Vol. 12, 2023, 201-208

DOI: 10.17512/bozpe.2023.12.22

Construction of optimized energy potential
Budownictwo o zoptymalizowanym potencjale energetycznym

ISSN 2299-8535 e-ISSN 2544-963X

Determining the optimal size of the basic element in a space grid structure

Liudmyla Tsyhanenko[1] (*orcid id: 0000-0002-6628-3635*)
Nataliia Sribniak[1][*] (*orcid id: 0000-0003-3205-433X*)
Hennadii Tsyhanenko[1] (*orcid id: 0000-0002-3335-4804*)
Valerii Lutskovskyi[1] (*orcid id: 0000-0003-0230-1029*)
Beata Ordon-Beska[2] (*orcid id: 0000-0003-2236-6065*)
[1] Sumy National Agrarian University, Ukraine
[2] Czestochowa University of Technology, Poland

Abstract: The article explores the matter of optimizing a metal structural covering with a focus on mini-mizing material usage. Through static and structural design of the metal structural covering, it conducts a comparative evaluation of various approaches to identify the most efficient dimen-sions for both the structural framework and the overall height of the metal structure.

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

Please, quote this article as follows:

Tsyhanenko L., Sribniak N., Tsyhanenko H., Lutskovskyi V., Ordon-Beska B., Determining the optimal size of the basic element in a space grid structure, Construction of Optimized Energy Potential (CoOEP), Vol. 12, 2023, 201-208, DOI: 10.17512/bozpe.2023.12.22

Introduction

The modern architectural forms of large urban buildings raise a number of requirements for the solution of their structural features, in particular, covering structures that can combine load-bearing and enclosing functions. Spatial coatings make it possible to provide buildings with significant architectural expressiveness and functionality by covering large areas without the use of additional supports (Dragan & Morilova, 2010). Compared to reinforced concrete (Rabun, 2000), lightweight

---

[*] Corresponding author: nataliya.sribnyak.17@gmail.com

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. These structures include spatial structures, consisting of multiple repeated spatial elements in a pyramidal shape. Spatial structures are long-span structures that cover large areas without intermediate supports, with certain assumptions regarding the connection of structural elements and the way in which loads are applied to them (Baby et al., 2019). Long-span space structures can be made of double-layer space or multilayer grids, have a curved grid in the form of arches, domes, etc. (Ashtul & Patil, 2020). For covering large spans of buildings, double-layer space or multilayer grids are the most common due to their regularity, minimal variation in the cross-sectional dimensions of load-bearing elements, simplicity of nodal connections and ease of installation.

However, when designing these structures (Rabun & Kelso, 2003), a number of problems related to the structural solution arises, which further affects their stress-strain state (DBN B.2.6-198, 2014). Design solutions of such buildings are very often complex and require a specialized approach and technical solution (Barabash et al., 2012; Fu & Parke, 2018; Mashkov et al., 2023).

1. Initial conditions

The experience of designing spatial systems shows that one of the most important issues in their formation is primarily related to their economic efficiency. The choice of a metal structure design solution is an optimization issue, since the material consumption of a structure is one of the most important indicators of structural efficiency (Hicks et al., 2004).

Patel and Jamani conducted a study of the performance of long-span steel spatial structures in comparison with flat systems and showed that the weight of the structure is a determining factor in the final choice of a structural solution (Patel & Jamani, 2017).

Madi has investigated double-layer space grids with the help of a specific structure as an example (Madi, 1986). The author analyzed various configurations of the modular grid, the number of supports in the structure and their location. They noted that the location of the structure's supports and their number have a significant impact on the distribution of forces in the elements, their deflection and, consequently, the final dimensions of the element cross-sections. Importantly, supports can only be positioned under the nodes (junctions) connecting the structural components to prevent local bending of the elements. As a result, the author notes that by changing the placement of supports, this allows for a reduction in the forces acting on the elements and, consequently, a reduction in the weight of the entire structure.

