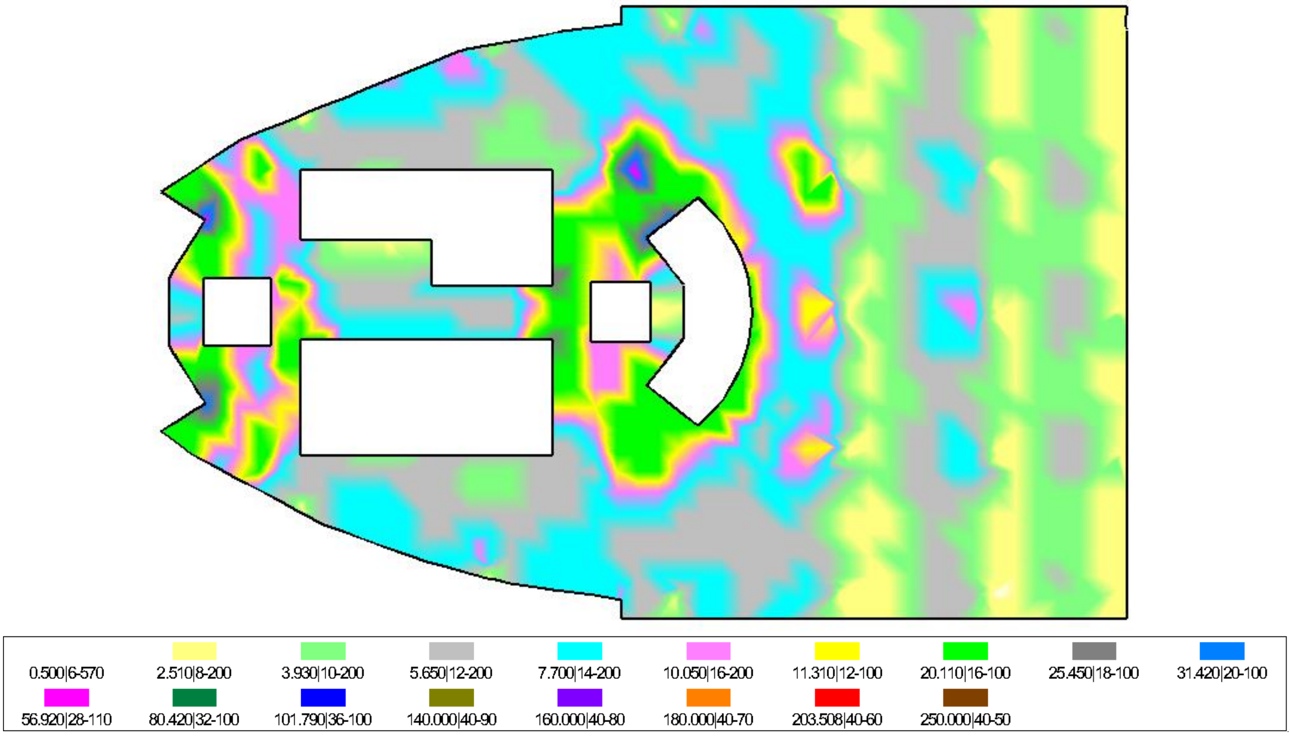


Fig. 28. Reinforcement of the floor slab of the eastern tower at +42.80 m. Lower longitudinal reinforcement in the direction of the axis *R*, cm$^2$/m [15]

