Steel Space Frame Structures of Long-span Buildings

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Abstract In the modern world of digital technologies, the goal of architectural and structural design is to organize a safe and comfortable environment for human life. Globalization leads to buildings becoming increasingly spacious and having more capacity. As the complexity of construction structures increases, they become more vulnerable to external natural and man-made disasters. Consequently, the application of steel space frames for designing objects of any complexity is proliferating in world practice.

The advantages of load-bearing space frames for large-span buildings are structural rigidity and geometric immutability, reliability and survivability, optimal material consumption, unification of elements and assemblies, choice in construction methods, visual "lightness" and aesthetics, freedom of internal planning, etc.

This study aims to develop a variable model of a steel space frame which can enable the transformation of the interior space of large-span buildings. The research analyses the evolution of steel frames given the development of technologies and architectural and construction design; justifies the application of a steel space frame for a railway station building and develops a constructive scheme; examines the digital model of a steel space frame; develops a universal building block module; outlines the future research into the model application.

The article describes the methodology of the steel space frame digital model development, stages and results of the experimental and theoretical research.

Keywords: Long-span building, Steel frame, Space frame, “Tree” column, Static calculation, Variable model.

1. INTRODUCTION

The main goal of the architectural and structural design has been and remains a safe and comfortable environment for people. The modern solutions might be achieved by harmonizing both construction environments: artificial environment and nature. Therefore, while creating any object, designers and constructors have to consider several factors that affect the viability of a future structure. In addition to urban planning, climatic and environmental conditions, socio-economic factors are not to be ignored as they can negate all the efforts of designers.

Globalization is changing the approaches to creating an architectural concept of design. The space of buildings is becoming increasingly large, there is a principal tendency of moving away from monofunctional to multifunctional buildings. As a result, the structural system of buildings and the interaction of the structures within the system is becoming more complicated.

Complexity makes the system vulnerable to external natural and man-made disasters. The application of digital technologies can improve space frame calculations related to predicted natural and man-made factors. In these conditions, technical solutions to ensure the strength, stability and durability of the object become even more relevant.

The world experience in designing and operating construction facilities has proved steel space frames’ reliability.

Therefore, the purpose of the research was to develop a variable model of a steel space frame that can enable the transformation of the interior space of large-span buildings.

It was accomplished by:

- analyzing a steel frame evolution influenced by the development of technologies and architectural and construction design of buildings and structures;
- justifying the application of a steel space frame for a railway station and developing a constructive scheme;
- exploring a digital model of a steel space frame, and developing a universal structural module based on structure optimization calculations;
- proposing the application of a space framework as a variable constructive model and outlining the future research into model application.

2. EXPERIMENTAL AND THEORETICAL STUDIES OF A STEEL SPACE FRAMES DIGITAL MODEL OF A LARGE-SPAN BUILDING

2.1 Modern steel frame evolution and design

Steel frames have been serving as load-bearing structures of buildings and facilities for 150 years. 2021 is the anniversary counting from "Solonier", a frame structured factory near Paris in 1871-72 [1] (Fig. 1).

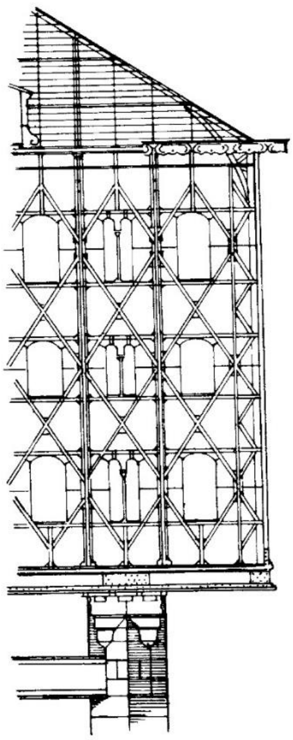

Fig. 1. “Solonier” factory building (1871 - 1872) [1].

A boost in the application of modern steel frames for architecture was provided by the progress in construction technologies that have become the main source of architects’ inspiration in recent years. The demonstrative individuality of modern buildings is created by expressive and even revolutionary forms, and by the unlimited freedom of internal spaces. F.L. Wright (1867-1959), an American architect, a founder of organic architecture, described his approach to design: "Today, the quintessence of the building are not walls or a roof, but the space...".

