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Stress-strain state of space grid structure

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One of the factors influencing the stress-strain state of the structure is the placement method of the columns and their step. The problem formulated in the article is to determine the design solution of the space grid structure with the least weight. The paper examines how the columns location, the number of support points, and the supports step affect the force values in the space grid structure rods and the supports (columns). The first variant of the model adopted a space grid structure supported in the corners of four columns. The second variant of the model adopted a space grid structure supported on two sides – six columns on each side. In the third variant, the structure is supported by 20 columns along the perimeter. It has been determined that the third method of supporting location is the most efficient.

Keywords: material capacity, optimization, space grid structure, stress-strain state regulation, tension regulator

Напружено-деформований стан структурної плити

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Структурні плити − це просторові стержньові конструкції. Форма структурної одиниці плити є подібною до форми природних кристалів, тому, очевидно, є ефективною та заслуговує на дослідження. Структура складається із просторових елементів за формою піраміди, що повторюються багаторазово. Структурні плити широко застосовуються для перекриття одноповерхових споруд і мають велике різноманіття конструктивних і архітектурних форм. Структурна конструкція є багато разів статично невизначуваною конструкцією. Одним із чинників, що впливають на напружено-деформований стан конструкції, є розташування колон. Схема, крок розташування колон, їх кількість впливають на величини зусиль в стержнях структури. Задача, що формулюється в статті, полягає у визначенні конструктивного вирішення структурної плити з найменшою вагою серед декількох конструктивних варіантів плит, що відрізняються різною кількістю опор, але мають однакові розміри в плані. В роботі досліджено, як саме розташування колон, кількість точок спирання та крок опор впливають на величини зусиль в усіх елементах структурної плити та в самих опорах (колонах).Базова структурна плита по верхньому поясу має розміри в плані 30×30 м. На базі цієї плити створено три розрахункові моделі, які відрізняються кроком колон та їх кількістю. При першому варіанті моделі прийняте спирання плити в кутах на чотири колони. Крок колон прийнято 27 м. При другому варіанті прийняте спирання плити по двом сторонам − на шість колон з кожного боку. Відстань між колонами 6 м. При третьому варіанті спирання структурна плита спирається на 20 колон по периметру, що розташовані з кроком 6 м. У висновках проаналізовано результати статичного розрахунку моделей структурної плити покриття з різним способом розташування опор. Визначено, що за критерієм металомісткісткості для розглянутих проектних рішень найбільш ефективний третій варіант розташування колон.

Ключові слова: структурна плита, регулювання НДС, структура, металоємність, оптимізація, регулятор напружень

Introduction

In the world construction practice, many unique and unusual constructions of public and industrial function have been created. The load-bearing structures are considered separately for each of the structures

Metal space grid roof structures are widely used. These roof systems are distinguished not only by original architectural forms but also by progressive design solutions. Pipe profiles occupy a special place in the design of large-role roofs. They have an efficient cross-section of the rod and perceive axial forces. [1, 2].

Structural slabs (structures) are spatial rod structures [1] similar in structure with crystalline metal grates [3, 4].

They are characterised by many positive properties: multiple connections, versatility, the possibility of production on high-performance production lines, simplicity of transportation [5]. The structure consists of spatial elements in the shape of a pyramid which is repeated many a time and oft [8]. Multiple connections cause a number of advantages of structural designs in comparison with traditional structures, which are made up of roof trusses, secondary trusses, girders [8].

As noted in [1], the structures can be used as a roof structure for large buildings in the plan [6]. Internal forces in space grid structures, therefore, cross-section and weight of the structural elements, largely depends on the accepted design parameters. Finding the most effective design solution for the structural plate is one of the tasks to be solved in the initial stages of design [7]. The option that is chosen directly affects the further labor intensity of manufacture, installation, and, ultimately, the cost of the structure.

