STUDY OF GRID COVER STRUCTURE BEHAVIOR

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Abstract. Spatial grid slab structures are effective solutions for roof plates for both civil and industrial buildings. Numerous studies confirm the rational and uniform distribution of axial forces in such systems, which allows for maximum unification of core elements and their rational design. The behavior of such grid plates, both flat and curved, depends on a change in a certain parameter with all other parameters remaining constant. Such a parameter (force regulator) can be the way the columns (supports) of the slab are arranged and their number (columns can be located in the corners of the slab, along the perimeter, along the long sides of the structure, with an offset deep into the slab). Another parameter is the shape of the basic (single) element, which forms the entire slab structure by multiplying this element along the width and length of the element. The main (basic) spatial element that defines the shape consists of a system of vertical, inclined and horizontal rods. These rods are arranged in an orderly arrangement within the base element, and their structure closely resembles that of crystals created by nature. In this study, three finite element models of the structural slab were simulated. The models differed from each other only in the shape of the forming the basic element. All other parameters, such as slab geometry, stiffness parameters of the rods, loads, and boundary conditions, remain unchanged. The stress-strain state of the FE models and stability parameters are analysed, and new cross-sections of structural elements are selected in accordance with the accepted design standards. The weight of each model was estimated, and the most efficient model was determined according to the material consumption criterion. Analysing the total weight of all model elements, we conclude that the model with the crystal shape of type 3 is the lightest compared to the weight of models 1 and 2, respectively (by 34.2% compared to model 1 and 21% compared to model 2).

Keywords: finite element models, numerical experiment, grid cover structure, basic element, material capacity.

Introduction

Space grid steel cover structures are one of the most efficient solutions in modern construction. They combine high strength, light weight and cost-effective materials, making them ideal for long spans without intermediate supports [1-3] and complex architectural forms. The main advantage of such structures is the even distribution of loads due to a rigid spatial pattern. This reduces the weight of the load-bearing elements and reduces overall material costs without any loss of strength and reliability. Due to their modular structure, such structures are easy to install, transport and adapt to different architectural solutions. Thus, spatial grid steel cover structures provide an optimal ratio of strength, cost-effectiveness and durability, making them one of the most efficient solutions in modern construction. Compared to reinforced concrete [4], lightweight metal core structures are more cost-effective and much easier to install, and the variety of their shapes and operating conditions allow for the creation of unique lightweight structures.

Taking into account the experience of designing grid spatial systems, it can be summarised that one of the most important issues for such structures (for example, those shown in Fig. 1) is the issue of economic efficiency. The choice of the most efficient solution is related to the issue of design optimisation, in particular, according to the criterion of the material consumption of the grid plate [5-7]. The material consumption of a spatial structure depends primarily on the stress-strain state of its individual groups of structural elements. [8; 9]. The stressed state of a core spatial structure can be regulated (changed) by changing the parameters of only one factor, for example, the method of arrangement and the number of supports [8]. Among the factors influencing the stress-strain state of the elements of core spatial structures are the following: application of tensioning along the lower belt of the core plate; column arrangement and number of columns; the method of settling the supports; the shape of the basic forming element; the height (thickness) of the structural slab; installation of rods that have deviations from the predefined geometrical parameters. Changing only one of the above parameters with the same other parameters (stiffness of the rods, load on the slab) significantly affects the magnitudes of forces in the rods and the nature of their distribution.

