BUILDING CONSTRUCTIONS, BUILDINGS AND ENGINEERING STRUCTURES

СТРОИТЕЛЬНЫЕ КОНСТРУКЦИИ, ЗДАНИЯ И СООРУЖЕНИЯ

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Evaluation of the Reliability of Design Solutions during the Reconstruction of a Cultural Heritage Site Taking into Account Seismic Impacts

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Abstract

Introduction. In order to ensure seismic resistance and reduce seismic loads, during the reconstruction of the cultural heritage site, a spatial calculation of the supporting structures of the cinema and variety hall was performed. This article analyzes the structural system, the calculation and dynamic model taking into account the main and special combinations of loads.

Materials and Methods. The calculations were carried out using the analytical method and the finite element method in the STARK ES software package.

Results. For the purpose of reconstructing the building of the cultural heritage site, the results of dynamic calculation were obtained for the main and special combinations of loads and corresponding combinations of internal forces in the calculated structures of the cinema and variety hall. In this case, only 25 loadings were used.

Discussion and Conclusions. The results of the calculation of the cinema building showed that the required load-bearing capacity of the building of a cultural heritage site is ensured in the considered design situation.

Keywords: building, reconstruction, seismic impact, calculation, load, structural system, seismic resistance, calculation-dynamic model

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Оригинальное эмпирическое исследование

Оценка надежности конструктивных решений при реконструкции объекта культурного наследия с учетом сейсмических воздействий

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Аннотация

Введение. С целью обеспечения сейсмостойкости и снижения сейсмических нагрузок при реконструкции объекта культурного наследия выполнен пространственный расчет несущих конструкций сооружений кино-эстрадного зала. В настоящей статье анализируются конструктивная система, расчетно-динамическая модель с учетом основных и особых сочетаний нагрузок.

Материалы и методы. Расчеты проводились аналитическим методом и методом конечных элементов 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 сооружений реконструируемого объекта (кино-эстрадного зала). При этом было использовано всего 25 загружений.

Обсуждение и заключение. Результаты расчета здания кинотеатра показали, что обеспечивается требуемая несущая способность здания объекта культурного наследия при рассматриваемой расчетной ситуации.

Ключевые слова: здание, реконструкция, сейсмическое воздействие, расчет, нагрузка, конструктивная система, сейсмостойкость, расчетно-динамическая модель

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Introduction. When there is renovation work occurring in cities, it is essential that cultural heritage sites that were designed taking into account old norms and calculation models are preserved.

To this end, the task is to conduct a spatial calculation of the load-bearing building structures of the cinema and variety hall of the cinema theatre to assess their reliability during reconstruction. The reconstructed building is a cultural heritage site and is in a seismically active area. [1–5, 14].

There must be scientific and technical assessment of the compliance of design solutions in compliance with the requirements of regulatory documents of the Russian Federation on building safety, as well as the development of recommendations for the design stage of "working documentation", accounting for possible changes in the design scheme of the structural model of the building during reconstruction.

Materials and Methods. The structural system being investigated is a trapezoidal cinema building, framed, with exterior side walls made of concrete blocks and bricks and with stained glass windows on the southern (main) and northern facades. The cinema theatre is made up of two halls: a large one with 1,200 seats and a small one with 80 seats. The cinema theatre is located on the stylobate. Most of the building is taken up by an audience hall with a widescreen screen and an amphitheater for seating.

The cinema theatre building is made up of two components (Fig. 1):

– administrative wing, in the axes 4–11/D–F;

– audience hall, in the axes 1–14/A–D, and the basement, in the axes Iп–IIп/C–F.

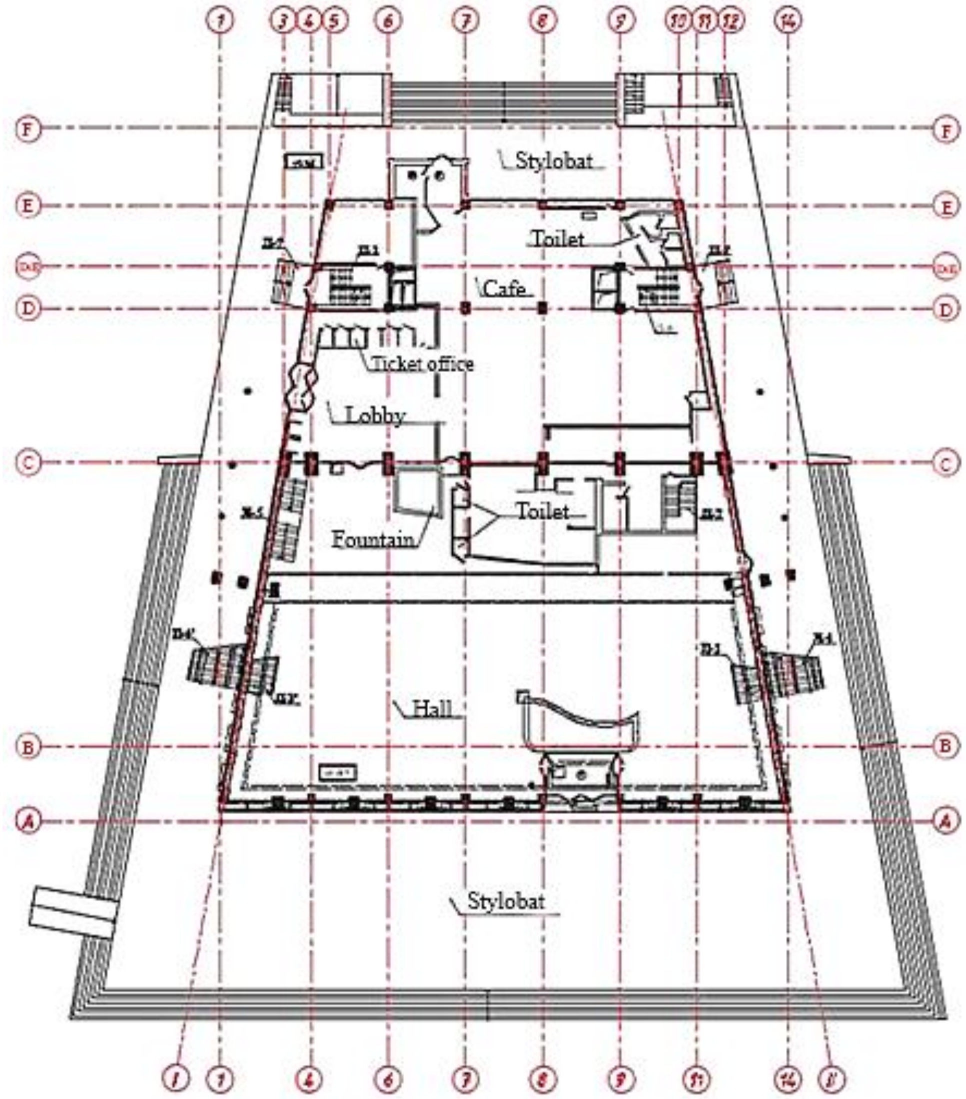


Fig. 1. Layout scheme of the building [14]

The administrative wing of the building is made of 4 storeys, the structural scheme is a monolithic reinforced concrete frame frame with a crossbar arrangeme+nt. Prefabricated hollow slabs laid along digital axes were used as elements of the interstory floors (coatings). The external wall filling of the frame is made in the form of lightweight ceramic brick masonry.

The audience hall of the building is 2-storied. The supporting elements are the frames installed along the digital axes of the building. The structural elements of the frame are reinforced concrete and inclined metal racks, reinforced concrete inclined crossbar and console with a span of 11.66 m. The reinforced concrete frame elements have a variable cross-section. The junction of the metal rack and the inclined bolt is hinged. A reinforced concrete tightening is provided to make up for the horizontal forces generated in the support unit of the metal rack. The support unit of the metal rack is hinged, the reinforced concrete rack is rigid. Precast reinforced concrete hollow slabs were used as the floor elements of the 1st floor. In order to ensure the spatial rigidity of the frames, monolithic reinforced concrete struts R-1 and R-2 were made at the top of the struts along the axes "A" and "C", precast reinforced concrete cross ties were installed along their entire length with a step of 5-6 m [1–5, 14].