Review of research sources and publications

Spatial structures are three-dimensional systems consisting of linear members, subjected to loads at their joints or along their length, and connected to each other using pin or moment connections. These structures can take various forms such as flat-double-layer grid (FDLG) or flat-multi-layer grid, braced barrel vault, or dome, or any other form (free-form). The decision to use rod systems as a roof structure is primarily associated with obtaining the most effective design solution for the space grid structure. The criterion for this decision may be material capacity. The choice of the orientation of the structural structure relative to the support contour directly affects the economic performance of the structure. For example, the internal forces in the chord of the structure are obtained by 27% less in the diagonal orientation of the structure relative to the square support contour than in the orientation of the structure parallel to the support contour. The maximum roof displacement is 4 times less than the displacement of the conventional trusses roofs [12]. In [12] it is indicated that the support of space grid structures with chord grids of triangular lattice on four or more nodes causes static indeterminate of the structure. In such a system, a change in the ratio of the rigidity of the rod causes a significant redistribution of internal forces in the rods. At the same time, there is no significant redistribution of internal forces in the statically determinate structure (when the lower triangular grid is supported by three nodes and the quadrangular grid by four nodes)

In addition, in order to obtain a structure with minimum weight, the regulation of the stress-strain state can be carried out by varying many parameters.

Such parameters that can change are: the class of steel rod elements of the plate, the choice of the orientation of the space grid structures relative to the support contour, different types of chord grid (triangular, rectangular, rotated relative to each other by 45° chord grids from square grids); number of columns and their location (in the corners, on the sides of the plate, on the perimeter of the plate) [12], methods of connecting the rods of the structure. So, the criteria and factors influencing the change of internal forces in rods of structure and on: internal force value are many enough. Separately, each of the factors needs research and analysis, because such a criterion of design efficiency as metal capacity is the most important criterion in the first stage of finding the optimal design. The second criterion of efficiency is the labour content of the erection of the structure.

The objective of the work and research methods

The aim of the work is to determine the least material capacity model of a spatial grid structure. Three options for the location of the support columns are accepted for stress regulators. The scheme, the interval of columns, the number of columns influence the force values in the rods of the structure.

Objectives that were formulated to achieve this goal:

– the creation of finite element models of space grid structures in the Lira-SAPR software for studying their structural behavior when changing the layout of columns and their number;

– selection of the cross-sections of the structural elements of the space grid structures models based on the results of static analysis;

– calculating the weights of each model of the space grid structure and determining the space grid structure model with the lowest weight. At the same time, the sufficient manufacturability of the model remains.

The ***object*** of the research is the space grid structure (structural rod plates of the roof) with chord grids of square lattices having a different number of supports.

The ***subject*** of the research is the stress-strain state of the structural rod plates of the roof with chord grids of square lattices, which have a different number of supports and their interval.

The ***research method*** is the method of computer modeling of structures using software systems that implement the finite element method (SP LIRA-SAPR).

The research ***results*** make it possible to determine the most effective of several possible space grid structures of the roof according to the criterion of effective material consumption, that is, according to the criterion of the lowest weight of the structure.

Basic material and results

As indicated in the study [4], there are 20 main types of rod plates of interest for the practice of designing structural roof slabs (space grid structures).

Among this set, one can single out a system of the type of inclined cross trusses of two directions [9].

A structural slab (Fig. 1–2) with dimensions in the plan of 30.0 × 30.0 m, having an orthogonal grid of chords with a cell of 3.0 × 3.0 m and a height along the axes of the chords 3.0 m.

The structural plate (Fig.1−2) with a plan size of 30.0 ×30.0 m, with an orthogonal grid of chords with a cell of 3.0 × 3.0 m and chords height of 3.0 m is taken as the structure to be researched. Thus, the height of the structure is 1/10 of the span, which is the optimal height for simply supported structural plates [13]. The nodes of the upper and bottom chords are connected by diagonal rod elements.

The crystals of the structural plate have the shape of a pyramid with a square base. The columns are 6,0 m high. The structural plate is supported on the columns along with the lower chords. The plate dimensions in the plan, the active load, the crystal type are taken as parameters, do not change.

The restrictions are the strength condition for the tensioned rods, the stability condition for the compressed rods, the limit slenderness and the limit deflection of the structure [14]. There are no intermediate supports in the structure (Fig. 2). The combination of all elements made in a hinged way, intersections of all elements − pipes electro-welded straight-seam according to GOST 10704-91.

The rod system on the square plan works in two directions and belongs to the most perfect types of space grid structures.

