Steel Spatial Frame Model

I.B. Luzenina[a)] and O.V. Videshkina[b)]

Ural State University of Railway Transport, Yekaterinburg, Russia

[a)] Corresponding author: ibluzenina@mail.ru
[b)] videshkina00@mail.ru

Abstract. One of the main tasks of designing buildings and structures has been and remains the formation of a safe and comfortable environment for human life. The special conditions of modern design are: an increase in the functional space and the potential transformation of an object, a non-linear calculation paradigm, and more. As the complexity and concentration of objects increase, their sensitivity to external natural influences and man-made disasters increases. Under these circumstances, steel spatial frames are increasingly being used as load-bearing structures. For buildings, spatial frames provide a number of advantages, such as optimal material consumption, unification of elements and assemblies, spatial rigidity and geometric invariability, reliability under special impacts, and etc. Spatial steel frame structures are capable of expressing natural forms with a provided load-bearing capacity. For such frames, a non-linear "sensitive" calculation is relevant, which requires a step-by-step qualitative and quantitative analysis of the design situation of the structural system. The purpose of our study is a variable model of a supporting steel spatial frame, which can serve as a module of buildings and structures with different functional content. Its constructive scheme was obtained as a result of optimization calculations. The article describes the methodology for formation of digital models for the design of the spatial frame of public and industrial buildings, the stages and results of experimental and theoretical studies.

INTRODUCTION

The goal of the innovative development of the construction industry of the Russian Federation is formation of a safe and comfortable environment for human life, which is noted in the draft Strategy for Development of the Industry [1]. The document outlines the main systemic challenges: globalization, technological changes, the human factor, raw material base, infrastructure and personnel qualifications, reflecting global and domestic trends.

Of course, population growth, technology development, digitalization, the desire for globalization and concentration, resource conservation and other features of the present time are correcting traditional approaches to the design of buildings and structures. Modern projects are characterized by expressive, progressive (up to revolutionary) and complex architectural solutions. Modern architectural and construction design is characterized by: an increase in the functional space and transformation of an object, a non-linear paradigm of calculation, and more.

As a consequence, in relation to the structural system of the object: the complication of the system and the nature of the interaction of structures in the system; increasing the sensitivity of the system to natural and man-made impacts; increasing relevance and importance of technical solutions to ensure the strength, stability and durability of structures; performance of a "sensitive" adaptive calculation of structures for a number of design situations, and etc. World and domestic experience in creation and operation of building objects confirms that steel spatial frames have reliably proven themselves in this regard.

The purpose of our study was to develop a variable model of a steel spatial frame, which can serve as a module of buildings and structures with different functional content. To achieve the goal, the following tasks were set and solved:

- an analysis of the evolution of steel frames was made, considering the development of technologies and architectural and construction design of buildings and structures;
- the form and spatial solution of the frame are substantiated, the structural scheme is formed;

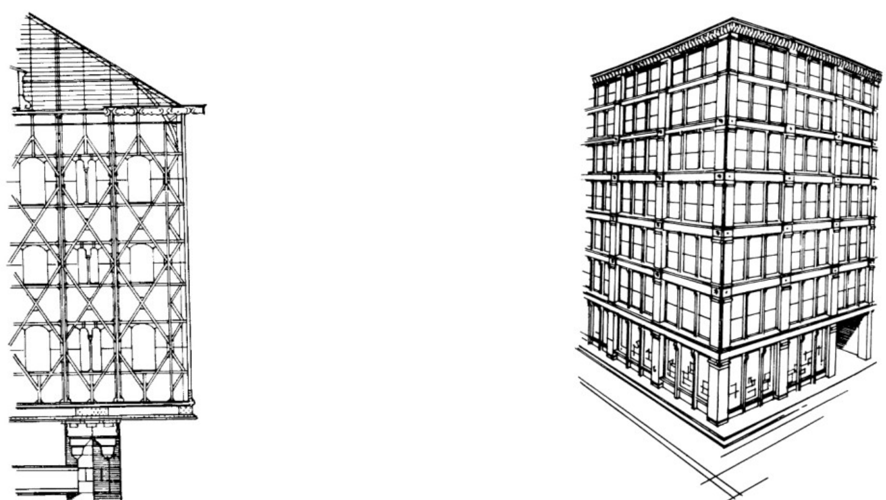
– a digital model of a spatial frame was studied, a universal structural module was identified based on the results of optimization calculations;
– use of a spatial frame as a variable model is offered, and promising directions for studying the structure are outlined.