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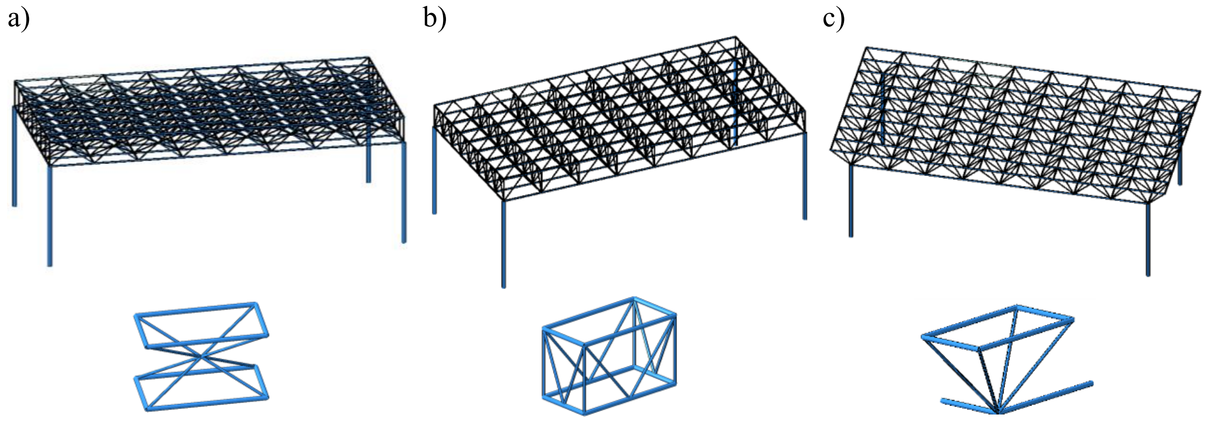

Fig. 1. **Models of the studied steel plate:** a – FE scheme No. 1 with a basic forming element of type 1; b – FE scheme No. 2 with a basic forming element of type 2; c – FE scheme No. 3 with a basic forming element of type 3

The choice of the most efficient model in terms of the stress-strain state, and hence material efficiency, is a multicriteria task. Thus, study [8] found that among the variants of structural slabs supported by columns in the corners, along the long sides and along the perimeter, the most rigid, and therefore the least deformable, was model 3, which is supported by columns along the perimeter. Its lowest deformability (the smallest vertical deflections of the nodes) caused the smallest forces in the rods compared to the other two models. This resulted in the selection of tubular elements with the smallest cross-section for this model, and hence the weight of this model was the smallest of the three. The minimal weight of the flat lattice structure itself also necessitated the use of columns with the smallest cross-section, although the number of such columns was the largest. In the future, as a continuation of the multicriteria study, model No. 3 [8] can be presented with a different basic forming element. And, according to the criterion of the lattice cyst shape, the optimal slab model among several can be found again. At the third stage of the study, it is possible to identify the most optimal slab thickness (its height) from several possible thickness options.

The design practice of spatial lattice structures indicates that pipe-shaped profiles are especially advantageous for this purpose. These profiles feature an optimized cross-section that efficiently absorbs axial loads, responding to them through axial tension and compression forces [11; 12].

In the numerical study, it is planned to determine the stress-strain state and material consumption of three finite element models of spatial core slabs of the coating according to Fig. 1, which differ from each other only by one parameter – the shape of the basic element.

Materials and methods

The finite element method, a widely used numerical approach for analysing building structures, plays a crucial role in structural mechanics. It has been implemented in the Lira-SAPR software package (Ukraine) for structural design. All rod elements are constructed from structural steel S 235, produced using hot-rolled pipe profiles. The key properties of this steel include a design resistance at the yield strength of R_y = 230 MPa, a characteristic resistance at the yield strength of *Ryn* = 235 MPa, an elastic modulus of $E = 2.06 \times 10^4$ kN·cm^{-2}, a density of γ = 78.5 kN·m^{-3}, and a Poisson's ratio of μ = 0.3 [13].

The design of structural element groups in the spatial grid structure follows regulatory standards [13]. This approach is integrated into the design module 'Metal' of the Lira-SAPR software package. The design module 'Metal' enables the assessment of cross-sectional area utilization for rod profiles defined during the initial design phase. Additionally, the methodology facilitates the selection of optimal cross-sections for all structural element groups based on design forces obtained from the static analysis of the finite element model. The selection process takes into account the strength, stability and stiffness requirements for elements in accordance with the building codes [13].