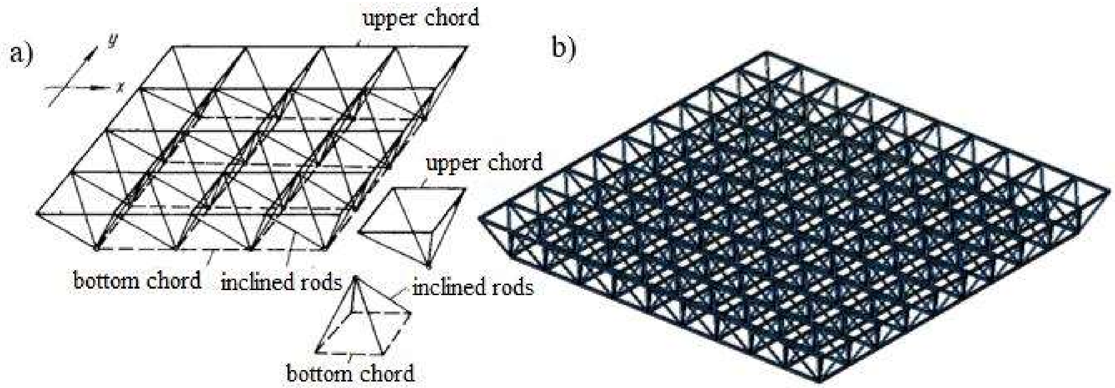

Figure 1 – The system of the type of inclined cross trusses in two directions and with chord grids of square lattices is used to model the structural plate (a); the spatial model of the structural plate is researched investigated (b)

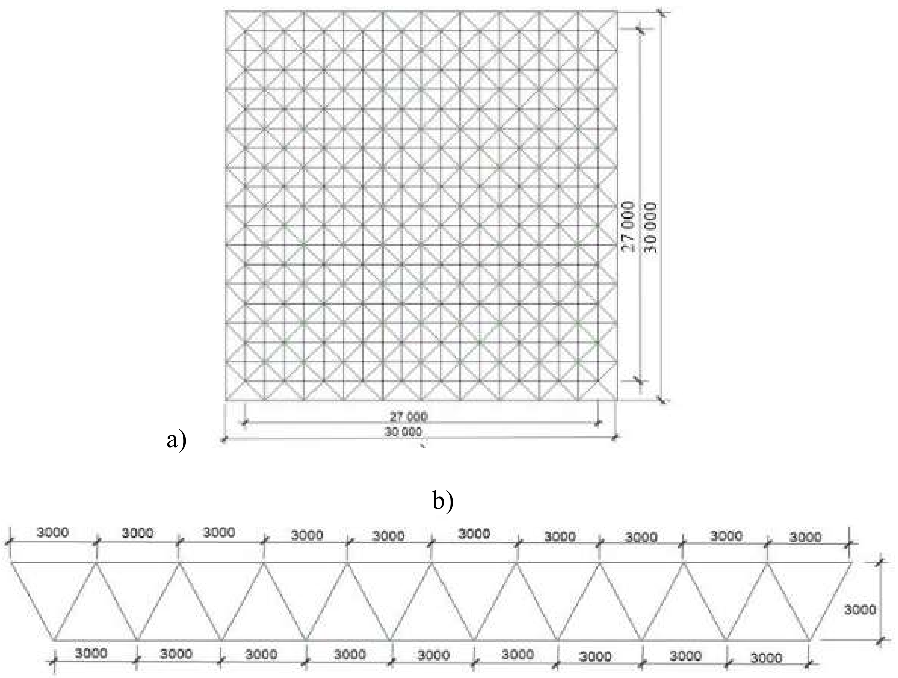

Figure 2 – Geometric scheme of the space grid structure: top view (plane XOY) (a); side view (plane XOZ or УOZ) (b)

There are no monitors and level differences in the building. To ensure the removal of atmospheric precipitation, as a rule, the space grid structure is made with a two-sided slope.

However, this design feature is neglected in this static analysis.

When a square space is overlapped, the space grid structure makes full use of its load-carrying capacity. It is the square form exactly, not the rectangular form, that is, the ratio of sides 1:1 determines its work in two directions. Data is given that with the height-to-width aspect ratio of 1:0.8, the space grid structure begins to work in only one direction and the difference in forces in the elements along and across the span is 2,25 times [15].