For "classical" designers, steel space frameworks have become one of the foundations for the organic approach to design. The frame structures can embody natural forms common for organic architecture. "The goal of design is to create the necessary space, to organize it and to give it semantic and emotional fullness" [3].

In addition to organicism, the priority of frames when choosing a load-bearing system is determined by globalization. Construction sites of the Big Data era have to have large spaces to accommodate people. Interaction of structural elements of space frames should achieve two design goals: architectural - to create a balanced living environment, design - to create a safe load-bearing system of the building.

In addition to structural schemes studies, Gottfried Semper (1803 – 1879) and E. Viollet-le-Duc (1814-1879), the founders of the architect organic movement, encourage to study new materials and identify their specific and significant shaping qualities. E. Viollet-le-Duc writes: "What is missing nowadays, first of all, are ideas ... even if they are bad" [4].

The subject of the current research aims at a structural scheme namely at construction steel as the structure material. Other interesting aspects of modern steel frame design remain beyond the current research.

Construction steel composition optimization and production improvement are associated with the names of Abraham Darby (1878-1717), Henry Cort (1740-1800), Henry Bessemer (1813-1898) and many others who later provided the industrial basis for steel structure manufacture.

In 1882, Robert Abbot Gadfield (1858-1940), an English metallurgist and researcher, found a new application of construction steel for load-bearing structures. R. A. Gadfield was the one who suggested using alloy steel with specific properties for mass production and a wide range of applications.

The analysis of the specific properties of metal alloys is based on the work of Johan Gadolin (1760-1852), a Finnish chemist, who was the first to identify and study the properties of rare earth metals (REM) and the unique properties of metal alloys with REM in the composition.

Nowadays, 17 elements of the REM group are known. The introduction of a small proportion of them into the composition allows achieving the necessary quality and quantity of metal alloys characteristics. Concerning construction steel, the introduction of alloy additives and REM significantly improves and simulates its mechanical, technological and operational properties. For example, the introduction of a small proportion of neodymium and vanadium can reduce the weight of steel structures by a third and increase their durability 2-3 times.

Central Research Ferrous Metallurgy Institute named after I. P. Bardin and other industrial enterprises introduced a program “Interindustry program of the development of new types of metallurgy products with rare earth metals for the period of 2020-2035". It plans to develop the production of metal alloys and steels with RM "for the aircraft, rocket and space industry, instrument and tank construction, chemical and heavy engineering, medical industry, etc. " [5]. The production of special steels with rare earth metals in their composition for the construction industry is still limited due to insufficient knowledge of alloy potential and their high cost. Thus, in designing buildings and other facilities, "... economic considerations lead away from an individualized approach" [6].

Undoubtedly, the use of metal alloys with rare earth metals in the composition can solve design problems in manufacturing modern building structures. For example, it can significantly reduce the weight of load-bearing large-span coating structures. James Edward Gordon (1913 — 1980), one of the founders of materials science and biomechanics, argues"...a reliable roof over your head is one of the primary conditions of a civilized existence but the roof is heavy and therefore the problem of supporting it is as old as civilization itself..." [7].

Steel space frame design is a complex and largely intuitive process. Special attention is paid to the reliability of calculations, the design of components and the unification of elements and joints.

As the complexity of technical systems increases, the relevance of experimental and theoretical studies increases. The studies aim at ensuring the structural safety and survivability of objects to maintain the specified parameters under the influence of external factors, including emergencies and catastrophes.

2.2 Methodology

We investigated the module of a steel space frame applicable for large-span buildings of various purposes. The constructive system is based on the principles of organicism in architecture. The model space-planning parameters are aimed at the railway station building.

