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Research paper

Parametric shaping of steel hall structures with modular curved roofs – preliminary comparative analysis

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Abstract: Structures of halls with curved roofs are gaining popularity in modern industrial architecture due to their unique aesthetic and functional advantages. This study presents a comparative analysis of the efficiency of steel hall structures featuring frame systems and curved roofs composed of hyperbolic paraboloid (HP) modules. Utilizing Rhinoceros 3D software along with its generative modeling and structural analysis plug-ins, a script was developed to parametrically define the structural models and preliminarily determine geometries within a specified range of variable parameters. These parameters included column heights, total frame heights, frame widths, frame spacing, and the spacing of the roof bar grid. Parametric modeling enabled the generation of numerous variants of single-nave hall structures with five frame systems. All halls were designed with a rectangular plan measuring 12 × 24 meters and a maximum height of 8 meters. Subsequently, structural analysis was conducted using Autodesk Robot Structural Analysis Professional software, focusing on optimization in terms of mass and dimensioning. The analysis considered the feasibility of using sheet metal roofing as well as flat panels, which required adjustments of the roof bar grid topology. Variants were selected based on their efficiency and functionality. The procedure for shaping steel halls with curved roofs using genetic algorithms proved to be highly beneficial in the design process. The results of the analysis provide valuable guidelines for designing halls with HP module roofs. While the amount of structural material is a key factor in determining efficiency, technological aspects also play a significant role. Given the structural similarities, it is assumed that these aspects are consistent across all structures, making mass a useful parameter for comparison. Future research will expand to include other factors influencing structural efficiency.

Keywords: bar structures, genetic algorithms, hyperbolic paraboloid, modular structures, parametric shaping, steel halls

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1. Introduction

Steel halls are widely used due to their versatility in a range of applications. These include industrial, warehouse, commercial, sports and entertainment, swimming pool and other public utility halls. In each of these applications, construction requirements may vary, but the basic structural scheme of steel halls remains similar. They consist of frames of the main load-bearing system, gable wall frames, wall and roof bracing, and the supporting structure of the wall cladding and roof sheathing. Halls, like other steel-structured buildings, must meet the requirements for load-bearing capacity and serviceability specified by standards [1–3]. An important advantage of steel hall structures is the possibility of using standard steel products and typical connections, which translates into low construction weight and low construction costs. Moreover, analyses comparing steel structures with structures made of other materials indicate steel as the most economical and ecological solution, which can be easily recycled [3–5]. While steel structures offer numerous benefits, optimizing them during the design phase is crucial. This need for optimization is driven by increasing demands and the continual development of commercial steel structure projects. The main goal of optimization is to improve the structure's load-bearing capacity while reducing its self-weight, which in turn lowers material, production, and transportation costs [6–10]. As a result, optimizing steel structures remains a significant research focus, driven by advancements in manufacturing technologies, construction methods, and enhancements in structural material properties. Research into the most efficient structural systems under specific requirements and design assumptions began in the latter half of the 20th century and continues to progress [11–14]. Previous studies have detailed the optimization of hall buildings, including goals, trends over time, and current research limitations with recommendations for future work [6]. Some studies mainly concern the optimization of individual structural systems such as roof girders or load-bearing frames [15–17]. Nowadays, the process of structural optimization is much easier to achieve due to the possibility of using advanced computer software, increasingly extensive research on new solutions, and greater technological and execution capabilities [18, 19]. Designers and researchers can conduct various simulations of structural behavior under loads [20–24] at an early stage of design, as well as compare possible structural solutions and choose the most effective variants [25–32].

Geometry of any hall structure plays a crucial role in its efficiency. While numerous studies have examined the behavior of steel hall structures with flat or flat-slope roofs under load, there is little research on hall structures with curved roofs. These structures are becoming increasingly popular due to their economic, construction, and aesthetic benefits, particularly for public utility buildings. To enhance the visual appeal of halls, glass is often used as a material for walls and roofs. Consequently, metal-glass structures are extensively researched and analyzed, with the primary goal of optimizing these structures and preventing design errors [33, 34]. An alternative approach involves using glass-glass photovoltaic panels, which, like glass panels, require an appropriate topology and geometry for the structural system [35].