The greater the difference in the height-to-width aspect ratio of the structure, the greater will be the uneven distribution of forces in its elements in two mutually perpendicular directions [8]. Thus, we will assume that in a structural plate with the height-to-width aspect ratio of 1: 1, the forces in its elements will be equal.

The number of columns and the method of their location on the plan will be taken as regulators of forces in the rods of the structure (Fig. 3). In model No.1, the distance between the columns is 27,0 m and the number of columns in the model is 4. In model No.2, the distance between the columns is 6,0 m and the number of columns in the model is 12. In model No. 3, the distance between the columns is 6,0 m, the number of columns in the model is 20.

The spatial model consisting of the space grid structure (plate) and columns was created for the static analysis. All elements of the structural plate were defined by the rods of a spatial truss with three statistical degrees of freedom: X, Y, Z, columns − spatial universal rods (FE No.10) with six statistical degrees of freedom: X, Y, Z, Ux, Uy, Uz.

Analytical models according to fig. 3 are shown in fig. 4.

All rods of a structural plate are accepted from common steel, made from hot-rolled pipe profiles. Accepted steel class C245 [16] with the following characteristics: R_y = 24,0 kN/cm^2, R_{yn} = 24,5 kN/cm^2, E = 2, 06·10^8 kN/cm^2, γ = 77,0085 kN/m^3, μ = 0,3.

The rods of the upper chord and bottom chord of the structural plate is made from hot-rolled pipe profile 242×32 mm, the inclined rods are made from hot-rolled pipe profile 168×25 mm. The columns have 6,0 m length and are made from a hot-rolled pipe profile 273×40 mm.

Construction loads are constant − roof load (from the steel sheets and the girders), the dead load of the structure, which was automatically set in the SP Lira-SAPR.

The live load is the snow load (characteristic for Sumy) is 1,64 kN / m^2. Since the slope of the upper chord of the structure is α <30 °, a uniform distribution of the snow cover over the entire roof is assumed [1].

The steel sheets are based on the girders. Girders are attached to the upper chord of the space grid structure. Thus, in the analytical models, a point load from the steel sheet and snow was applied to the nodes of the upper chord of the space grid structure (Fig. 5).

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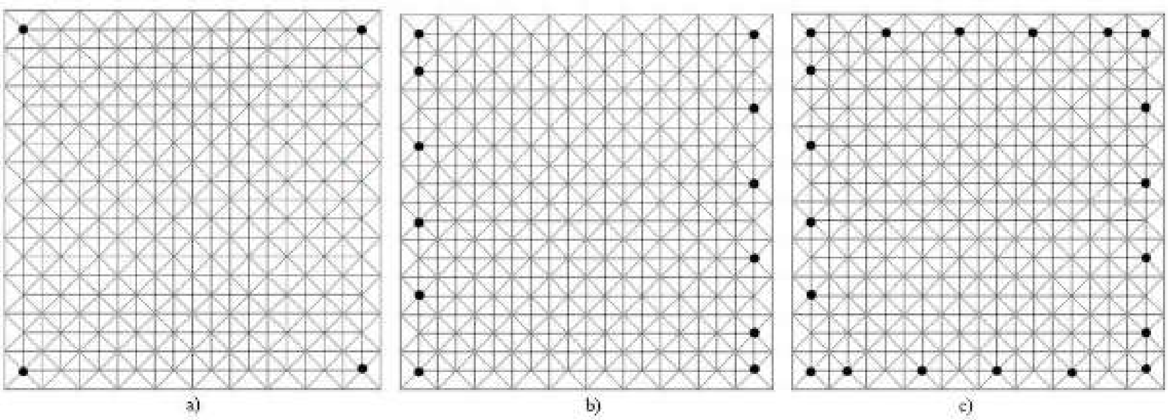


Figure 3 – Analytical model of location column:
a − model No.1 (in four corners of the bottom chord), b − model No.2 (on both sides of the bottom chord), c − model No.3 (on four sides of the bottom chord with a step of 6,0 m)