At the same time, the main requirement is that the structure must meet the strength and stiffness criteria and at the same time have the lowest possible weight while meeting the above conditions (Bilyk, 2014; 2018; Bilyk et al., 2015).

However, recommendations for the design of these structures do not specify the recommended dimensions of the structural grid and its height, referring to the need to perform optimization design specifically for each case. Therefore, the purpose of this research is to obtain an effective type of structural grid in terms of minimum material consumption (Lakshmikandhan et al., 2010). The choice of an effective type is based on the principle of maximizing the use of material strength in load-bearing elements, i.e., the decision on optimality is determined by the criterion of reducing the weight of the structure.

2. Research methodology

One of the mathematical methods – the finite element method (FEM) was used to obtain the results of the numerical experiment. This method is used in structural mechanics for complex structural systems that are statically indeterminate. Modeling of the structural plate and a static analysis to determine the forces in the structural rods was performed in the Lira-CAD software complex.

3. Main research

The metal structure consists of multiple repeated spatial elements in the form of a pyramid, the shape, size, and location in space of which affects the stress-strain state of the structure as a whole and the optimality of its performance and material consumption. Therefore, to determine the optimal structural solution for a particular metal structure, it is necessary to perform comparative analyzes of several types of coatings.

The advantages of the architectural plan of structural constructions include a relatively low building height, reaching 1/15-1/50 of the span. Taking into account these limits, it is assumed that a structure with a minimum height of 0.5 m and a maximum height of 2 m is subject to calculation, respectively, the following heights were taken for the study: 0.5 m, 1 m, 1.5 m, 2 m with structural grid dimensions of 1.5 x 1.5 m and 2 x 2 m. The calculation was performed using the software package Lira-SAPR, and the results were processed using Excel. The analysis was carried out for a structural covering with a size of 27 x 20 m (Fig. 1).

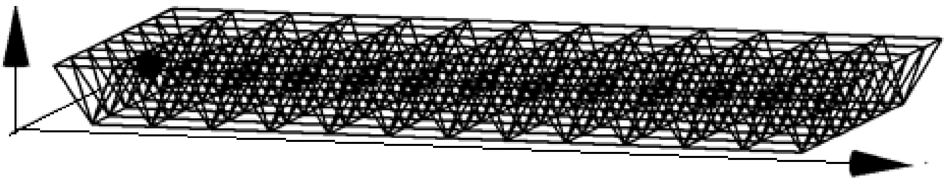

Fig. 1. Analysis scheme of metal structure in Lira-SAPR (*own research*)

The results obtained were analyzed by the deformation and stress state of the structural grid elements. The deformed covering scheme of the structure with a grid of 1.5 x 1.5 m, which has a height of 0.5 m, shows a symmetrical deflection with a maximum value in the middle of the span of the structure, the value of which is 35 cm, with this indicator exceeding the maximum possible [*f*] = 1/300 *L* = 9 cm.

The stress state analysis was conducted on the elements that experienced the maximum tensile and compressive forces. As the analysis reveals, these elements are part of the support zone of the covering. The maximum tensile forces are observed in the elements of the upper grid chord, amounting to +314.5 kN. The maximum compressive forces occur in the brace belonging to the first supporting grid and amount to –127.89 kN.

The analysis of the structure with a 1.5 x 1.5 m grid, which has a height of 1 m in terms of deformations, expectedly showed a symmetrical deflection with a maximum value in the middle of the span, but a smaller value of 9.82 cm. Consequently, the compressive and tensile forces decreased to +149.7 kN and –77.59 kN, respectively. However, the analysis of the structural grid measuring 1.5 x 1.5 m and having a height of 1.5 m in a stressed state revealed a change in the location of the maximum tensile force (Fig. 2).