Main part

Three slabs in the form of a spatial rod structure (Fig. 1, a, c, d) are considered as structures to be investigated. The slab is designed as a flat slab with parallel horizontal upper and lower belts. The slab has a plan dimension of 24.0×12.0 m. The height of the slab is constant and amounts to 1.8 m. The dimensions of the forming element are 3.0×1.2×1.8 m.

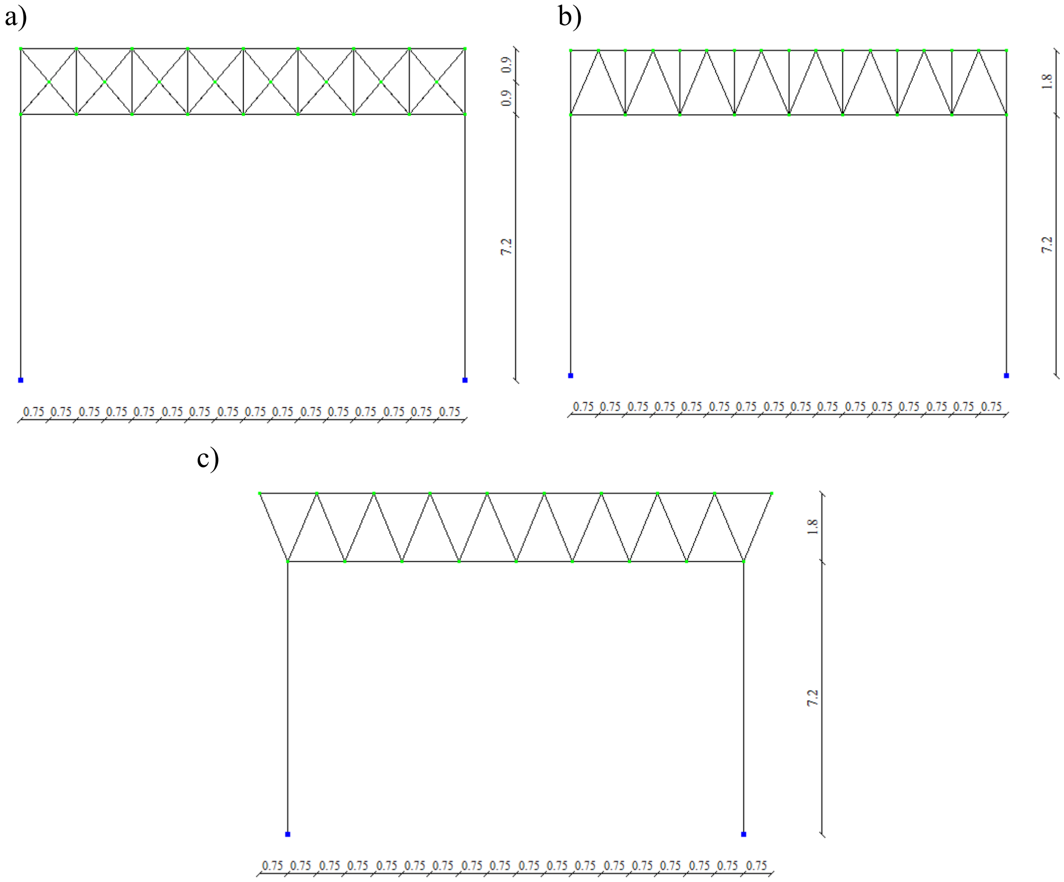

Fig. 2. **View of FE models in Lira CAD software in the YOZ plane:** a – FE scheme No.1; b – FE scheme No.2; c – FE scheme No. 3

Keeping all parameters unchanged – including slab dimensions, rod cross-sections, steel grade, and connection methods – modifying only a single parameter, namely the shape of the base element, can lead to a significant variation in the structure's stress-strain state. It is planned to evaluate the stress-strain state of each model and determine its weight in accordance with the design methodology according to the standards.