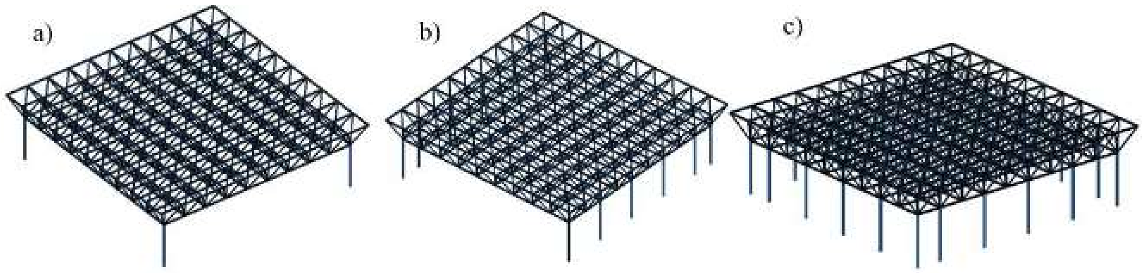


Figure 4 – Spatial analytical models of the space grid structure that are being researched: analytical model No.1 (a); analytical model No.2 (b); analytical model No.3 (c)

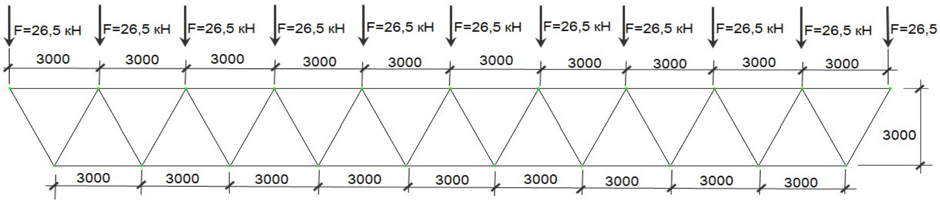


Figure 5 – The application scheme of nodal load on the space grid structure

The results of the numerical research of space grid structure

The static analysis was conducted to determine the stress-strain state of the whole structure. The selection of the cross section of tensioned elements was carried out based on strength analysis, compressed elements were carried out based on strength and durability analysis. The static analysis also took into account the limited slenderness of the elements and vertical linear displacements of the whole structure. Structure designed by the elastic method of analysis [1].

The upper chord rods are under the influence of the axial compression forces and the bottom chord rods are under the influence of the axial tension forces.

The axial force *N* in the inclined rods has an alternating value, so the rods are in both tension and compression. Fig. 6 shows the simple bar charts of the maximum forces in the rods of the structures.

Thus, the charts in Fig. 6 show that the forces in all chord systems and inclined rods decrease, but at this time there is an increasing number of structural supports. There are forces uniform in value in the rods of the chord systems.

Thus, the maximum compression forces in analytical model No.2 decreased in comparison with these forces in analytical model No.1 by 1,71 times, and the maximum compression forces in analytical model No. 3 decreased in comparison with these forces in analytical model No.1 by 3,12 times. The maximum tensile forces in analytical model No.2 decreased in comparison with these forces in analytical model No.1 by 1,85 times, and the maximum tensile forces in analytical model No.3 decreased in comparison with these forces in analytical model No.1 by 4,16 times. The maximum compression forces in the inclined rod in analytical model No.2 decreased in comparison to these forces in analytical model No.1 by 2,53 times, and the maximum compression forces in analytical model No.3 decreased in comparison to these forces in analytical model No.1 by 3,97 times.