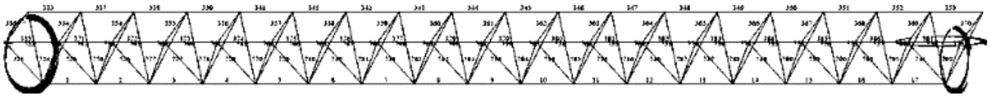

Fig. 2. Change in the location of maximum forces in the grid (*own research*)

The analysis of the structural grid with a 2 x 2 m grid and the following heights: 0.5 m, 1 m, 1.5 m, 2 m, showed that starting from a height of 1 m, there is a change in the location of the maximum force, which was not observed in the structure with a 1.5 x 1.5 m grid size. Elements with the maximum tensile force changed their position with the height of the grid, as shown in (Fig. 3).

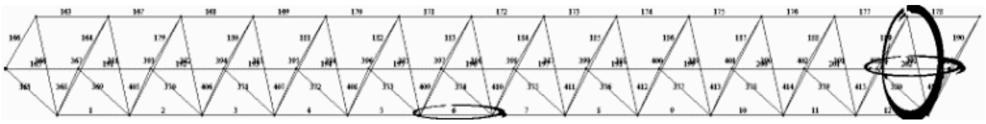

Fig. 3. Changing the location of the maximum force in the grid (*own research*)

Furthermore, the grid with a height of 0.5 m exhibited a deflection that exceeds the limit deflection value.

Table 1. Data on the structural grid 1.5 x 1.5 m (*own research*)

Node/element	0.5 m	1 m	1.5 m	2 m
node movement [cm]	35	9.82	5	2.1
max tension, supporting element of the upper chord [kN]	+314	+149	+90.6	+41
max tensile strength, support bracing			+100.6	+66
compression, support bracing [kN]	–128	–77.6	–59.2	–33.1

Table 2. Results for the 2 x 2 m structural grid (*own research*)

Node/element	0.5 m	1 m	1.5 m	2 m
node movement [cm]	24.1	6.6	3.26	2.1
max tension, supporting element of the upper chord [kN]	+172			
max tension, span element [kN]		+91.6	+66.4	
max tensile strength, support bracing				+59.1
compression, support bracing [kN]	–83.7	–48.8	–36.8	–30.6

A comparative analysis of the results obtained for both types of structural grids under study showed their differences in the stress-strain state. The structure with a grid of 1.5 x 1.5 m has larger deflections due to the greater dead weight of the structure (Table 1). In addition, at a height of 0.5 m and 1 m, the deflections exceed the limit values. Another situation is with a 2 x 2 m grid structure (Table 2). Comparing both graphs, we see that at a grid height of 2 m, the maximum deflections in both variants are almost equal, so further use of the increased height to find the optimal size is not necessary. The same results are obtained by comparing the diagrams of the distribution of compression and tension forces in the elements with the maximum value. Table 3 shows a comparison of the maximum tensile forces in the elements with the ultimate tensile force value.

Table 3. Tensile force in structural grid elements (*own research*)

Grid size 1.5 x 1.5 m				Grid size 2 x 2 m		
height	No. elements	N [kN]	N (limiting value) [kN]	No. elements	N [kN]	N (limiting value) [kN]
0.5	387	314.5	176	202	172.06	176
1		149.7			84.2	
1.5	721	90.68		6	53.047	
2		61.15			36.9	

Analyzing Table 3, it is seen that with a grid height of 0.5 m and a size of 1.5 x 1.5 m, the tensile force in the elements exceeds the limit value, so the grid with these dimensions is not operational. Figure 4 shows comparative deflection diagrams of structures with different grid sizes and heights and the maximum compression and tension force diagrams, respectively. Analyzing the graphs, it shows that at a grid height of 0.5 m and a grid size of 1.5 x 1.5 m, the value of the tensile strength exceeds its limit value, which excludes these dimensions from further calculations, and the values of the maximum compressive forces do not exceed the limit forces for each element separately, which indicates a safety margin for the elements working in compression.