Metal beams of a composite I-beam section with a height of 1.7 m were used as supporting structures of the coating. The console with a span of 11.66 m is supported along the "A" axis by an inclined metal rack of the supporting frame through a metal rack Ст-1 supported by a monolithic reinforced concrete strut P-1, along the "D" axis by columns of the frame of the administrative wing of the building. The spatial stability of the load-bearing elements of the coating is ensured by the presence of vertical metal bracing trusses, horizontal struts and cross ties installed along the upper and lower girder belts. The coating structures are precast reinforced concrete ribbed slabs.

Prefabricated blocks made of expanded clay concrete not connected to the columns of the frame were used as enclosing structures (exterior walls) of the main part of the building.

Transitional galleries at the 3rd floor level are provided in the axes I/A–D and II/A–D of the audience hall for communication between the camera room and the administrative wing of the building (Fig. 1).

The reconstruction project involves preservation of the spatial appearance of the building as part of the adaptation to modern use for concert events. According to the reconstruction project, existing structures are to be partially dismantled and later restored and the preserved structures are to be reinforced [6–11].

According to the architectural concept of the reconstruction of the facility, it is planned to build a developed underground basement around the cinema theatre for more modern functionality and to expand recreational opportunities in terms of the location of blocks C1–C5 around block A1 with a functional connection between the buildings (Fig. 2).

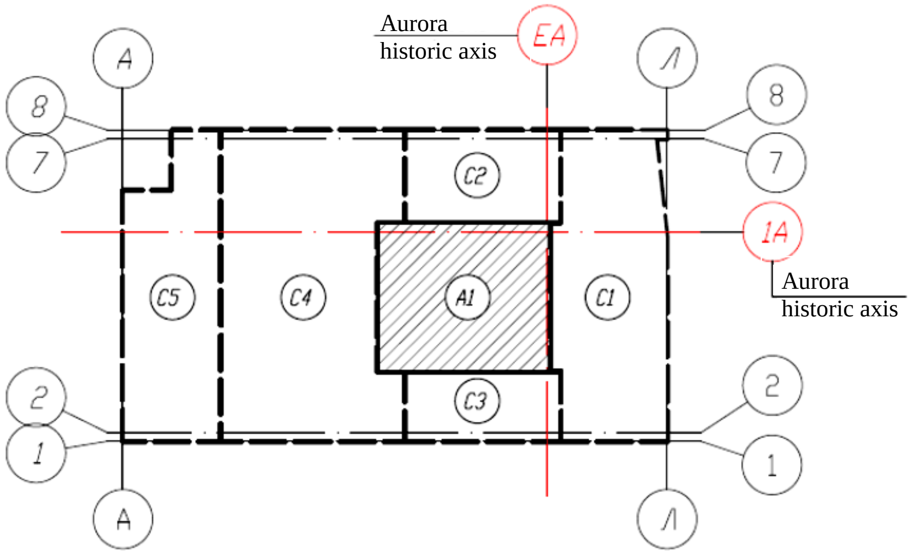


Fig. 2. Situational scheme of the area

The following structural and spatial planning measures are seen as part of the reconstruction of the main building:

– expanding the audience hall due to the space of the administrative wing. To this end, in the latter, some of the frame is to be dismantled from the basement to the 4th floor (columns, beams, ceilings, basement walls, curtain walls) with the construction of a new frame and the installation of two reinforced concrete beams covering the hall with a span of 21.1 m and 18.3 m. In order to support the beams of the coating, two stiffness cores are performed in axes 4–6/D–E and 9–11/D–E with pilaster columns for the projected beams;

– the existing internal stairwells are to be dismantled. Evacuation stairwells are built inside the projected rigidity cores;

– the existing stylobate part of the administrative block in the axes is to be dismantled and rebuilt. $I_{п}$–I, $II_{п}$–II, E–F;

– the V-shaped beams of the auditorium B-1.1 are preserved with their reinforcement according to the calculation;

– the audience hall is undergoing reconstruction of the existing technological galleries and two levels of projected balconies are being installed along the side walls of the building. Balconies and galleries are supported by projected columns mounted on V-shaped beams. Balconies and galleries are made in a steel frame to reduce the weight. Recessed columns are installed in the existing exterior wall of the building to support balconies and galleries;

– the existing exterior walls of the audience hall along axes I and II are to be reconstructed and reinforced with concrete pilaster columns;

– the existing foundations are reinforced by installing additional borehole injection piles and reinforced cement elements around the perimeter;

– new pile foundations are to be built for the projected load-bearing structures;

– an underground gallery is to be built for a passage under the cinema building between the attached museum and cinemas on the southern side, and a cafe on the northern side.

The following measures are provided in order to reduce the load on the building:

– dismantling of the existing floors and partitions with the installation of modern lightweight materials — drywall and gypsum fiber sheet, aerated concrete blocks of autoclave hardening;

– dismantling of the hall floor covering (including prefabricated reinforced concrete slabs that fail to comply with the requirements for coatings in seismic areas according to the survey results) with the installation of a lightweight membrane coating on a profiled sheet;

– dismantling of the existing galleries along the hall with the installation of new galleries, ceilings and balconies on steel beams and columns;

– dismantling of the curtain walls of the administrative wing with the installation of earthquake-resistant curtain walls made of aerated concrete blocks of autoclave hardening.

For possibly installing an attached underground part and protecting the reconstructed building, a wall in the ground (tongue–and-groove fencing) with a thickness of 600–800 mm is installed along the perimeter of the reconstructed building and along the perimeter of the attached underground space with a spacer system made of steel pipes and anchoring on two to four levels. The spacer system is dismantled as the underground part is built and the wall is supported in the ground on the frame of the projected stylobate.

The existing pile foundations are reinforced with borehole injection piles to transfer loads from existing foundations to dense sands at the base of the building and the possibility of hanging existing foundations accounting for the arrangement of the attached underground part below the tip of the existing piles [12–15].

In order to bring the building to the requirements of seismic standards, the lobby block with the audience hall and the former administrative wing are combined into a single seismic compartment. The projected rigidity cores of the administrative part are included in the operation of the main lobby — audiencer hall seismic unit. With this solution, the beams of the coating are supported by a combined seismic unit.

Individual elements of columns and beams with insufficient load-bearing capacity are also structurally reinforced according to the calculations for the main and special combination of the loads.

The steel elements of the inclined columns of the main lobby are reinforced according to the calculation. The support points of the inclined columns are reinforced as rigid ones.

The roof beams of the audience hall B1 are preserved and reinforced according to the calculation. Dismantling the frame of the administrative wing involves re-supporting the roof beams on temporary supports installed along the axis C. After dismantling and erecting the projected administrative part of the newly designed beams along the axis, the existing metal beams are re-supported on them. There is reconstruction of the support joint of the beams along the D axis.

The cantilever trusses along the I, II axes are dismantled and rebuilt attached to the built–in wall frame along the I, II axis. The communication system in the canopy in the A1–A/B axes is to be replaced.

The elements of reinforced concrete structures with defects identified during the examination are restored and reinforced according to the calculation.

External escape ladders are to be dismantled and rebuilt in monolithic reinforced concrete on the projected stylobate. The existing staircase in the foyer is to be retained and reinforced.

In order to assess the reliability of the design solutions employed in the project, a verification calculation of the spatial model of the structure for design loads and impacts was performed. The calculation was performed using the STARK ES software package.

A spatial shell-rod model was used as a computational model where the supporting columns, crossbars and truss elements are represented by general rod elements, the coating shell, floor slabs and walls are represented by elements of a flat shell (Fig. 3).

The elements of the built–in rooms in axes C–D/1–3, C–D/7–11, C–D/15–18 and the roof extensions in axes A1–A/7–13 are specified only for collecting and transferring the load to the load-bearing elements of the frame.