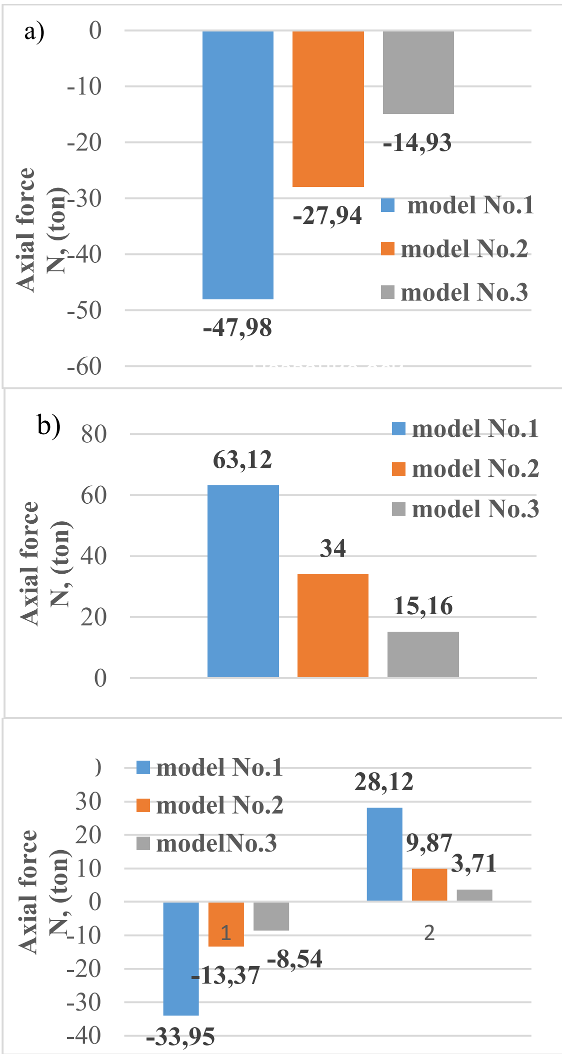


Figure 6 – Maximum forces «N» in the rods of the structures: axial forces in the rods of the upper chord (a); axial forces in the rods of the bottom chord (b); axial forces in the inclined rods (c)

The maximal tensile forces in model No.2 are 2,84 times less than those in model No.1 and the maximal tensile forces in model No.3 are 7,57 times less than those in model No.1. Fig. 7–8 shows the bar charts of forces in the columns.

Maximum compression forces in columns in analytical model No.2 are 2,7 times less than in analytical model No.1 and maximum compression forces in columns in analytical model No.3 are 3,77 times less than in analytical model No.1. The bending moments in columns also decrease with the increase of the support points for the space grid structure.

It should be noted that the forces in analytical models No.2 and No.3 (both in the structure rods and in the columns) decrease in comparison with the forces in the most stressful analytical model (analytical model No.1) by approximately the same value. Fig. 9 shows charts of vertical load deflections at the nodes of the structure in its cross-section.

For example, Fig. 9 shows that the least rigidity will be a structure in analytical model No.1, supported by four columns in the corners. The most rigid scheme will be analytical model No.3 – with the support of the structural plate around the perimeter. The general view of the deformed analytical models is given in Fig. 10.

The deformability of all models is within acceptable limits [17], and the maximum actual deflection for all analytical models does not exceed the maximum allowable value of 90 mm.

$$f_u = l / 300 = 27000 / 300 = 90 \text{ мм}$$

Cross-section analysis of structural rods

Strength analysis of steel elements with characteristic strength $R_{yn} \leq 440$ N/mm^2 with axial tension and compression, it should be performed according to the formula (1.4.1) [16]:

$$N / A_n \cdot R_y \cdot \gamma_c \leq 1 \quad (1)$$

Stability analysis of the elements under axial compression should be calculated by the formula (1.4.3) [16]:

$$N / \varphi \cdot A_n \cdot R_y \cdot \gamma_c \leq 1 \quad (2)$$

Thus, the required cross-section area with axial tensile strength:

$$A_n = N / R_y \cdot \gamma_c \quad (3)$$

Thus, the required cross-section area with axial compressive strength:

$$A_n = N / \varphi \cdot R_y \cdot \gamma_c \quad (4)$$

Tables 1 and 2 show the maximum axial forces occurring in the rods of the structure and the columns. Based on these data, we will find the necessary cross-sectional area of the rods according to the strength (1) and stability (2) conditions for a compressed rod.

The cross-sectional area of the rod required with the strength condition is calculated according to (3) and (4) and written in tables 1–4. We will also select a pipe profile according to the schedule of pipes (GOST 8639-82), calculate its weight and the total weight of the upper chord, bottom chord, inclined rods and columns.

Fig. 11 shows the ratio of the space grid structures and the weight of the columns.

As the number of supports increases, the weight of the roof plate decreases, and the weight of the columns increases (Fig. 12).