EXPERIMENTAL AND THEORETICAL STUDIES OF THE MODEL OF A STEEL SPATIAL FRAME

Evolution and Design Features of Modern Steel Frames

Steel frames for one and a half centuries serve as load-bearing structures of buildings and structures. The current year 2021 can be considered an anniversary year, if we start counting from the frame structure of the Solognier company (Fig. 1, a) erected near Paris in 1871-72 [2]. Technical solutions for the frame structure, such as leaning on the powerful buttresses of the river dam, cantilever outriggers, cross ties, and others are relevant to the present.

The triumph of the possibilities of modern steel frames was preceded by a whole era of progress in building technology. Structural capabilities and load-bearing capacity of frames are implemented through use of metal as a building material. The identification of the specific properties of metal alloys is associated with the names of such researchers as Abbot Hadfield (1858-1940), Johan Gadolin (1760-1852) and many others, who predetermined use of building steel for load-bearing structures and the industrial basis for the manufacture of steel building structures. Also, what is relevant for



(a) (b)

FIGURE 1. a) The factory building of the Solognier company (1871-72) [2], b) the Lighter Building, Chicago, USA, 1889 [2].

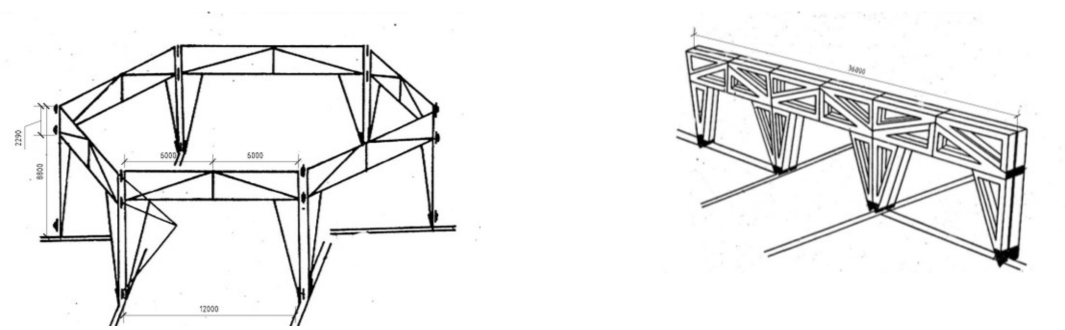
today, they have offered a way to improve and simulate the mechanical, technological and operational properties of the material. Stable qualitative and quantitative characteristics of structural steel make it possible to obtain a reliable result of structural analysis [3], which is especially important when analyzing the operation of complex structural systems.

The head of the architectural school, William LeBaron Jenny (1832-1907) justified the frame system (for high-rise buildings). Under his leadership, in 1889 in Chicago, the first multi-storey building "Lighter Building II" was built with a full load-bearing steel frame from a rolled I-beam (Fig. 1, b) [2]. The advantages of the frame system were expressed in an increase in the number of storeys of commercial and office buildings, using the same type of structural elements. The construction laboratory for the design of buildings and structures made of metal was the fourth world industrial exhibition in Paris in 1889. The audacity of technical thought and the impressive size of the pavilions were many years ahead of the world building practice [4].

For the first time, J.K. Freitag classified frames in 1901. In his published paper "Architectural Engineering", he established "two stages" in the development of the frame structure: load-bearing and incomplete [2]. Particular attention was paid to the fire protection of structures, the typification of structural elements, and the structural provision of the spatial rigidity of the frame.

The 20th century is distinguished by success in the design of spatial structural systems. Thanks to the transition from riveted to welded joints and connections on high-strength bolts, it became possible to consider the spatial relationship of the structural elements of the frame.

The desire to increase the functionality of the structure by changing its length and width led to creation of a transformable frame structure. An example is the design of a transformable frame patented in the USSR in the 80s of the last century (Fig. 2), authors V.P. Ignatiev, P.E. Manokhin, V.P. Kotsegubov [5].



(a) (b)

FIGURE 2 . Transformable structure frame [5]: a) in the design position, b) assembled.

Modern steel framing provides one of the foundations on which an organic design approach can be implemented. "The ideal of organic architecture ... consists in integrity and unity with nature ..." F. L. Wright [6]. Spatial steel frame structures are capable of expressing intricate natural forms with a provided load-bearing capacity. “The task of the design is to create the necessary space, arrange it, give it a semantic and emotional content” [7].