To enhance the attractiveness of hall facilities while maintaining their efficiency, modular roofs composed of curved surface modules can be utilized. Among the curvilinear surfaces that can be used to shape roofs, ruled surfaces, which are formed by rectilinear generators, deserve special attention. The method of shaping modular roofs formed from the segments of ruled surfaces has been presented in previous studies [36–38]. However, there are few solutions for the construction of steel halls with modular roofs composed of ruled surface segments.

Therefore, the subject of the research was to develop procedures for the effective shaping of hall structures with roofs consisting of such modules, especially hyperbolic paraboloid (HP) modules, while maintaining a frame structural system. In addition, the aim of the research was also a comparative analysis of the obtained optimization results in order to search for the most effective structures.

2. Materials and methods

The hall structures were shaped parametrically in Rhinoceros 3D using the Grasshopper visual programming plug-in [39]. Rhinoceros 3D allows for the creation of complex shapes and forms, which is commonly used in architecture, engineering, industry, and art. With additional plug-ins, it enables the use of an extended range of functions. One of the most popular plug-ins is Grasshopper, which is used for visual programming through components logically connected to each other. Modeling structures through visual programming enables quick modification of parameters and generation of multiple design variants. The geometry of the halls was shaped using five parallel frame systems. However, as the surface used to shape the roof modules, a hyperbolic paraboloid was selected due to its ability to be defined by straight lines [40]. Each rectilinear fragment of the frame girder was assumed to act as the directrix of a HP module. Conversely, the bars of the curvilinear roof modules were to be supported by the opposite elements of the girders, as well as the edge and ridge beams, Fig. 1.

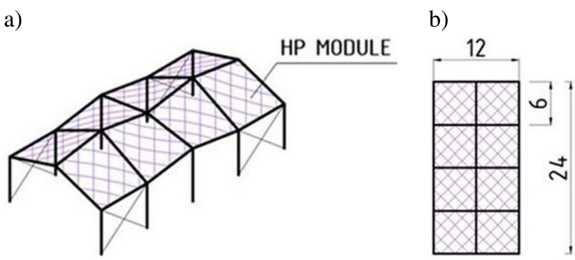

Fig. 1. Diagram of the frame layout of a hall structure with a curvilinear modular roof: (a) axonometric view, (b) top view

In order to enable comparison of the considered structures, each variant of the structure was designed on a rectangular plan with the same dimensions of 12×24 m and with the same total height of 8 m. However, the structures differed in the form and topology of the individual roof elements, Fig. 1. The research presented in this study was divided into three main stages. The first stage involved shaping the geometry of the hall structures in an optimized manner using Rhinoceros 3D with the Grasshopper plug-in for geometry shaping and Karamba 3D for structural analysis [41]. The second stage included static-strength calculations and the dimensioning of individual structural elements in Autodesk Robot Structural Analysis Professional for the specific geometric forms of the hall frame systems obtained through optimization using Karamba 3D. Finally, the third stage consisted of a comparative analysis of the optimization results and the selection of the most efficient structures.

3. Shaping of steel hall structures

3.1. Preliminary selection of structure geometries

In the Rhinoceros 3D software, a block script was created using a visual programming plug-in to describe geometry of steel hall structures in a parametric manner, Fig. 2.

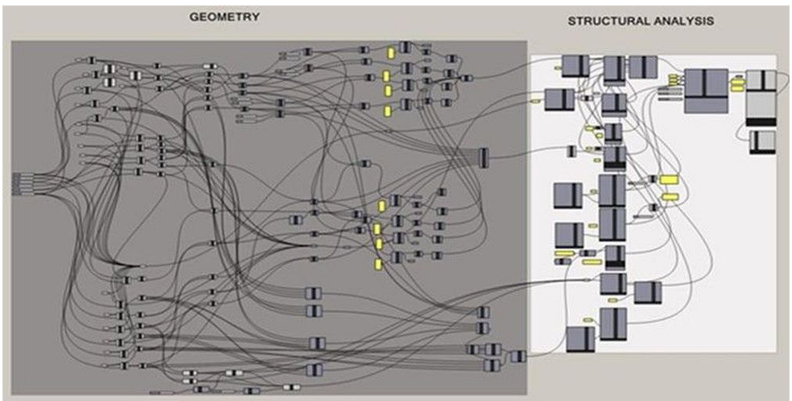

Fig. 2. A block script defining the structures

The geometry of the structure was defined using components connected to each other by wires enabling the flow of information between them. Each hall structure was composed of five portal frames, four ridge beams, eight edge beams, eight roof grid modules, and four pairs of wall bracing, Fig. 1.