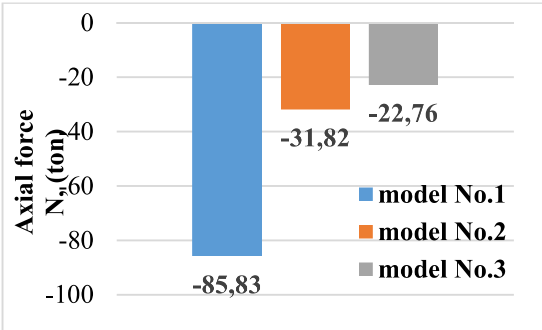


Figure 7 – Internal maximum forces "N" in the columns

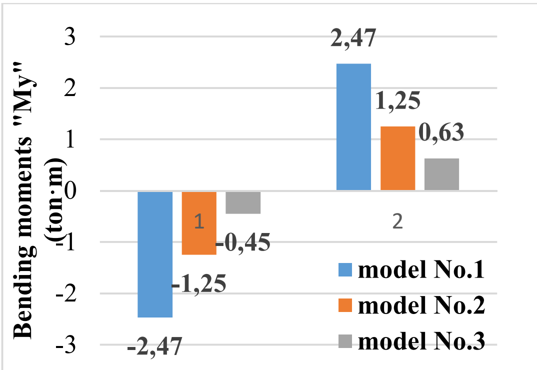


Figure 8 – Maximum bending moments "My" in columns

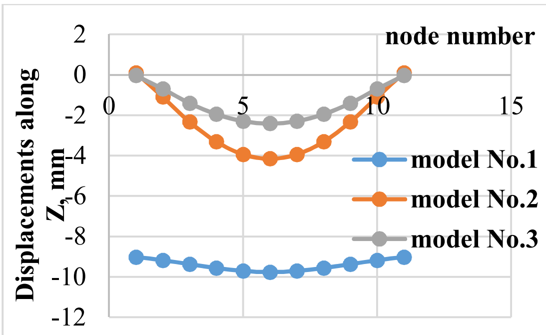


Figure 9 – Charts of the nodes vertical deflections of the structure in its cross-section

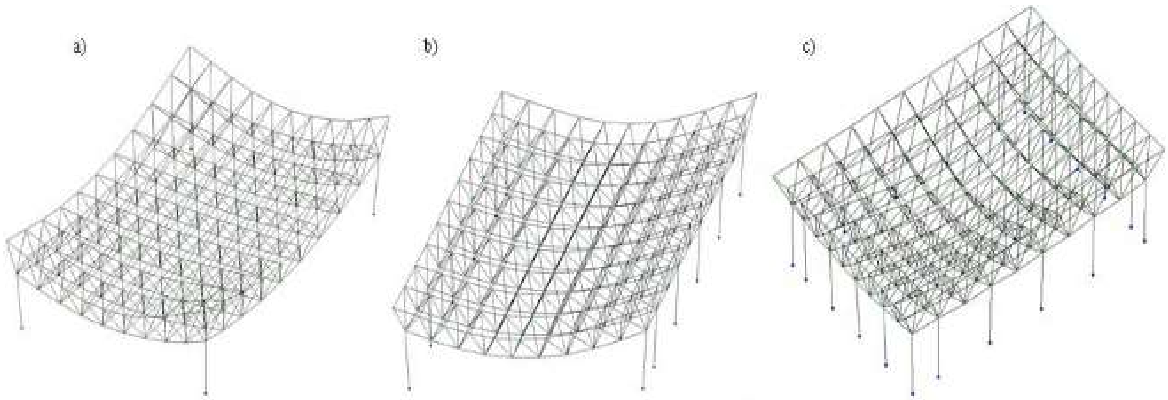


Figure 10 – Deformed structure: analytical model No. 1 (a); analytical model No. 2 (b); analytical model No. 3 (c)

Table 1 – Upper Chord Weight Count

Model №	Maximum forces N, kN	Cross-sec-tional area A, sm^2	Pipe profile	Pipe profile, A, sm^2	Weight of 1 r.mprofile, kg	Weight of 1 r.mprofile, ton	Chordro-dlength, m	Weight, ton
1	470,68	19,61	80×7	19,6	15,38	0,01538	660	**10,15**
2	274,09	11,42	80×4	11,88	9,33	0,00933	660	**6,16**
3	146,46	6,10	50×3,5	37,74	4,94	0,00494	660	**3,26**