A guarantee of the reliability of the supporting steel frame is its calculation by the method of limit states [3]. The calculation of structures for limiting states is carried out from 1955 to the present. A great contribution to development of this calculation method was made by Soviet scientists led by N.S. Streletsky.

The traditional theory of calculation is based on a linear statement of the problem. The linearization of calculations is based on the hypotheses of structural mechanics. The initial equations for the linear problem are: equilibrium, compatibility, and physical one. The calculation scheme of structures is a linearly deformed system, for which the principle of independence of the action of forces is valid [8].

The work of multi-element spatial systems is quite difficult to reconstruct by analytical methods. As the complexity of systems increases, the relevance of experimental and theoretical studies aimed primarily at ensuring the constructive safety of the object, increases.

The subject of the study presented in this article is the structural scheme of the frame. Based on the idea of limitism, we have created and studied models of spatial frames of public and industrial buildings. Many aspects of creation of modern steel frames remain outside the scope of research, causing questions and interest of designers.

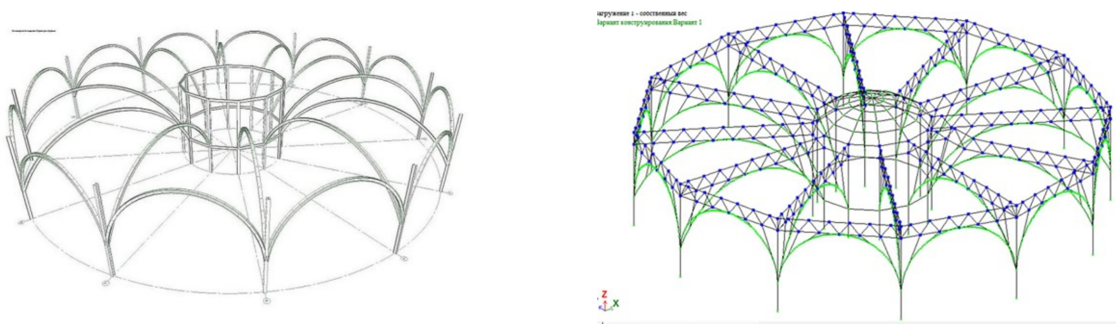
Frame Design Models and Study Results

The space-planning parameters of the public object model were assigned to the station building considering the following. Firstly, the station building is the main object of a powerful, technically complex and technologically equipped logistics system. Secondly, the station complex is an object with a mass gathering of people who often experience serious emotional stress. To level the contradictory qualities of a transport object, it is advisable to apply the methods of organic architecture. Examples of such an implementation are the implemented projects of the Oriente railway stations in Lisbon (architect S. Calatrava), Ladoga railway station in St. Petersburg (architect N.I. Yavein).

The idea is to create a structural system, while maintaining the effect of a stable and, at the same time, a dynamic transport environment, was carried out thanks to step-by-step modeling considering the space-planning and design capabilities, as well as manufacturing and installation capabilities. Detailed information about shaping, the stages of creating a structural system, its parameters and optimization is presented in publications [9, 10].

The result of constructive modeling is a steel frame in the form of a 12-beam spatial frame (Fig. 3, a). The frame is formed by bearing columns located along the inner and outer diameter of the frame and arched elements. The arched elements of the cover are oriented in the radial and circular directions, adjacent to the posts of the inner contour radially, to the posts of the outer contour - in three planes. The arched elements ascending from the rack imitate the “crown” of the so-called tree-like columns. Presumably, the supporting structure of the covering of the central zone of the atrium is a ribbed-ring dome, the adjacent covering is made of a light structural slab, with nodal support on the "branches" of the column.

The result of optimization design calculations is a static scheme in the form of a spatial rod system (Fig. 3, b). Calculations of the frame elements are made considering the specifics of the structure, assembly schemes, the rationality of manufacturing the structure, and etc. [11, 12].



(a) (b)

FIGURE 3. a) Structural model of a 12-beam spatial frame [10], b) Scheme of a spatial frame [11].

A feature of the offered frame with a supporting 12-beam frame is the variability of application for various objects of the transport infrastructure, both a module and a separate structural element - in the form of a "tree" column. For example, for the station building (Fig. 4), as well as the construction of the platform, pedestrian crossings, and etc. The undeniable advantage of the design of the universal module is expressed in the ability to create a single system of the transport complex based on the same type of design technique.