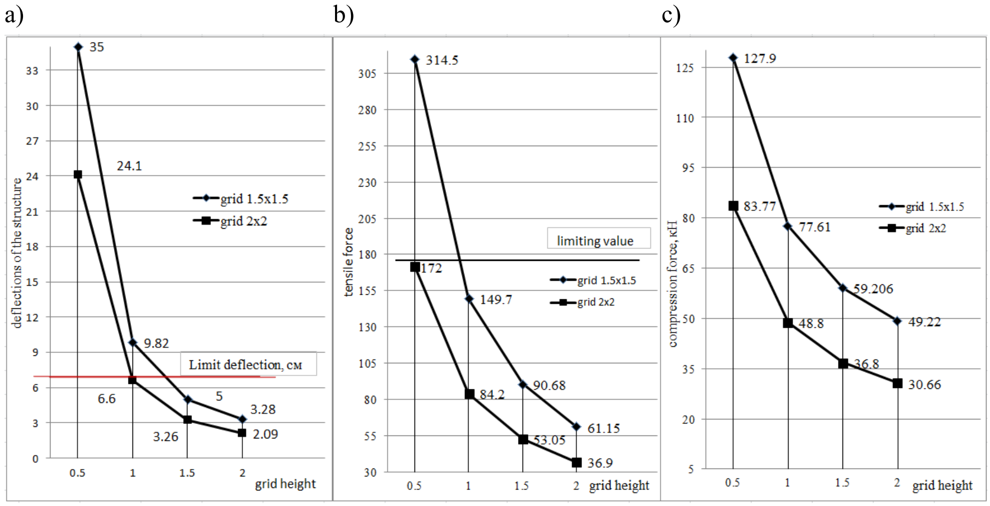

Fig. 4. Distribution of deflections and forces in structural grids: a) diagram of deflections, b) diagram of tensile forces, c) diagram of compressive forces (*own research*)

One of the crucial indicators that helps determine the most economical option for the structural grid is the material intensity indicator, which has an impact on the final cost of the structure and the labor required for its construction.

Here is a calculation of the weight of structural coverings according to the variants in order to determine the material consumption (Fig. 5).

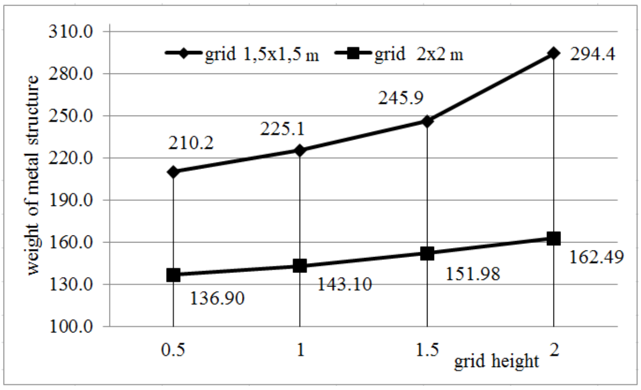

Fig. 5. Weight of structural coverings (*own research*)

Conclusions

Deformation comparison: the structure with a grid height of 1.5 m has larger deflections due to the greater self-weight of the structure. At grid heights of 0.5 m and 1 m, the deflections exceed the limit values. The situation is different for a structure with a 2 x 2 m grid. At a grid height of 2 m, the maximum deflections in both variants are practically equal, so further use of the increased height to find the optimal size is not necessary. In this case, when comparing the deflection graphs, the 2 x 2 m grid size with a height of 1.0 m is the most optimal.

Tensile force comparison: in the 1.5 x 1.5 m structural grid with a height of 0.5 m, the tensile force exceeds the limit value. In contrast, this is not the case for the 2 x 2 m structural grid.

The compression force comparison: it was determined that in all cases of calculation, the maximum compressive forces do not exceed the limit value. This indicates the safety margin of the elements working in compression.