All structural slab models are upheld by four corner columns. The slab is carried by columns positioned at the lower belt level. All slab elements are grouped into the following types according to their structural characteristics: upper belt rods; lower belt rods; and lattice rods. In the first iteration, the stiffness characteristics for the structural groups of rods were adopted: upper belt (pipe 114×20), lower belt (pipe 114×20), lattice (pipe 68×6) and columns (pipe 273×40). The main loads acting on the slab are: 1) its own weight (computed in Lira SAPR software automatically); 2) the weight of all roofing layers (0.0914 $kN \cdot m^{-2}$); 3) the snow load (1.67 $kN \cdot m^{-2}$ [14]). Studies show that the effect of wind loads can be ignored, as wind forces are only about 1%.

The static analysis in the elastic stage was performed according to the methodology of the Design Load Combination (DLC) according to the norms [14]. The load from the roof weight and the snow load in the design models are applied to the nodes of the upper belt of the structural spatial grid slab.

Results and discussion

Table 1 presents the maximum values of axial compression-tension forces for all core structure groups, while Table 2 displays the highest forces that occur in the columns from the most critical load combination.

Table 1

Belt peak axial forces (N)

FE scheme No	Top belt		Lower belt		Bracing	
	Compression	Tension	Compression	Tension	Compression	Tension
1	-65.50	5.18	-3.62	68.9	-66.2	60.15
2	-55.96	0.60	-0.39	54.5	-34.7	33.92
3	-60.50	2.83	-2.08	79.4	-43.3	33.70

Table 2

Column peak forces

FE scheme No 1			FE scheme No 2			FE scheme No 3		
N, t	M_y, t·m	M_z, t·m	N, tones	M_y, t·m	M_z, t·m	N, t	M_y, t·m	M_z, t·m
-69.9	±2.6	±4.74	-58.0	±1.63	±1.98	-86.3	±1.96	±2.61

The highest vertical displacement values under the most unfavorable load combination are as follows: 60.4 mm for FE scheme No.1, 52.4 mm for FE scheme No 2, and 50.2 mm for FE scheme No 3. Figure 3 presents the graphics of vertical movements of the nodes in the central section of the bottom belt resulting from the most unfavorable design load combination (DCL No.2).

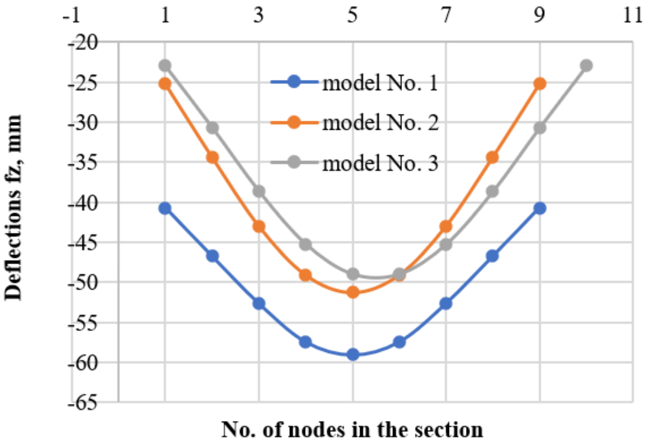

Fig. 3. **Displacement graphics of the lower belt nodes along the Z-axis in a section along the span of the structure**

The maximum permissible vertical displacement according to the standards [15] is 96 mm. As it can be seen in Fig. 3, all maximum deflections in the models remain within this permissible limit.

Table 3 presents the highest percentage of section utilization specified in the input data for the three spatial grid plate models. These values were obtained after the initial iteration of the static analysis, conducted in accordance with the criteria for determining the first group of limit states as per [13].