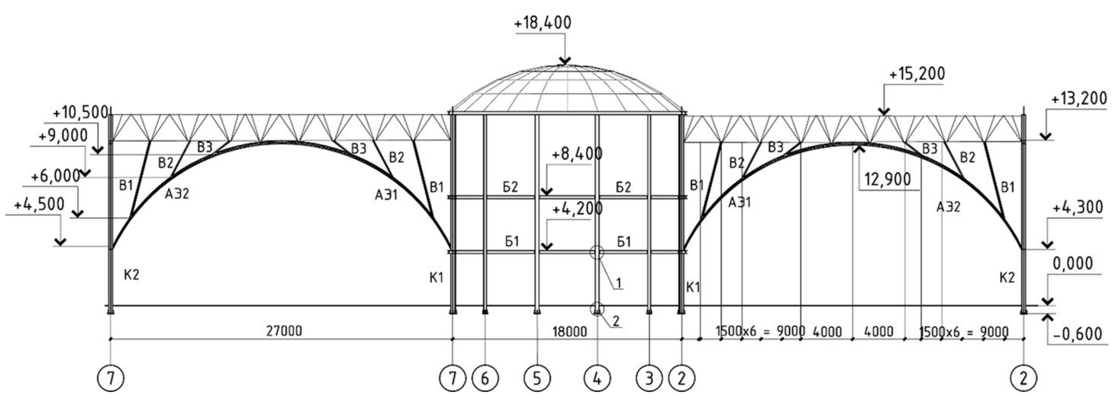


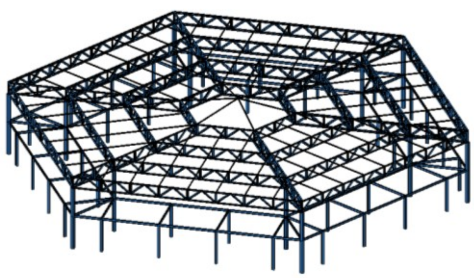
FIGURE 4. Drawing of the central part of the station building [10].

Further study of the spatial structural system was carried out from the standpoint of the rational interaction of adjacent elements with an increase in the area of the object. The space-planning parameters of the following model were assigned to an industrial building (with the potential for expansion), using the example of a multi-stage waste processing plant.

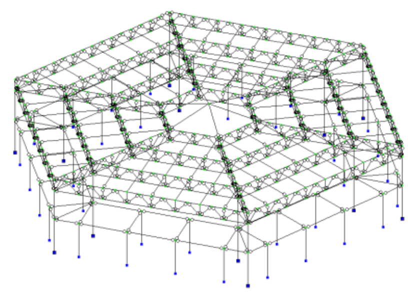
The idea is to create a constructive system capable of uniting with "their own kind" to form an inseparable space that ensures the interaction of adjacent elements and structures.

The shaping of the module was performed from the point of view of the full implementation of the volume. The tiling of the three-dimensional space with previously formed 12-angled prisms involved the inclusion of additional triangular prisms. This led to the complication of the structural system of the object, as well as to the deviation from the modularity and uniformity of structural elements. As a result, without violating the principles of organicism, it was decided to create and study a constructive system in the form of a regular 6-angle prism.

The structure of the frame was identified during step-by-step modeling, considering the space-planning, design and construction possibilities. The result of constructive modeling is a frame in the form of the 6-beam spatial frame (Fig. 5, a). The frame is formed by load-bearing columns, trusses and beams. Frames were considered without and with (along the outer perimeter) the observation gallery. The central space of the module is hexagonal in plan. The bearing structure of the covering of the central zone is presumably a ribbed dome. Adjacent coverage is arranged by runs.



(a)



(b)

FIGURE 5. a) Structural model of the 6-beam spatial frame with the gallery, b) Calculation scheme of the spatial frame with the gallery.

The main parameters of the module: shape – hexagonal prism. The distance between the posts along the small diameter is 18 m, along the outer diameter - 24 m, the diametrical distance between the extreme posts is 48 m, the span of the gallery is 6 m, the height of the posts is 9.9 m.