Material intensity comparison: in terms of the total weight of the metal structure, the structure with a 2 x 2 m grid and a height of 1.0 m is considered the most optimal.

Bibliography

Ashtul, S.A. & Patil, S.N. (2020) Review on study of space frame structure system. *International Research Journal of Engineering and Technology*, 4(7), 667-672.

Baby, B., Lakshmi, B.S., Narayani, Ch., Salilan, D. & Mathews M. (2019) Space truss design using STADD. Pro Software. *International Research Journal of Engineering and Technology*, 4(6), 3777-3782.

Barabash, M., Kozlov, S. & Medvedenko, D. (2012) *Kompiuterni tekhnolohii proektuvannia metalevykh konstruktsii* (*Computer technologies for designing metal structures*). Kyiv, NAU.

Bilyk, A.S. (2014) Optymalnyi vybir konstruktsii z dyskretno zminnoiu skhemoiu navantazhennia (The optimal choice of design with a discrete change in the load scheme). *Zbirnyk naukovykh prats Ukrainskoho instytutu stalevykh konstruktsii im. V.M. Shymanovskoho*, 14, 70-78.

Bilyk, A.S. (2018) *Stal v rekonstruktsii budivel* (*Steel in building reconstruction*). Kyiv, TOV "Obnova kompani".

Bilyk, A.S., Ternovyi, M.I. & Khmelnytskyi, S.V. (2015) Alhorytmichna optymizatsiia karkasiv bahatopoverkhovykh budivel za kryteriiem metaloiemnosti (Algorithmic optimization of frames of multi-story buildings according to the criterion of metal capacity). *Zbirnyk naukovykh prats Ukrainskoho instytutu stalevykh konstruktsii im. V.M. Shymanovskoho*, 15, 103-111.

Dragan, V. & Morilova, H. (2010) Long-span metal structural structures of the BrGTU system. (Bolsheproletnie metallycheskye strukturmie konstruktsyy systemi «BrHTU»). *Zbirnyk naukovykh prats Ukrainskoho naukovo-doslidnoho ta proektnoho instytutu stalevykh konstruktsii im. V.M. Shymanovskoho*, 5, 72-82.

Fu, F. & Parke, G.A.R. (2018) Assessment of the progressive collapse resistance of double-layer grid space structures using implicit and explicit methods. *International Journal of Steel Structures*, 3(18), 831-842.

Hicks, S.J., Lawson, R.M., Rackham, J.W. & Fordham, P. (2004) *Comparative Structure Cost of Modern Commercial Buildings*. Berkshire, The Steel Construction Institute.

Lakshmikandhan, K.N., Senthil, R, Jayachandran, A.S., Sivakumar, P. & Ravichandran, R. (2010) Parametric studies on the behavior of steel and composite space structures. *International Journal of Space Structure*, 3(25), 169-183.

Madi, U.R. (1987) An investigation into the design parameters of double layer space frame grids. *International Journal of Space Structures*, 4(2), 215-222.

Mashkov, I., Skrebnieva, S., Baranetska, D. & Hlushanytsia, A. (2023) Analiz efektyvnosti roboty elementiv prostorovoho pokryttia (Analysis of the efficiency of the spatial covering elements). Teoriia ta praktyka dyzainu. *Arkhitektura ta budivnytstvo*, 1(27), 63-68.

Patel, B. & Jamani, A. (2017) Parametric study of different structural systems for long span industrial structures. *International Research Journal of Engineering and Technology*, 4(4), 2164-2167.

Rabun, J.S. (2000) *Structural Analysis of Historic Buildings: Restoration, Preservation and Adaptive Reuse Applications for Architects and Engineers*. New Jersey, Wiley & Sons.

Rabun, J.S. & Kelso, R. (2003) *Building Evaluation for Adaptive Reuse and Preservation*. New Jersey, Wiley & Sons.

DBN B.2.6-198:2014 *Steel structures*. *Design standards*.