Table 3

Cross-sectional load-bearing capacity for structural rod groups after initial iterative analysis

Designation of the structure	Cross-sectional load-bearing capacity, %.		
	FE scheme No. 1	FE scheme No.2	FE scheme No. 3
Upper belt	57.1	49.6	52.8
Lower belt	49.7	47.8	54.0
Bracing	73.6	75.0	84.6
Columns	26.5	19.6	22.6

The data in Table 3 show that all rods in both the upper and lower belts are understressed (they are only 50% loaded in total). However, the lattice rods for all models are fully effective and have a sectional safety margin of about 20%. The columns of all three models are also only partially utilising their load-bearing potential. Consequently, the initially adopted sections of the model rods (for the first iterative analysis) for the upper and lower belts of the spatial rod systems are not rational. More rational solutions should be adopted for these rods. For this purpose in the module of Lira-SAPR software, which deals with the design of elements according to the norms [13], we will select new cross-sections for all rod elements of the models (Table 4).

Table 4

Selected cross-sections of rods of the spatial grid plate

FE scheme No		Pipe profile selected in the initial iteration	Cross -section determined using Lira-SAPR software from static analysis data		Weight of 1 m.p. of profile, t	Length of the belt rods, m	Weight, t
			Steel	Pipe profile, mm			
Upper belt	1	114×20	S 235	194×5.0	0.0232956	324.00	7.55
	2	114×20		168×5.5	0.0220320	324.00	7.14
	3	114×20		180×5.0	0.0215700	405.00	8.74
Lower belt	1	114×20	S 235	146×5.5	0.0190494	324.00	6.17
	2	114×20		152×6.0	0.0215950	324.00	6.99
	3	114×20		152×7.0	0.0250210	324.00	8.11
Bracing	1	68×6	S 235	133×7.5	0.0232032	1118.60	25.96
	2	68×6		140×4.5	0.0150310	1244.04	18.70
	3	68×6		146×4.5	0.0156970	797.04	12.51
Columns	1	273×40	S 235	273×8.0	0.0522611	28.80	1.51
	2	273×40		245×7.0	0.0410690	28.80	1.18
	3	273×40		273×7.0	0.0459010	28.80	1.32

Table 5 shows the updated rod cross-sections and calculated weights of the upper and lower belts, braces and columns for all FE schemes of the space grid structure.

Table 5

Total weight of the structure

FE scheme No	Upper belt weight, t	Lower belt weight, t	Bracing weight, t	Structural plate weight, t	Column weight, t	Total weight, t
1	7.55	7.14	8.74	**39.68**	1.51	**41.19**
2	6.17	7.00	8.11	**32.84**	1.18	**34.02**
3	25.96	18.70	12.51	**29.36**	1.32	**30.68**

Conclusions

1. The spatial grid cover slab is an efficient and well-designed structural solution that enables the coverage of extensive expanses. Also, this design is characterized by high rigidity and technological efficiency (the presence of unified elements).
2. Changes in the geometric parameters of the crystal that forms the shape of a structure essentially impact the tension-strain state of the slab rods. Therefore, the shape of the basic (unit) element has a considerable impact on the tension-strain state, assuming the other parameters and conditions remain unchanged.
3. Thus, analysing the tension state of the elements of the top belt, it should be noted that the stresses in these belts for models 1 and 2 are higher by 8.26% and 17%, respectively, compared to the stresses in the upper girdle of model No. 3. Analysing the tension state of the lower girders, it should be noted that the stresses in the lower belt in model No. 3 are higher than the tensile force in the lower belt of models No. 1 and No. 2 by 15.24% and 45.7%.
4. The most stressed are the lattice elements for model 1 compared to the axial tensile (compressive) forces occurring in models 2 and 3 (by 90.8% and 52.9% for compressive forces and 77.3% and 78.5% for tensile forces, respectively).
5. The strainability of the models is in the permissible range. The most rigid model is the one with a basic element of the third type. Model No. 1 has the highest deformability.
6. Analyzing the total weight of all model elements, we conclude that the model with the crystal shape of type 3 is the lightest compared to the weight of models 1 and 2, respectively (by 34.2% compared to model 1 and by 21% compared to model No.2). Thus, guided by only one change in the criterion,

the shape of the basic element, with other parameters remaining unchanged, it should be concluded that this criterion can significantly affect both the system's VAT and the material consumption of the plate variant under study.