The objects of transport infrastructure include railway stations, station squares, platforms, technical facilities, etc. Traditionally, they are designed as elements of a single, powerful, technically complex and technologically equipped logistics system. However, a railway station is, first of all, the object of passengers and people congestion. They are late, rush, and therefore experience emotional stress. Organic architecture can neutralize the emotional tension, balance the contradictory qualities of a transport object and create confidence and natural harmony. Examples of such projects are the Oriente Railway Stations in Lisbon, the Ladoga Railway Station in St. Petersburg (Fig. 2).

a

b

Fig. 2. Railway stations: (a) "Oriente", Lisbon (architect S. Calatrava), (b) Ladoga Railway Station, St. Petersburg (architect N. I. Yavein)

The idea was to design a structure that could create the effect of a stable and dynamic transport environment. It has been achieved by steady modelling coupled with space-planning and design capacity. In a closed and static space of the transport complex, preference is initially given to rounded outlines with a designated centre. Circles and straight sections create the effect of circular dynamics. Radial columns support centric and linear characteristics of the space. Later, a passenger area in the central part of the railway station building became the subject of a detailed study.

At the initial stage, the steel frame module presented a space frame consisted of supporting columns and arched elements, as shown in Fig. 3.

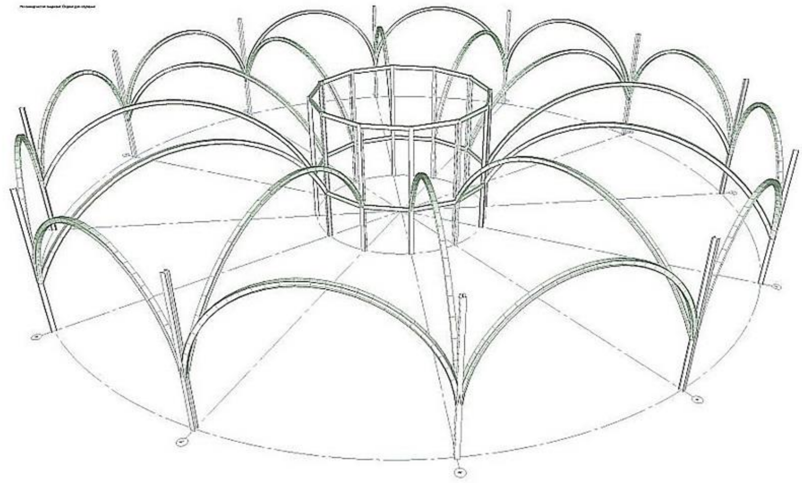

Fig. 3. Structural model of the space frames [8].

There are 12 pillars along the inner and outer ring: a step in a radial direction is L = 27 m; a step in a transverse direction along the small diameter, B = 4.65 m; a step in a transverse direction along the outer diameter, B = 18.6 m; the height of a column, h = 15.2 m; the height of an arch element, ha = 8.8 m. Arch elements run radially and circularly; they radically adjoint to the inner contour posts and the outer contour posts on three planes. Arched elements rise from the rod and imitate the “crown” of “tree-shaped” columns. Presumably, the supporting structure of an atrium central zone is a ribbed-ring dome, an adjacent covering is made in the form of a light structural plate with nodal support on column " branches" [9, 10].

Based on preliminary calculations, we proposed a design solution for the railway station building and adapted a 3D model of the interior space for a real railway station building (Fig. 4) [11].