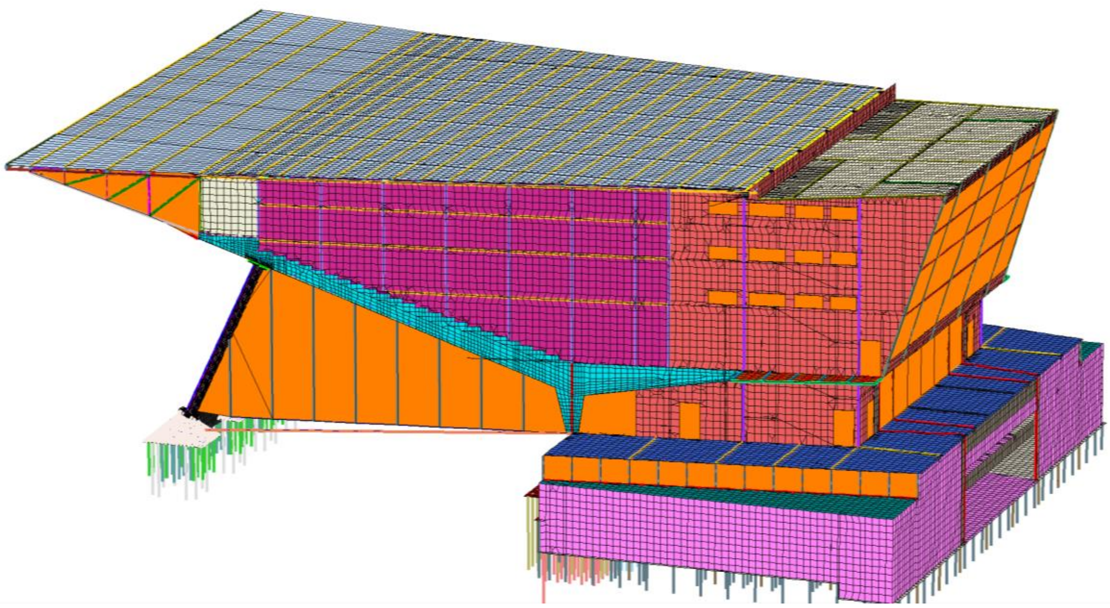


Fig. 3. Finite-element model of the cinema hall (block A1) [14]

While calculating the building, the following loads and impacts were accounted for:

– vertical constant loads from the own weight of load-bearing and enclosing structures;

– long-term loads from engineering equipment;

– temporary loads on floors and coatings;

– snow load;

– average and pulsation components of the wind load;

– seismic impact on the structure;

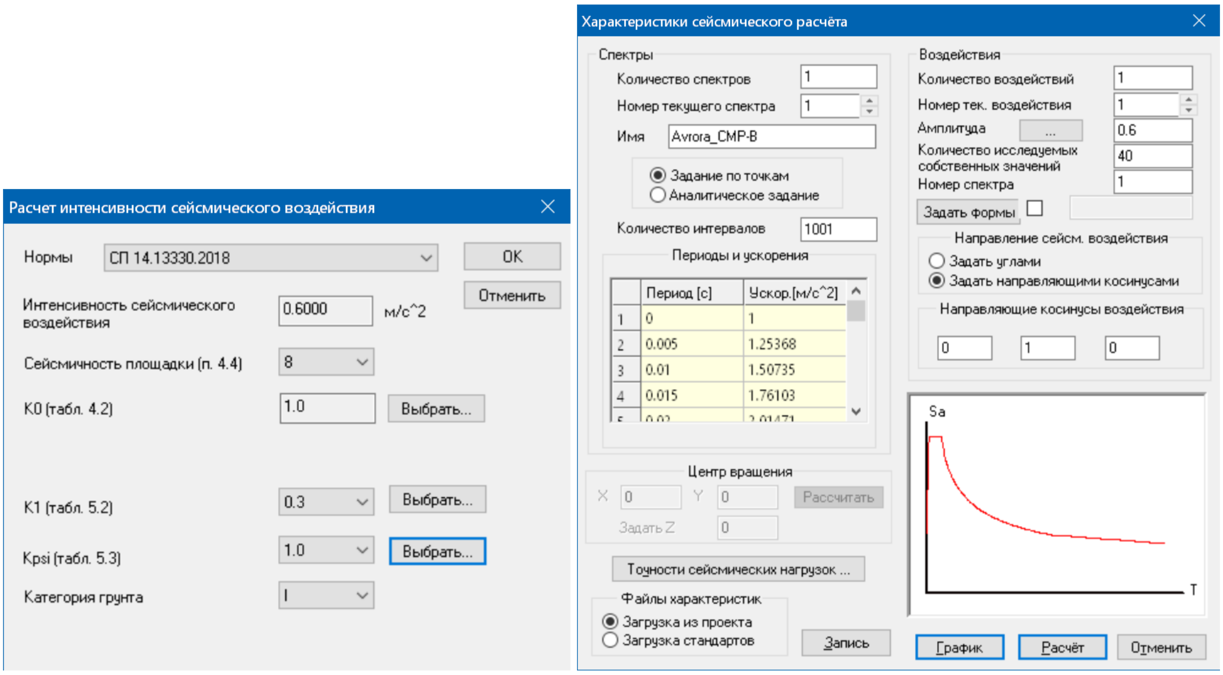
– special emergency impacts as a special combination of loads accounting for extreme climatic influences.

The normalized parameters and conditions of the construction object are shown in Table 1. Fig. 4 shows the values of the parameters for calculating the seismic impact.

Table 1

Standardized parameters and conditions of the construction object

Name	**Value**	**Normative document, section**
The level and class of responsibility of the facility, the reliability coefficient in terms of responsibility	Normal, КС–2	№ 190-FL, section 48.1 № 384-FL
The value of the reliability coefficient for the responsibility of the facility, γ_n	1,0	GOST 27751-2014
Wind load: – wind area; – standard value of wind pressure, kPa.	IV 0,48	SP 20.13330.2016
Snow load: – snow area; – normative value of the snow cover weight, kPa.	II 1,1	SP 20.13330.2016
Climatic area/subarea	III/IIIБ,	SP 131.13330.2020
Гололедная нагрузка	III 10 mm	SP 20.13330.2016
Seismicity of the construction area – map A – map B	7 points 8 points	Seismic microzoning



a) *b)*

Fig. 4. Parameter values for calculating the seismic impact: *a* — calculation of seismic impact intensity; *b* — characteristics of the seismic calculation

A total of 25 downloads was used in the calculated model of the cinema hall to account for all the loads. Fig. 5–6 shows the schemes for applying wind loads in the +*X* and +*Y* directions, respectively.

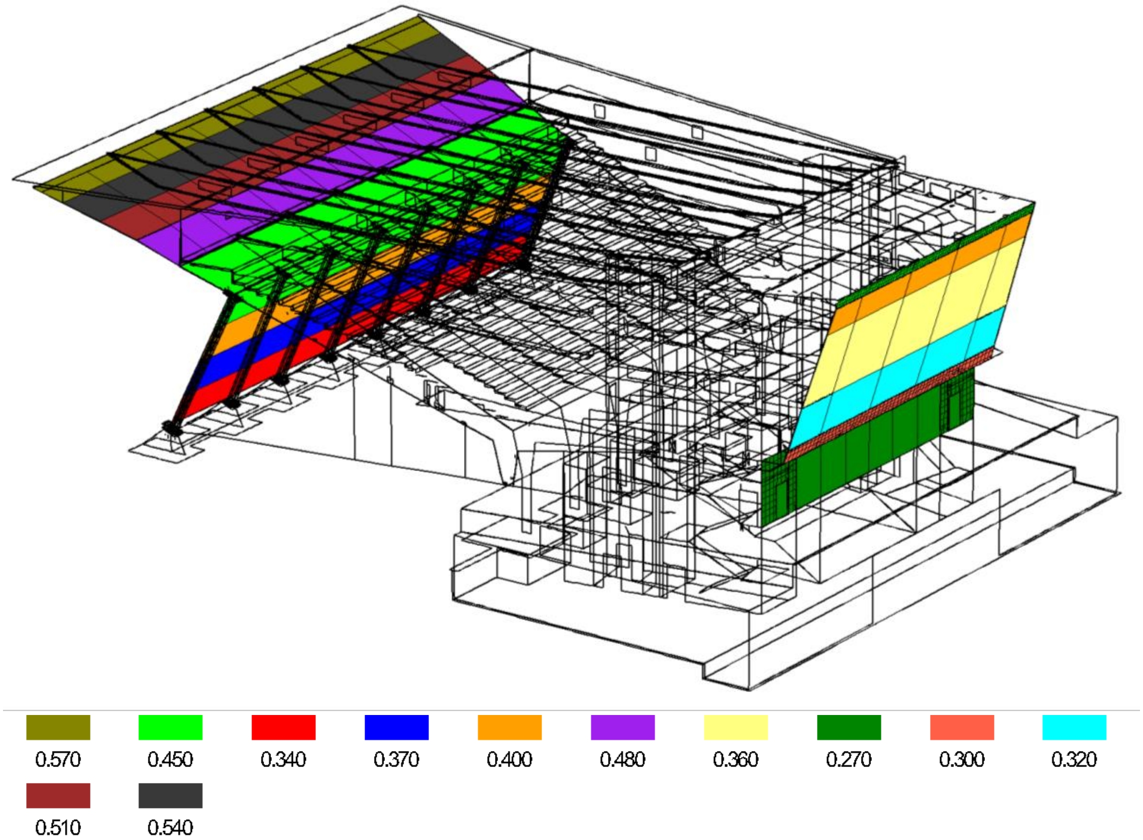


Fig. 5. Wind load application scheme. Direction +*X*, kN/m^2 [14]