Research perspectives

To achieve a more accurate and effective design, multiple analysis iterations must be carried out to guarantee the cross-sectional area of the bars is optimized in the construction. In the second iteration, groups of bars should be formed for different force ranges *N* and assigned to the appropriate pipe profiles. Moreover, further repetitive iterations must be carried out until the cross-sectional efficiency for the majority of the rods in the design set reaches 80-85%**.** This will greatly decrease the slab weight, though it will lead to an increased quantity of rod dimensions within the structure. For a comprehensive assessment of the effectiveness of each model, it should also be analysed in terms of labour costs for manufacturing and installation.

Author contributions

Conceptualization, N.S.; methodology, N.S and L. Ts.; investigation, N.S., S.H.; software, H.Ts., S.H., O.D.; writing – original draft preparation, N.S., V.L; writing – review and editing, N.S., L. Ts. All authors have read and agreed to the published version of the manuscript.

References

[1] Li Z. X. Structure mechanics analysis with different construction schemes in large-span space grid structure. Advanced Materials Research, vol. 788, 2013, pp. 534-537

[2] Drahan V. I. Development of new effective large-span metal structures of 'BrGTU' system and methodology of unreliability assessment at the design stage. Technology of construction and reconstruction (TCR-2015) : collection of reports of the International Scientific and Technical Conference. 2017, pp. 107-115.

[3] Baby, B., Lakshmi, B.S., Narayani, Ch., Salilan, D. & Mathews M. Space truss design using STADD. Pro Software. International Research Journal of Engineering and Technology, 4(6), 2019

[4] Sparks, Patrick S., & Rabun J. Stanley. Structural Analysis of Historic Buildings: Restoration, Preservation, and Adaptive Reuse Applications for Architects and Engineers. APT Bulletin, vol. 31, no. 2/3, 2000, pp. 76-76.

[5] Hicks, S.J., Lawson, R.M., Rackham, J.W. & Fordham, P. Comparative Structure Cost of Modern Commercial Buildings. Ascot : The Steel Construction Institute, 2004, P.317

[6] Yongpeng He, Shepherd P., Wang J. Enhancement layout optimisation of grid structures with stability constraints. Structures. vol. 66, 2024

[7] Bilyk A. The choice of optimal constructive solutions of steel roof trusses. PhD thesis abstract. Kyiv National University of Construction and Architecture, 2009. (In Ukrainian)

[8] Sribniak N., Lutskovskyi V., Tsyhanenko L., Halushka S., Tsyhanenko H., Rohovyi S. Regulation of the stress-strain state of the structural plate of the covering. Conference proceedings of the 23-rd International Scientific Conference ENGINEERING FOR RURAL DEVELOPMENT, Jelgava, Latvia, May 22-24, 2024. pp.448-459

[9] Tsyhanenko L., Sribniak N., Tsyhanenko H., Lutskovskyi V. and Ordon-Beska B. Determining the optimal size of the basic element in a space grid structure.Construction of Optimized Energy Potential Budownictwo o Zoptymalizowanym Potencjale Energetycznym vol.12, no.1, 2023, pp.201-208

[10] Lakshmikandhan K. N., Senthil R., Jayachandran A. S., Sivakumar P. and Ravichandran R. Parametric Studies on the Behavior of Steel and Composite Space Structures. International Journal of Space Structures, vol. 25(3), 2009, pp. 169-183

[11] Chilton J. Space Grid Structures. Taylor & Francis Group, 2007. 180 p

[12] Ashtul S.A., Patil S.N. Review on Study of Space Frame Structure System. International Research Journal of Engineering and Technology, vol. 7(4), 2020, pp. 667-672

[13] DBN B.2.6-198:2014 design code "Steel structures". (In Ukrainian)

[14] DBN B.1.2-2:2006 design code "Loads and actions". (In Ukrainian)

[15] DSTU B V.1.2-3:2006 design requirements "Deflections and displacements". (In Ukrainian)