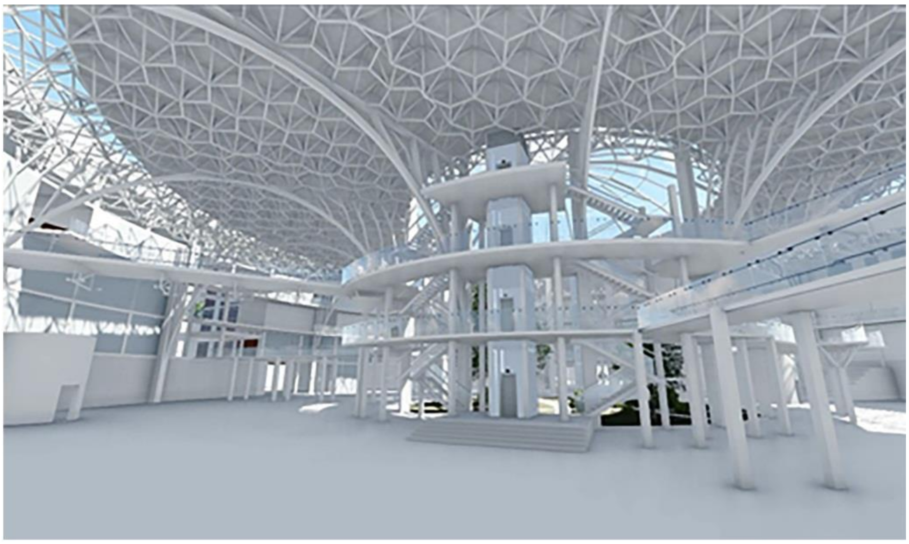

Fig. 4. 3D model of the internal space of the station building [11].

2.3 Research Results

Software calculations and strain-stress distribution analysis led to the transformation of the contour, adjustments of geometry variables and details of the arched structure. For example, additional “branches” were added to the “crown” of the column (Fig. 5). The elements serve as additional support for the coating plate and equalize loads and stresses in the structure. The structural coating plate was introduced into the design scheme in the form of flat trusses resting on the “branches” of a “tree” column.

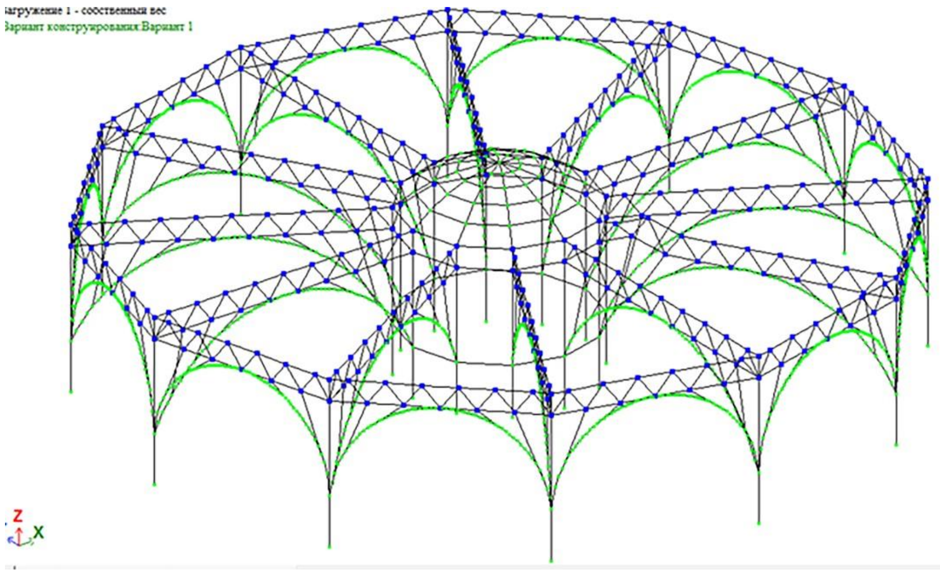

Fig. 5. Structural design of a space frame.

The specification of the static scheme of the space frame has been developed adjusted for expediency, manufacturing feasibility for nodal interfaces of elements, etc. Recalculations of the space frame eliminated inaccuracies and contradictions in design schemes. Cross-sections for frame elements were selected to enhance the strength and stability of the structure in operation. Structural calculations were made given space frame assembly schemes, presented in Fig. 6. Figure 7 shows a layout of the central part of the building. Successive calculations with the specification of stiffness values optimized the cross-sections of the mainframe elements. Deformation and the whole structure values confirmed the space rigidity and geometric invariability of the structural system of the three-dimensional module.