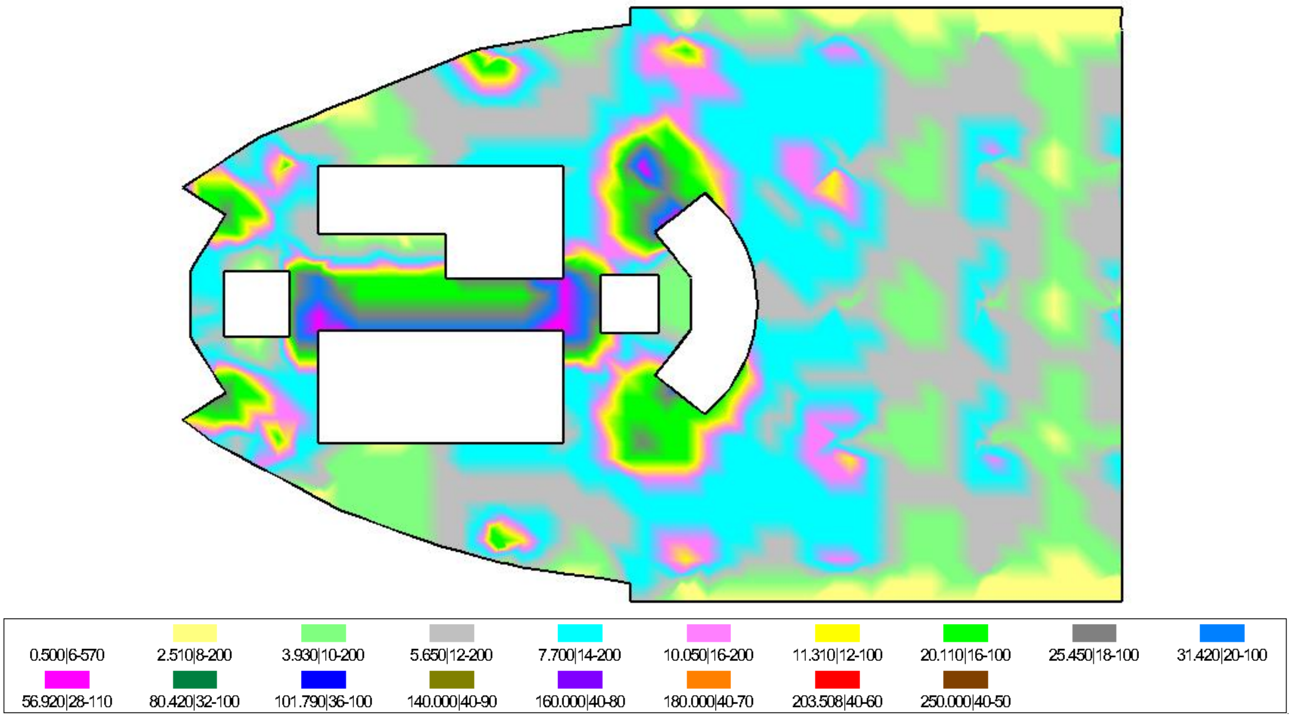


Fig. 29. Reinforcement of the floor slab of the eastern tower at +42.80 m. Lower longitudinal reinforcement in the direction of the axis *S*, cm$^2$/m [15]

As part of the calculations of the load-bearing structures of a multi-storey building of complex shape, the following works were performed:

1. Analysis of project documentation and research materials. spatial design scheme taking into account the structures of the pile foundation.

2. Collecting loads on structures taking into account the requirements of the norms of the Republic of Azerbaijan, recommendations for the purpose of snow and wind loads.

3. Calculations of the stress-strain and natural oscillations of the spatial calculation schemes of the FEM including verification calculations including for a special combination of loads taking into account seismic effects.

4. Checking the overall rigidity of the load-bearing system of a building, foundation sedimentation, and vertical plate deflections under major combinations of loads and impacts.

5. Calculation of the main elements of load-bearing structures by limiting conditions.

**Discussion and Conclusion.**

An analysis of the results of spatial calculation of the load-bearing structures of a 29-storey building of complex shape with a frame-braced frame, stiffness cores and a unique mega-truss confirmed the operability of the design decisions made under conditions of seismic impact with an intensity of 8 points. The calculations were performed using the finite element method in the STARK ES PC taking into account 53 loads including special combinations of loads.

The theoretical significance of the study is a comprehensive assessment of the stress-strain of a combined structural system joining monolithic reinforced concrete cores and a 90 m long steel mega-truss. The results obtained confirm the effectiveness of using spatial finite element models to predict the dynamic characteristics of buildings of complex geometric shape. The results of the modal analysis (the first three natural oscillation frequencies: 0.340 Hz, 0.459 Hz and 0.484 Hz) can serve as reference points for verifying similar calculation models and clarifying regulatory approaches to identifying the dynamic parameters of high-rise buildings on weak soils of coastal territories.

The practical significance of the study is due to a possibility of direct application of the results obtained in the design of multifunctional complexes in earthquake-prone areas, including on the drained lands of the Caspian Sea. The key findings important for engineering practice are as follows:

- The maximum foundation draft (50.2 mm) and the relative draft difference (0.00016) are not beyond the regulatory limits, which confirms the reliability of the pile foundation and the rigidity of the foundation plate.

- Horizontal displacements of the top of the building (163.4 mm) are significantly lower than the allowed 300 mm, which guarantees the comfort of operation and the safety of facade systems.

- The deflections of the floor slabs (from 1.2 to 13.8 mm) comply with the requirements of the second group of limit conditions.

- The critical stability parameter (10.4) indicates a high margin of overall stability of the system.

- The selected reinforcement (Fig. 18–29) is sufficient to comply with the requirements of AzDTN 2.3-1, AzDTN 2.16-1 and ensures the load-bearing capacity and crack resistance of reinforced concrete slabs, walls of stiffness cores under basic and special combinations of loads including seismic ones.

- The strength of metal beams complies with the requirements of AzDTN 2.18-1.

- The forces in the piles are not beyond the permissible values.

The suggested structural solutions – stiffness cores combined at the 27th floor level by a steel mega-truss — can be recommended for high–rise buildings of complex shape as an effective way to perceive horizontal seismic loads and ensure spatial rigidity.

Hence the structural solutions adopted in the design of a multi-storey building of complex shape ensure reliability, strength, rigidity and stability of load-bearing building structures with basic and special combinations of design loads and impacts, and the results can serve as a foundation for optimizing the design of such unique structures.

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**KKh Mazhiev:** participation in the implementation of the study, analysis of the results, correction of the manuscript, formulation of the conclusions.

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**YuV Panasenko:** development of a computational and dynamic model of the building, calculations, implementation of the main stages of the study, processing and analysis of the results, formulation of the conclusions.

**AKh Mazhiev:** participation in calculations, implementation of the main stages of the research, processing and analysis of the results, formulation of the conclusions, preparation of the illustrations, original manuscript and general design of the manuscript.

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