The result of optimization design calculations is the static scheme of the frame, in the form of a spatial rod system. The calculations of the frame elements are made considering the specifics of designing the junctions of adjacent modules, handling equipment, galleries along the perimeter, and etc. The calculation scheme of the frame module with the main parameters is shown in Fig. 5, b, a section of the waste processing plant building from adjacent modules - in Fig. 6.

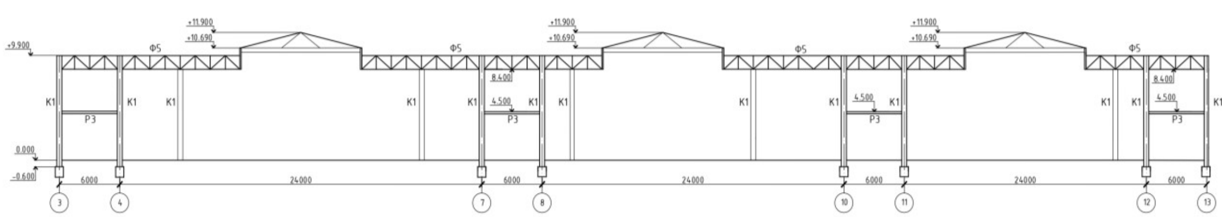


FIGURE 6. Building section.

A feature of the design of the universal module based on a 6-beam spatial frame is the constructive focus of the module on the transformation of the object in the conditions of modernization, expansion and reconstruction of production. The indisputable advantage of the offered modular frame is the continuity of the formed space with the variability of transformation (Fig. 7).

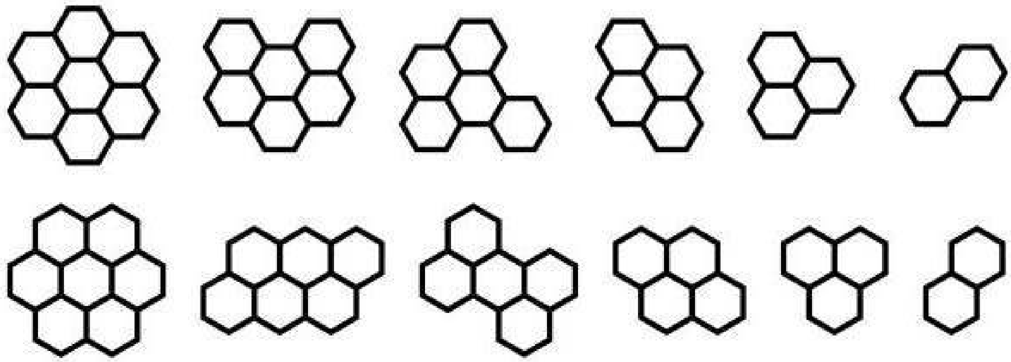


FIGURE 7. Options for transforming a building on a plan.

Discussion of the Progress and Results of the Study

It shall be noted that the modeling and calculation of the spatial frame is a laborious process reduced to solving multifactorial problems and, in many respects, intuitive. In the course of the study, for each of the options, constructive solutions for a number of frames were analyzed.

As a result of refining calculations in the software package and subsequent analysis of the stress strain behavior, the frame structures underwent some transformation and reconstruction. Refinement of static schemes of frames was made considering the feasibility, the possibilities of manufacturing structural elements and execution of nodal interfaces of elements, installation technologies and other factors. Inaccuracies and contradictions in the design and calculation schemes were eliminated in the process of successive recalculations. Selection of sections of frame elements is derived from the conditions of strength and stability, according to the operational design situation.

Recalculations of the structure made it possible to optimize the sections of the main elements with the provided bearing capacity. The indications of the deformation values of the elements and the structure as a whole did not raise doubts about the spatial rigidity and geometric invariability of the studied schemes of bulk modules. An image of the optimized scheme of a 6-beam frame is shown in Fig. 8.

With the introduction of innovative building materials, as construction technologies develop and calculation methods improve, the space-planning parameters of objects increase [13, 14, 15]. In the spirit of our time, there is revolutionary forms of buildings and unlimited freedom of interior spaces. “The quintessence of the building is now not the walls and the roof, but the space ...” - writes the American architect, one of the creators of organic architecture F.L. Wright (1867-1959) about his approach to the design [16].