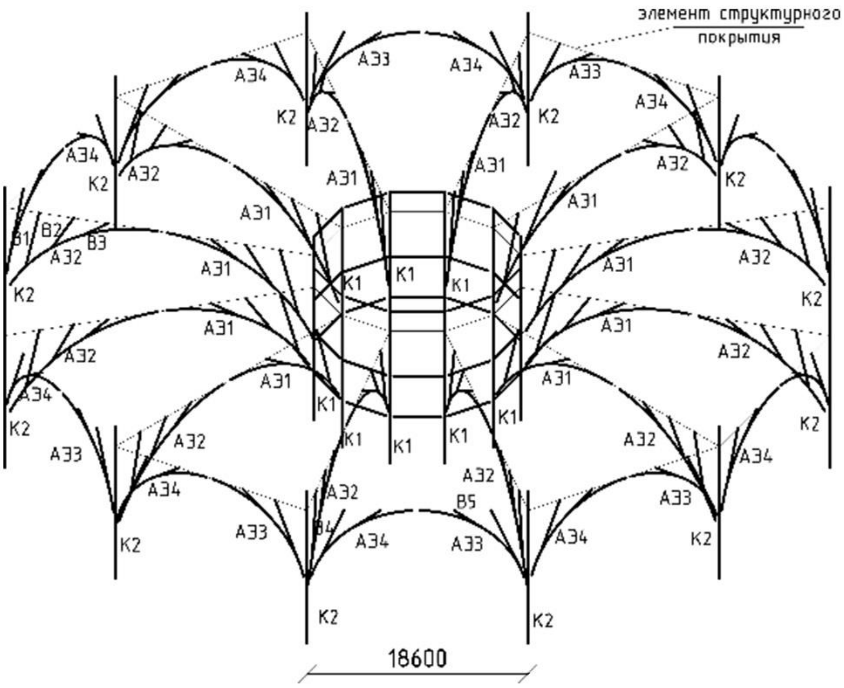

Fig. 6. Diagram of the space frame elements.

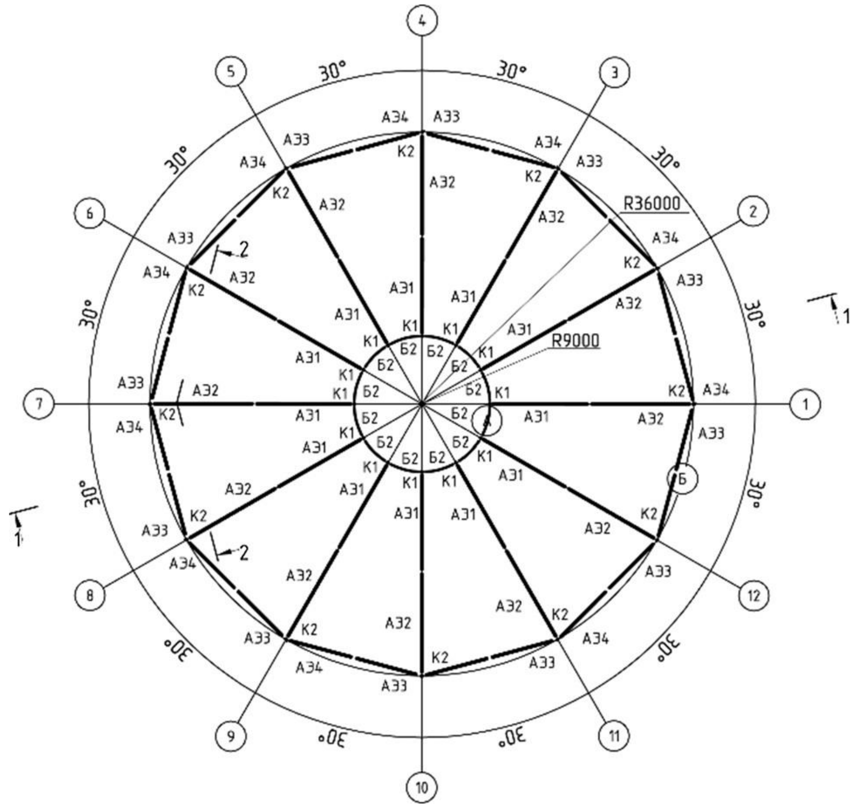

Fig. 7. A layout of the central part of the building.

The designed load-bearing frame can be used in transport infrastructure objects, for example, railway station buildings in Fig. 8. We propose to apply a space-framed universal module and a "tree" column to a variety of objects, such as railway platform structures, pedestrian crossings, etc., creating an entire transport infrastructure, a transport hub.