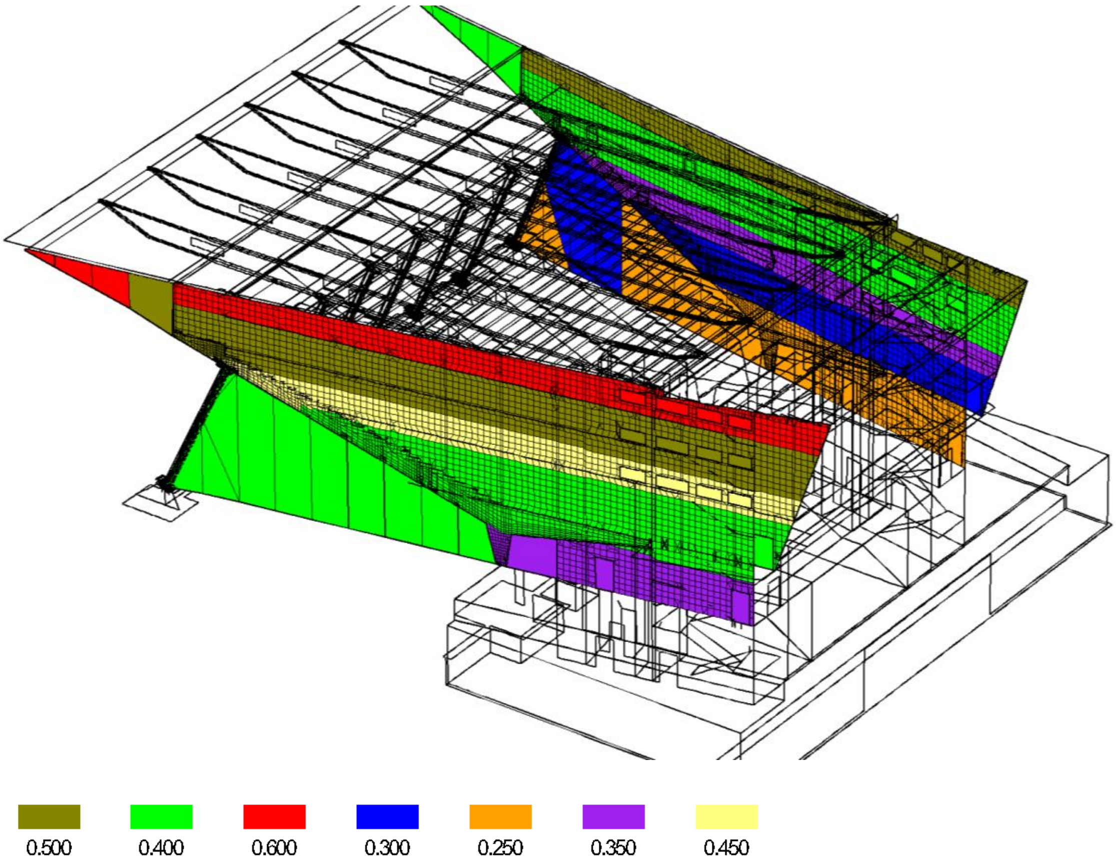


Fig. 6. Wind load application scheme. Direction +*Y*, kN/m^2 [14]

Research Results. The foundation sediment was evaluated for the main combinations of the full values of the standard loads. The foundation sediment is shown in Fig. 7. The maximum precipitation was 12.4 mm.

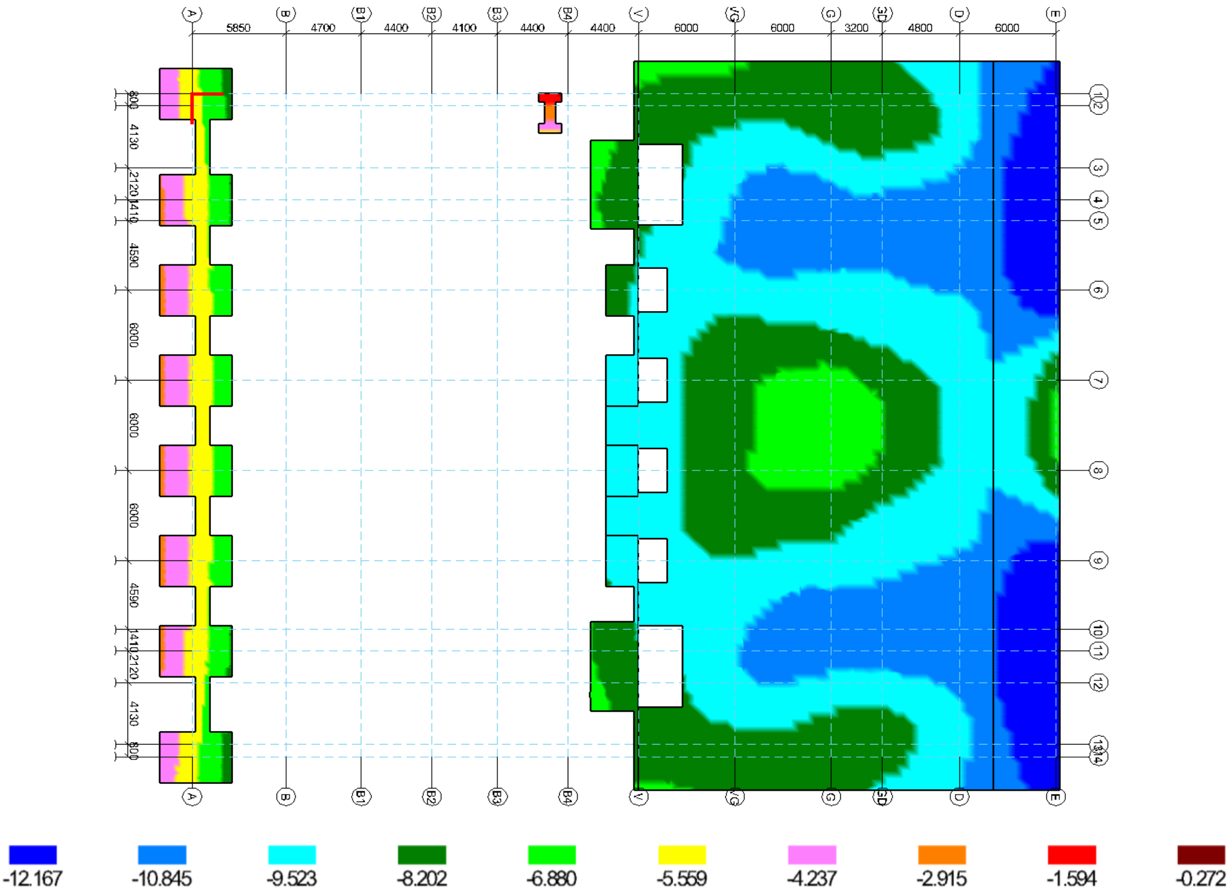


Fig. 7. Sediment of the foundation *Uz* [14]

The maximum value of the relative difference in the sediment from the main load combinations was $\Delta s/L$ = 0.00032, which is not over the permissible value of 0.004.