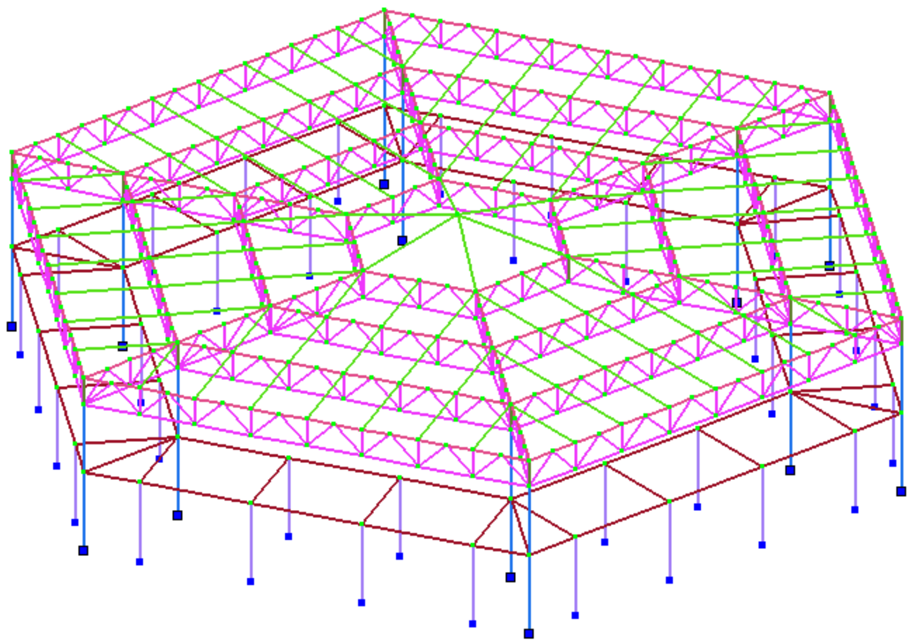


FIGURE 8. Spatial hexagonal frame model with gallery.

The load-bearing frame system contributes to the construction of multifunctional buildings and complexes with large spaces and a flexible planning structure [17]. A special place among such buildings is occupied by transport infrastructure facilities, which are currently combined into transport interchange complexes [18]. The era of Big Data is characterized not only by public facilities with a massive crowd of people, but also by the concentration of man-made complexes of industrial enterprises. Special attention is paid to ensuring the safe operation of construction objects of this type [19]. The process of predicting the operation of structures in time, considering the sudden impacts, including emergency ones, is becoming an increasingly important condition for the design of buildings and structures.

In such a situation, buildings with a load-bearing spatial steel frame have undeniable advantages. Such as geometric invariability and spatial rigidity, reliability and survivability under special impacts, optimal material consumption, unification of elements and assemblies, flexibility in choosing construction methods, visual "lightness" and aesthetics, freedom of internal planning, and other.

However, in addition to the listed advantages, the design of such objects causes a number of difficulties. Namely, when implementing a task, designers face complex issues of choosing design and design schemes, materials, loads, design situations, and etc., which would allow to display accurately the architectural solutions, as well as ensure the efficiency and reliability of the object.

It is especially important to note that the digital modeling and analysis of the operation of the supporting frame becomes much more complicated. It is obvious that the calculation of the limit states of multi-element spatial systems can be described by linear functions with a large share of conventions. In the process of calculation, a dangerous accumulation of errors occurs and, therefore, the probability of an unreliable result is high.

Therefore, current regulatory documents [20] regulate the calculation of structures that have no analogues in a non-linear formulation. They strive to create a digital model, as if "playing" the behavior of the structure, considering all the non-linear aspects of the physical, geometric and constructive characteristics. Calculation of this type provides structural reliability, but it is complicated, it requires a step-by-step qualitative and quantitative analysis of the design situation of the structural system.

CONCLUSION

Powerful software systems and digital technologies allow performing multi-factor "sensitive" design calculations. The tendency to abandon the linearization of the calculation is reduced to the desire to most reliably simulate the operation of the structure for its entire life period, predicting possible design situations [21]. Calculation in a non-linear setting can be interpreted as computer simulation of processes: erection, loading, changes of the stress strain behavior during the operational period, and etc.

Guided by the nonlinear paradigm of design thinking, further study of the offered constructive model of the spatial frame involves solving such problems as optimization of the design scheme and sections of the main frame elements, considering constructive nonlinearity; identification of an expedient assembly scheme; optimal design of assembly and factory interfaces (considering the adjoining structures of adjacent objects); identification of universal elements; analysis of the work of the frame structure for design situations, considering progressive loads; assessment of system survivability in case of local damage.