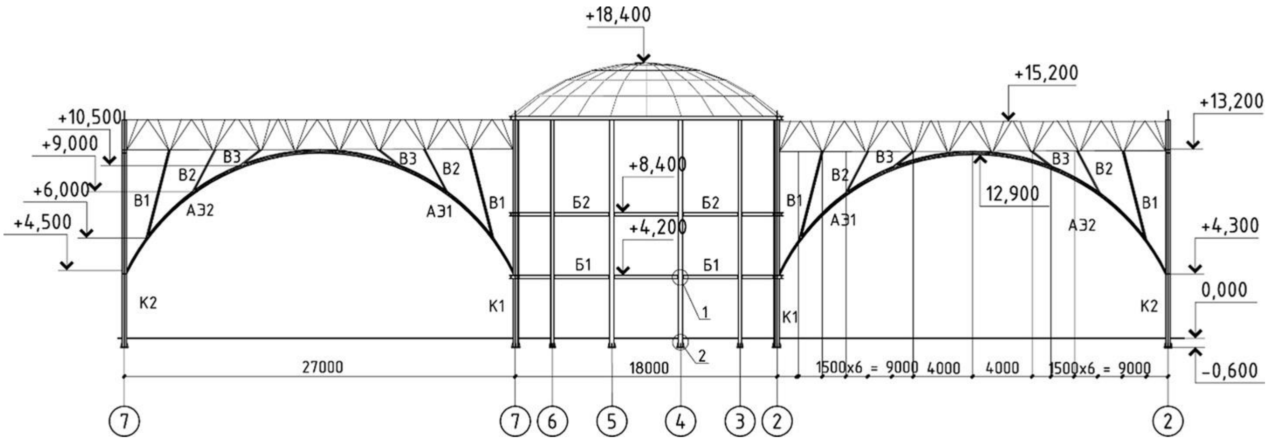

Fig. 8. Drawing of the central part of the building.

2.4 Discussion

Predicting the operation of building structures under sudden impacts of man-made or emergency nature over time has become a relevant requirement for the design of large-span buildings. The issues of the safe and comfortable operation of buildings have become critical [12]. The objects can include sports facilities and concert halls, religious buildings and exhibition halls, shopping malls and entertainment complexes, and many others. Innovative building materials, construction technologies and improvement of calculation methods enforce new space-planning characteristics of objects [13, 14, 15]. A focus is to transport infrastructure: air terminals, railway and bus stations combined into transport and transfer hubs [16].

Despite the advantages of large-span buildings as free space and architectural expressiveness, their design and construction cause some difficulties. For example, customers have to deal with high labour intensity, low use of space over time (about 25%) and inadequate load (up to 30%) at a significant cost of construction and maintenance [17]. Therefore, multifunctional buildings and complexes with a flexible open-plan structure that allows transforming free spaces for various purposes have become a modern trend [18].

Thus, space frameworks as load-bearing structures of large-span buildings have several advantages. They are space rigidity and geometric immutability, reliability and survivability, optimal material consumption, unified elements and assemblies, variety of construction methods, visual "lightness" and aesthetics, freedom of internal planning, etc.

The effectiveness of the design is achieved by the cooperation and combined efforts of architects and designers to create multifunctional convenient spaces based on rational and accurate calculations [19].

3 CONCLUSION

Given the development of digital technologies based on software systems, there is a trend towards a multi-factor "sensitive" calculation of structures that can simulate various design situations for the loaded construction [20].

Further research of the space frame structural model aims at solving several problems. They include optimizing the design scheme and cross-sections of the main elements of the frame given structural nonlinearity; identifying an appropriate assembly scheme; designing assembly and factory interfaces; identifying universal elements; analyzing the impact of the frame structure on progressive loads; assessing the survivability of the system in case of local damage.

The solution to the problems contributes to the implementation of organic architecture ideas in the development of constructive solutions; additionally, it has a great practical value. In the future, a variable module will allow adapting free internal spaces of buildings and structures in a sustained style for various purposes. E. Viollet-le-Duc states, "…style is a visible realization of an idea based on a single principle" [3, 21].

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