The horizontal deviations of the top of the building were evaluated for the main combinations of the full values of the standard loads (Fig. 8).

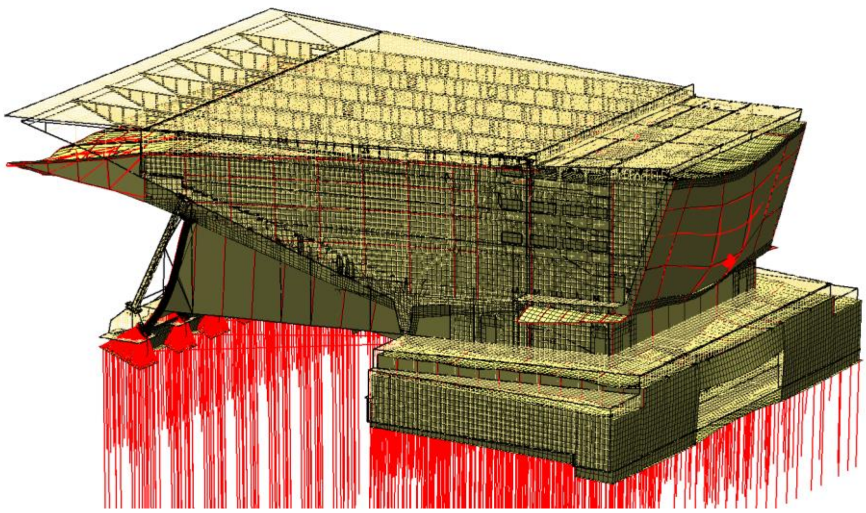


Fig. 8. Horizontal displacement of the top of the building [14]

The maximum horizontal displacement of the top of the building from the standard load values is 19.3 mm, which is not over the maximum permissible value of 36 mm.

The results of the calculation of the first form of stability loss and the corresponding critical load parameter P_{cr} are given in Fig. 9.

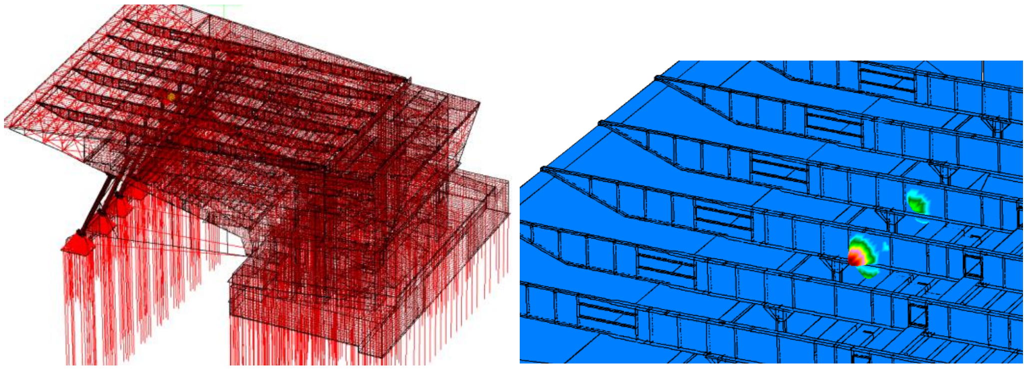
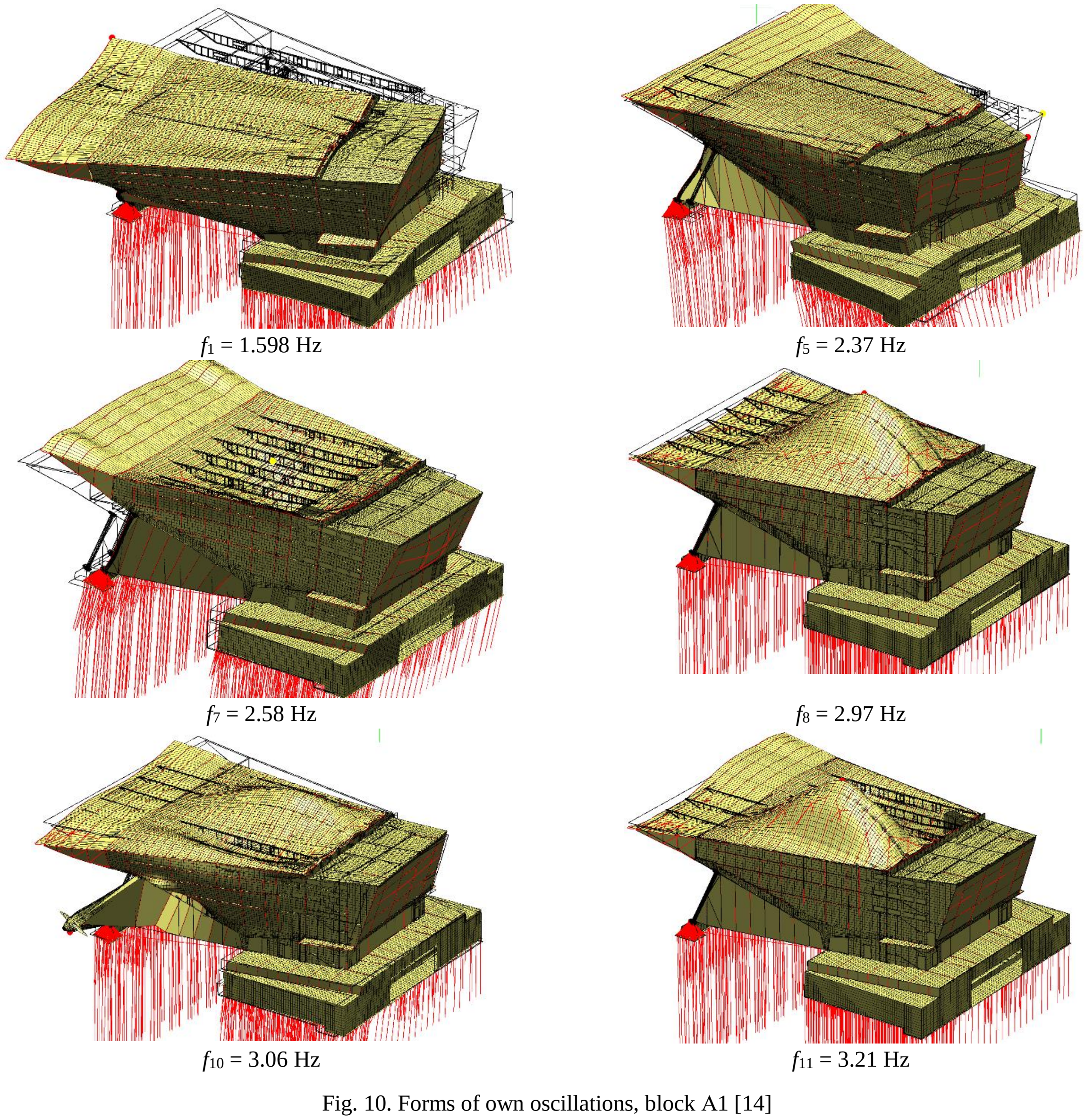


Fig. 9. Form 1 of the stability loss [14]

The lowest critical load parameter (stability margin) accounting for the reliability coefficient of responsibility is 1.56. The overall stability of the load-bearing structures of the building is ensured.

In order to enhance the reliability of the historical structures of the coating beams, it was recommended that the wall stability in the support zones to the value is increased to P_{cr} of no less than 2.0.

Fig.10 shows the first general forms of natural oscillations of the cinema hall.



f_1 = 1.598 Hz f_5 = 2.37 Hz

f_7 = 2.58 Hz f_8 = 2.97 Hz

f_{10} = 3.06 Hz f_{11} = 3.21 Hz

Fig. 10. Forms of own oscillations, block A1 [14]

The amount of reinforcement was calculated for the main load combinations, accounting for the conditions of strength and crack resistance. The material characteristics of reinforced concrete structures are shown in Table 2.

Table 2

Characteristics of structural materials

Structure	Concrete grade	Longitudinal reinforcement class	Transverse reinforcement class	Thickness of the protective layer			
				SO, mm	SU, mm	RO, mm	RU, mm
Foundation	B30	A500C	A240	50	80	80	50
V-beam B1.1 historic	B25	AII	AII	40	40	60	60
V-beam B1.1 reinforced shotcrete	B30	A500C	A240	20	20	45	45

The results of the selection of the necessary foundation reinforcement are in Fig. 11–14 below.