The solution of these and other problems not only contributes to implementation of the ideas of organic architecture within development of constructive solutions, but also has great practical value. The real structure under study is a more than once statically indeterminate system, the material of which has the property of plasticity. Calculation in a nonlinear formulation will allow determining the reserve of the bearing capacity of structures and making it economically more attractive [22].

The principle of interaction of structural elements of spatial frameworks is ideal for fulfilling the "humane" conditions of design tasks: architectural - to create a comfortable living environment, design - to create a building load-bearing system safe for humans, financial - with a careful attitude to resources.

REFERENCES

1. Strategy for development of the construction industry of the Russian Federation until 2030 with a forecast for the period up to 2035 (2019). https://minstroyrf.gov.ru/docs/18723/.
2. F. Hart, *Atlas of steel structures*, edited by A. N. Popova *et al.* (Moscow: Stroyizdat, 1977), p. 351.
3. SP 16.13330.2017 Steel structures. Updated edition of SNIP II-23-81 * - Introduced on August 28 (Ministry of Regional Development of Russia, 2017), p. 159.
4. Ferdinand Dutert. Galérie des Machines 1889. https://atlasofplaces.com/architecture/galerie-des-machines/.
5. Pat. SU 1557275 A1, Union of Soviet Socialist Republics, E 04 B 1/343, E 04 H 15/48, E 04 B 1/18. Transformable structure frame / V.P. Ignatiev, P.E. Manokhin, V.P. Kotsegubov; applicant and patent holder Leningrad. eng.-constr. in-t. - No. 4330769/23-33; appl. October 20, 1987; publ. on April 15, 1090, Bull. No. 14. - 4 p.
6. An Interview with Santiago Calatrava R. Ivy// Architectural Record. Galjtrava. http:// architecturalinterviews.blogspot.com/2009/12/interview-with-santiago-calatrava.html.
7. T. Yu. Bystrova, Academic Bulletin UralNIIproekt RAASN **1**, pp. 41-48 (2014).
8. I. B. Luzenina, *Theory of calculation and design. Lecture notes* (Yekaterinburg: UrGUPS, 2020), pp. 42-50.
9. I. B. Luzenina and Yu. V. Chistyakova, Magazine “Modern Technologies in Construction. Theory and Practice" **1**, pp. 336-342 (2019).
10. I. B. Luzenina and Yu. V. Chistyakova, Magazine "Modern Technologies in Construction. Theory and Practice" **1**, pp. 251-258 (2019).
11. D. B. Kiselev, «Operation of the combined arch system considering the geometric nonlinearity and the sequence of installation,» Ph.D. thesis, 2009.
12. V. V. Gorev, B. Yu. Uvarov and V. V. Filippov *et al.*, *Steel structres, 1, Structural elements,* edited by V. V. Gorev (Higher School, 2004), p. 551.
13. A. L. Gelfond, *Architectural design of public buildings and structures* (Moscow: Integral, 2013), p. 278.
14. A. I. Makovetsky, *The architecture of the new time. Historical sketch of the development of architecture in the 19th-20th centuries* (Perm, 2004), p. 148.
15. V. F. Fomina, *Architectural and constructive design of public buildings* (Ulyanovsk: UlGTU, 2007), p. 97.
16. C. Bultmann, *Ist Santiago Calatrava ein organischer Architekt*. https://www.academia.edu/1156111.
17. *A book about useful and beautiful architecture. Architectural policy as a driver of urban development* (Moscow: KB Strelka, 2016), p. 368.
18. S. P. Vakulenko and N. Yu. Evreenova, *Technical equipment and technology of operation of transport interchange hubs formed with the participation of railway transport* (Moscow: MIIT, 2015), p. 195.
19. Federal Law No. 384-FZ of December 30, 2009 (as amended on July 2, 2013) "Technical Regulations on the Safety of Buildings and Structures".
20. GOST 27751-2014 "Reliability of building structures and foundations. Basic Provisions". - Introduced on December 11 of 2014 (NITs Construction, 2015), p. 34.

21. G. G. Kashevarova, A. E. Semina and S. V. Maksimova, International Journal for Computational Civil and Structural Engineering **17(2)**, pp. 22-33 (2021).
22. I. B. Khamudisova, «Evaluation of the reserves of the bearing capacity of statically indeterminate steel girders operating beyond the limits of elasticity,» Ph.D. thesis, Yekaterinburg, 2002.