Table 2 – Bottom Chord Weight Count

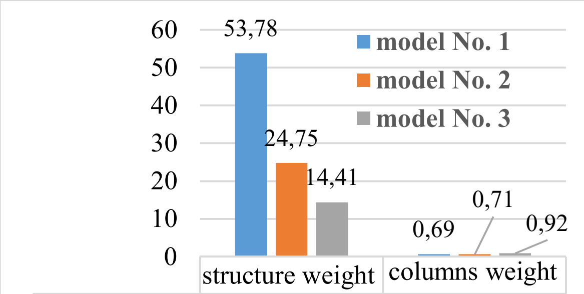
Model №	Maximum forces N, kN	Cross-sec-tional area A, sm^2	Pipe profile	Pipe profile, A, sm^2	Weight of 1 r.mprofile, kg	Weight of 1 r.mprofile, ton	Chordro-dlength, m	Weight, ton
1	619,20	25,80	120×76	26,74	20,99	0,02099	540	**11,33**
2	333,54	13,90	60×77	14	11	0,011	540	**5,94**
3	148,71	6,20	50×73,5	6,3	4,94	0,00494	540	**2,67**

Table 3 – Inclined Rods Weight Count

Model №	Maximum forces N, kN	Cross-sec-tional area A, sm^2	Pipe profile	Pipe profile, A, sm^2	Weight of 1 r.mprofile, kg	Weight of 1 r.mprofile, ton	Chordro-dlength, m	Weight, ton
1	333,04	13,88	60×7	14	11	0,011	2936	**32,30**
2	131,15	5,46	50×3	5,48	4,31	0,00431	2936	**12,65**
3	83,78	3,49	35×3	3,68	2,89	0,00289	2936	**8,49**

Table 4 – Columns Weight Count

Model №	N, kN	A, sm^2	Pipe profile	Cross-sec-tional area A, sm^2	Weight of 1 r.mprofile, kg	Weight of 1 column, ton	Number of columns in the model	Total weight of columns in the model, ton
1	841,99	35,08	140×7	36,4	28,57	0,17142	4	**0,69**
2	312,15	13,01	70×5	12,57	9,87	0,05922	12	**0,71**
3	223,27	9,30	45×7	9,8	7,69	0,04614	20	**0,92**



	structure weight	columns weight
model No. 1	53,78	0,69
model No. 2	24,75	0,71
model No. 3	14,41	0,92

Figure 11 – The ratio of the weight of the space grid structure and the weight of the columns

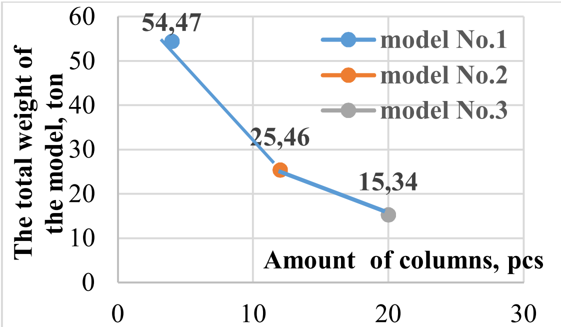


Figure 12 – Weight changes in space grid structure depending on the number of columns according to the variants of their location
(model No. 1– 4 columns, model No. 2– 12 columns, model No.3 – 20 columns)

Conclusions

As the number of supports increases, the weight of the space grid structure itself decreases and the weight of the columns increases (see Tables 4–5). The model according to variant No.3 has the lowest weight, despite the largest number of columns in this model. As can be seen in Fig. 11 the weights of the columns in the weight of each model are values of the same order. The weight of the columns is from 0,7 to 0,9 tons, and the weight of the space grid structure differs by 2,17−3,8 times relative to the heaviest structure (according to model No.1). The most rigid is model No.3, the least rigid is model No.1 (when the space grid structure is supported by four columns at the corners). Based on the analysis of the obtained results, we can conclude that the criterion of metal consumption for the considered design solutions is the most effective third option for the location of the columns (along the perimeter of the lower chord of the space grid structure with a step of 6,0 m). In this case, the total weight of the whole structure would be the lowest. Prospects for further research are: the study of plate structures models with different variants of steel classes of construction and the labour content during the model erection.

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