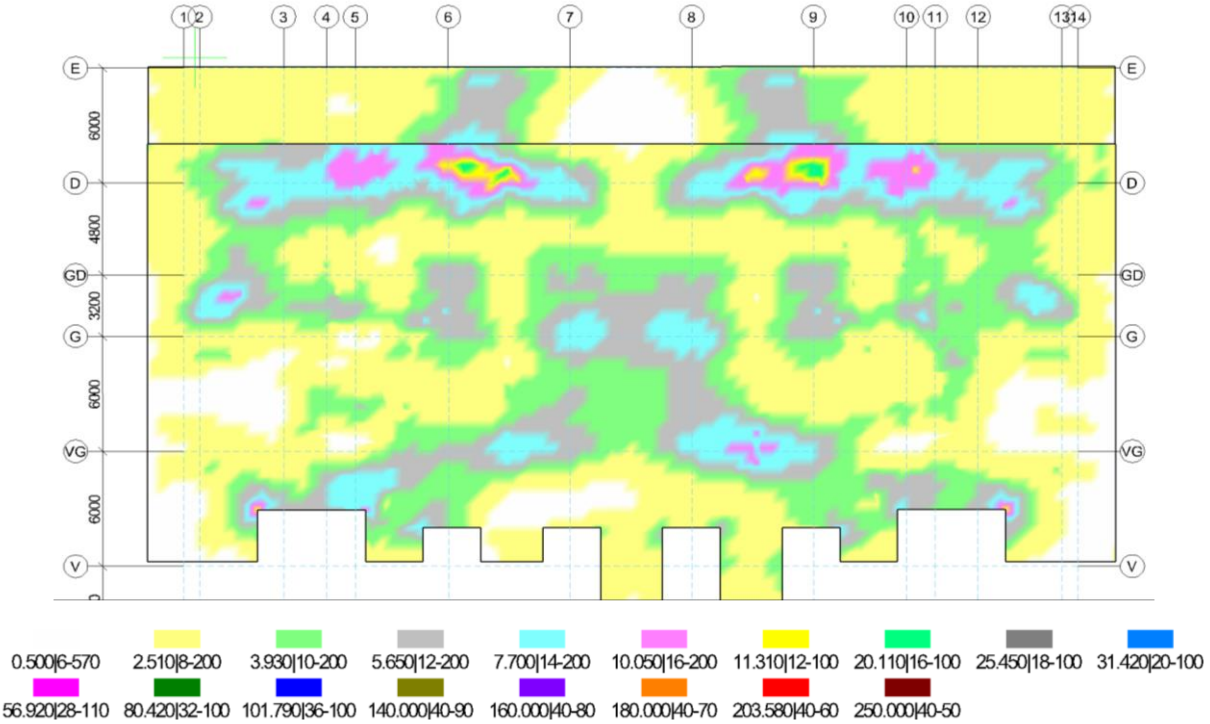


Fig. 11. Reinforcement of the foundation. Upper longitudinal reinforcement in the direction of the axis *R*, cm^2/m [14]

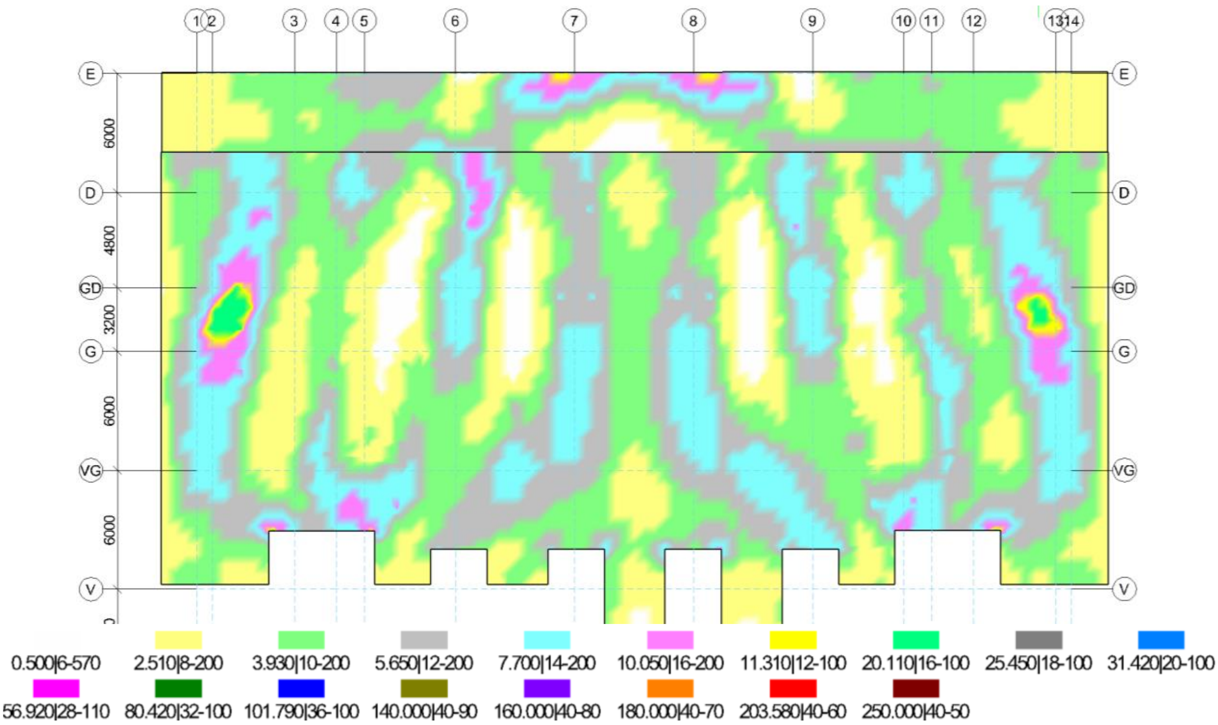


Fig. 12. Reinforcement of the foundation. Upper longitudinal reinforcement in the direction of the axis *S*, cm^2/m [14]

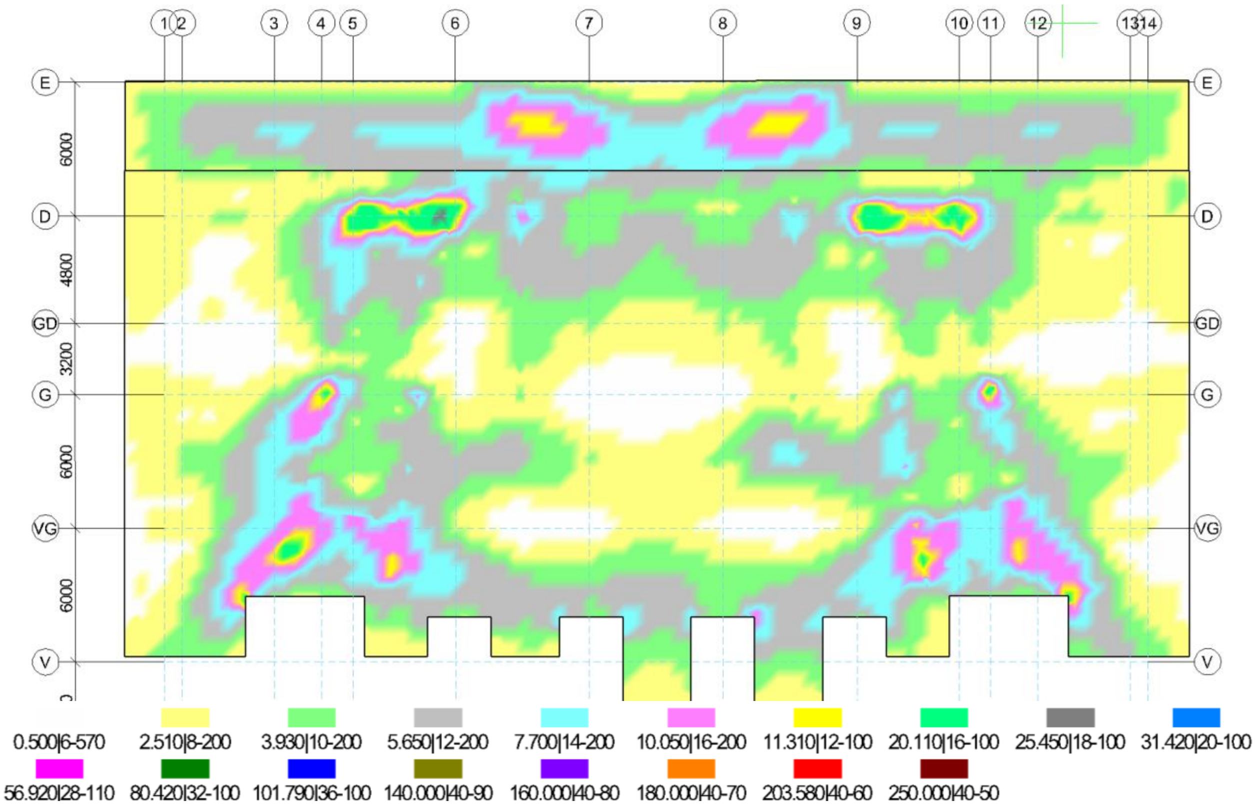


Fig. 13. Reinforcement of the foundation. Lower longitudinal reinforcement in the direction of the axis *R*, cm^2/m [14]

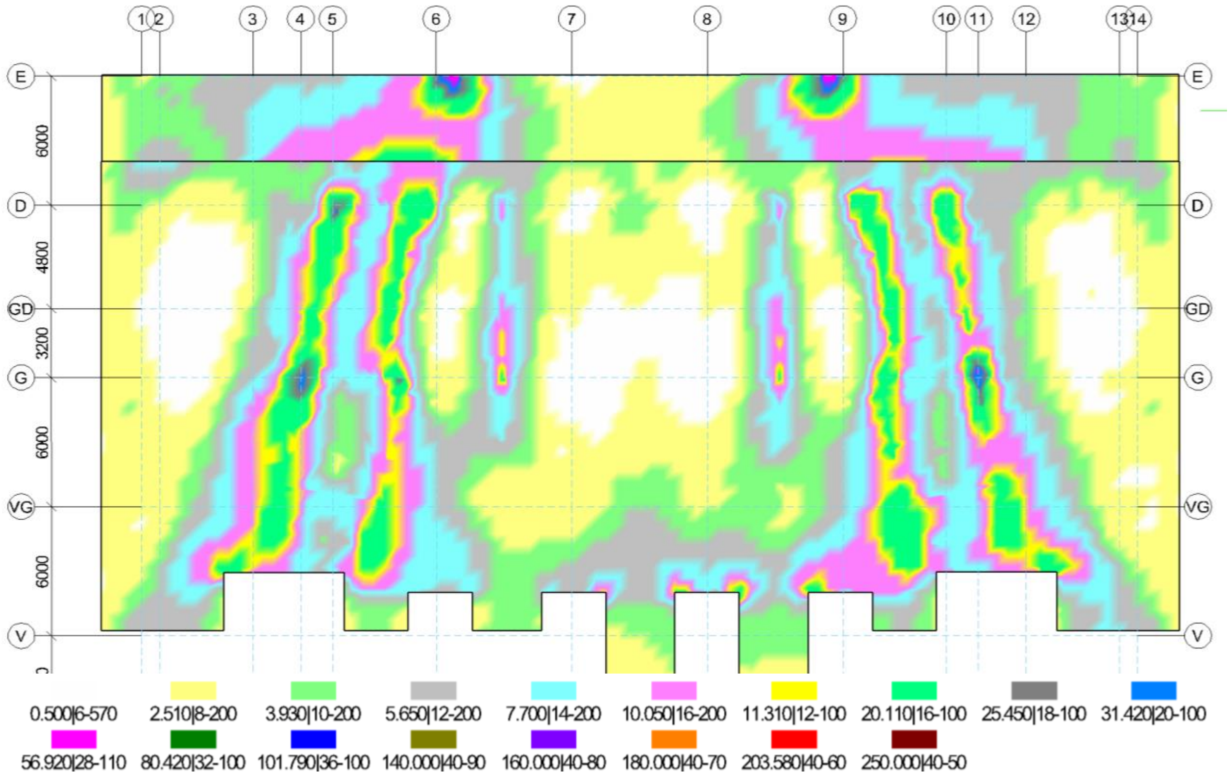


Fig. 14. Reinforcement of the foundation. Lower longitudinal reinforcement in the direction of the axis *S*, cm^2/m [14]

The required reinforcement of the existing V-beam is in Fig. 15–16.

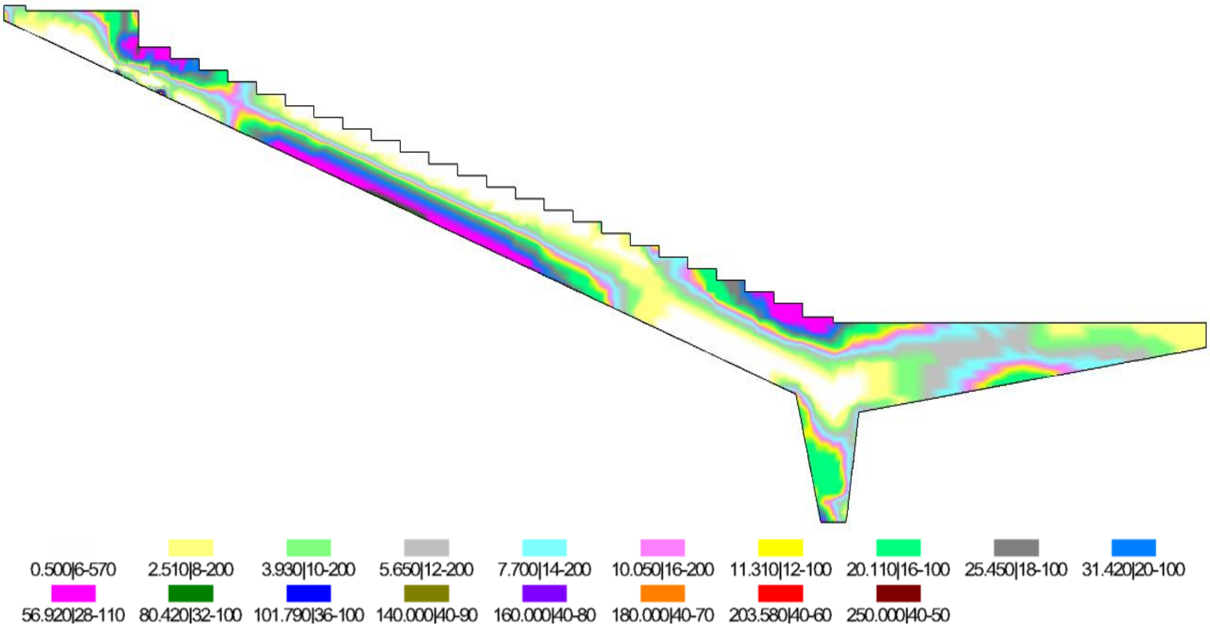


Fig. 15. Reinforcement of the existing V-beam. Upper and lower longitudinal reinforcement in the direction of the axis *R*, cm^2/m [14]

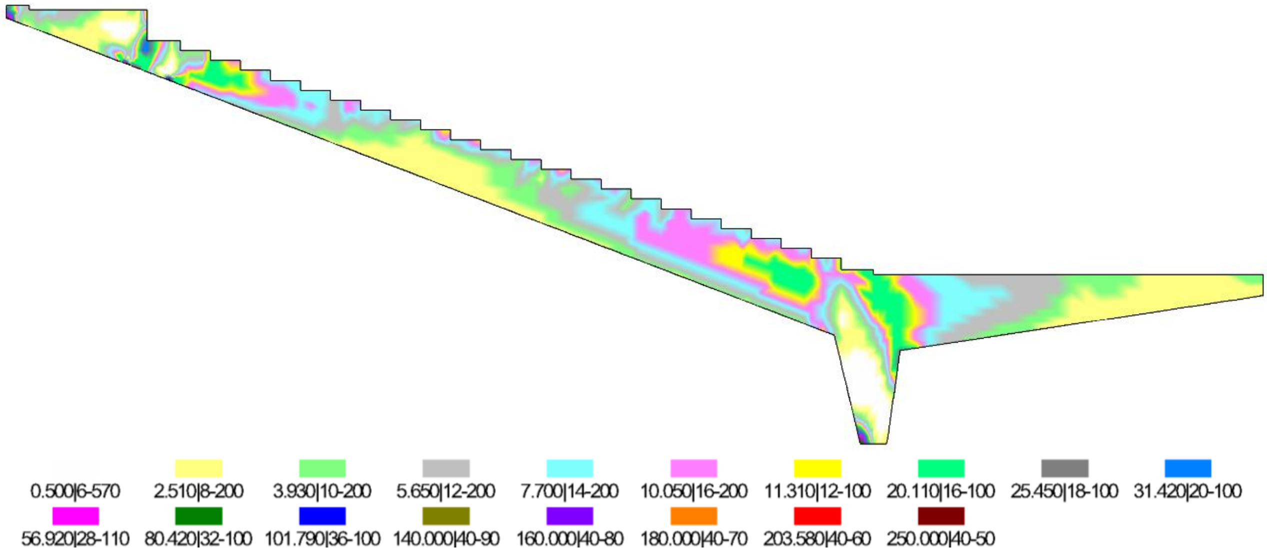
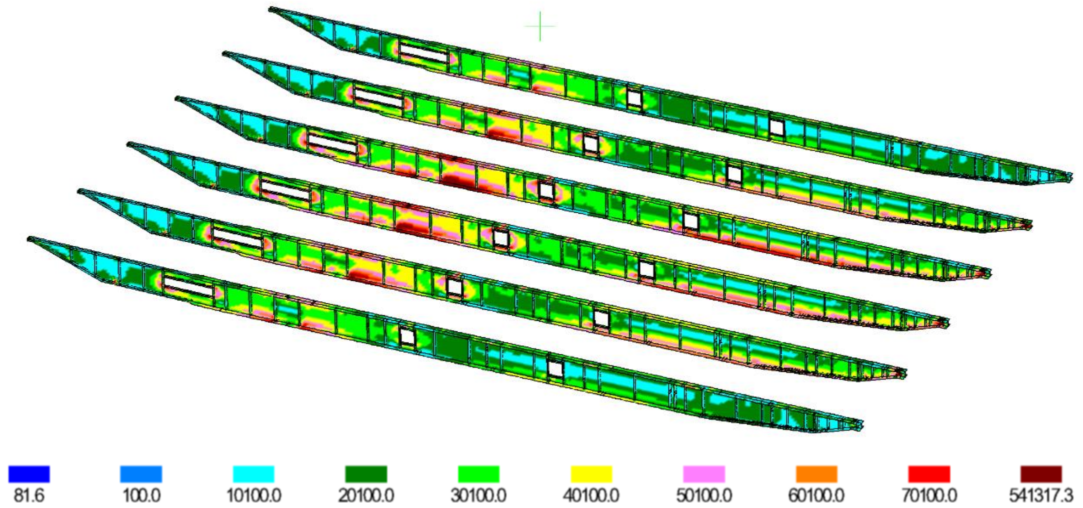


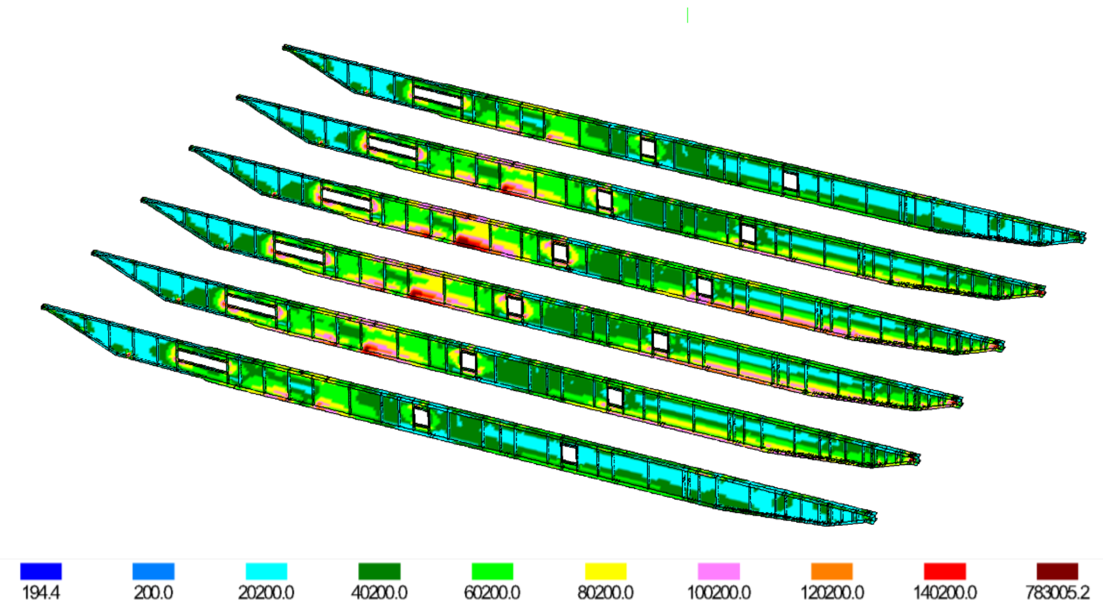
Fig. 16. Reinforcement of the existing V-beam. Upper and lower longitudinal reinforcement in the direction of the axis *S*, cm^2/m [14]

The stresses in the steel beams of the coating are estimated using the Huber-Mises strength theory for *min/max* superposition for a variety of combinations. The results are shown in Fig.17–18.



Min: SeM kN/m^2

Fig. 17. Stresses in the steel beams of the coating for *min* superposition for a variety of combinations [14]



Max: SeM kN/m^2

Fig. 18. Stresses in the steel beams of the coating for *max* superposition for a variety of combinations [14]

The load-bearing capacity of the elements of the coating beams in the A–C axes is provided for basic and special combinations of loads.

Results and Conclusion. As part of the calculations of the supporting structures of the cinema and variety hall (Block 1), the following was carried out:

1. Analysis of the project documentation and research materials.
2. Formation of a spatial design scheme of a building using a proven and certified STARK ES PC software package.
3. Collecting loads on structures based on the provided documentation accounting for the requirements of the standards.
4. Calculation of the shapes and frequencies of own vibrations of the structures.
5. Verification of the overall linear-elastic stability of the load-bearing system of the building for the main combinations of loads and impacts.
6. Inspecting the overall rigidity of the load-bearing system of the building, foundation sedimentation, and vertical plate deflections for major combinations of loads and impacts.
7. Calculation of the main elements of reinforced concrete and steel structures of a building according to the limiting conditions.

Based on the analysis of the results of the verification calculation of the load-bearing structures of the cinema hall under basic and special combinations of loads and impacts (accounting for the special loads from seismic impacts, fire trucks and emergency snow impacts), the following conclusions are made:

1. The overall rigidity and linear-elastic stability of the load-bearing system of the building are ensured.
2. The foundation sediment and horizontal displacement of the building structures are not over the limit values.
3. The stresses in the elements of steel structures are not over the design resistances of steel.
4. The amount of reinforcement in the reinforced concrete structures of the building should be assumed to be no less than that in the calculation results.

Hence the design solutions employed in the design of the cinema hall (block A1) ensure reliability, strength, rigidity and stability of load-bearing building structures under basic and special combinations of design loads and impacts.

While developing design documentation at the regulatory documentation stage, as well as during the construction, it is recommended that:

1. Tests of facade structures are performed in order to verify design solutions and validate mechanical safety.
2. Regulatory documentation is developed for reinforcing the steel beams of the coating, accounting for all of the stages of installation (dismantling) of structures based on appropriate calculations. It is necessary to allow for possible changes in the design scheme of the beam and that in the scheme of loosening the belt structures and walls.
3. Scientific and technical support is provided during the development of reinforcement of reinforced concrete V-beams of stands at the regulatory documentation stage and during the production of works. While calculating the reinforcement, it is necessary to account for the stages of installation and the joint work of the old and new material, as well as the requirements for the fire resistance of structures.

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