The variable parameters used in the script were: the spacing of the structural frames, the total height of the frames, the span of the frames, the height of the columns and the division of the grid of bars shaping the curvilinear roof. After creating the geometric part of the script with Grasshopper, the script was extended using the Karamba 3D structural analysis plug-in. The support, load, material and connections of the structures were determined using appropriate components and then preliminary static calculations were performed using first-order linear analysis. S235 steel was used as the structural material, rectangular profiles of the structural elements were adopted, and rigid connections were used. The script's operation diagram is shown in Fig. 3.

In order to optimize the structure and select the most effective geometry, it was initially assumed that the structure of each hall consisted of five portal frames 12.0 m wide and spaced every 6.0 m. Furthermore, it was assumed that the total height of the frames varied within the

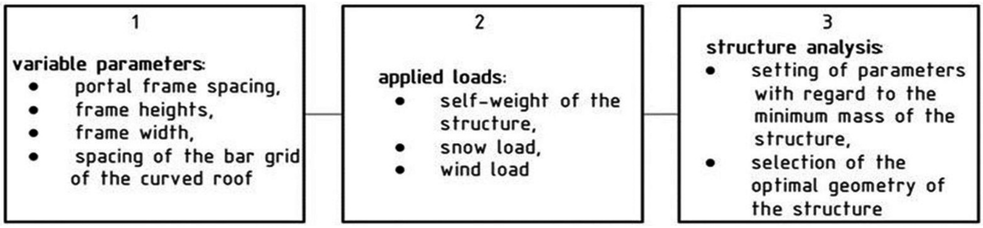

Fig. 3. Schematic diagram of the script for structure analysis using Karamba 3D

range of 7–8 m, while the height of the columns varied within the range of 5–6 m. Each roof module was divided by a grid of bars, assuming a division into 4 parts. It was assumed that the structure of each hall was symmetrical with respect to two vertical planes of symmetry. The analysis incorporated a permanent vertical load representing the structure's self-weight and the sheet metal roofing. In addition, a vertical snow load of 1.2 kN/m^2 with a roof shape coefficient of 0.8 was applied and a horizontal wind load acting alternatively from two perpendicular directions with wind velocity pressure equal to 0.30 kN/m^2. Using Karamba 3D, it was possible to integrate the definition of a parametric geometric hall model with finite element calculations and optimization algorithm, such as Galapagos, to explore various shapes. Therefore, several genetic optimizations were carried out for various load case scenarios using the Galapagos evolutionary solver, optimizing the cross-sections. The mass of each structure was minimized, additionally making some initial assumptions regarding the height of some frames or columns, as shown in Fig. 4(a), Fig. 5(a), Fig. 6(a), Fig. 7(a), Fig. 8(a), Fig. 9(a). These assumptions were necessary to avoid obtaining halls with flat roofs as a result of the simulation. Moreover, to reduce the time needed to perform each simulation, the design space was limited, i.e. only the total values of the column heights and ridge beam heights were taken into account. The simulation resulted in the geometry of the structure that has the lowest mass with the applied criteria. The results of the six most significant simulations are shown below. The black dots in the figures indicate the locations where the initial frame or column height (in meters) was assumed, while the red numbers indicate the heights (in meters) of the frames or columns generated during optimization. Fig. 4(b), Fig. 5(b), Fig. 6(b), Fig. 7(b), Fig. 8(b), Fig. 9(b) show axonometric views of the results.

a) b)

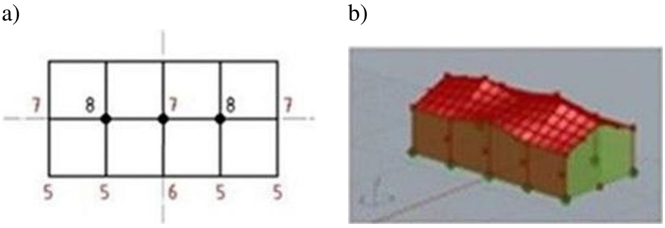

Fig. 4. Results of the first optimization: (a) obtained heights of frames and columns in meters presented (in red) on the plan of hall 1, (b) axonometric view of the hall 1

a) b)

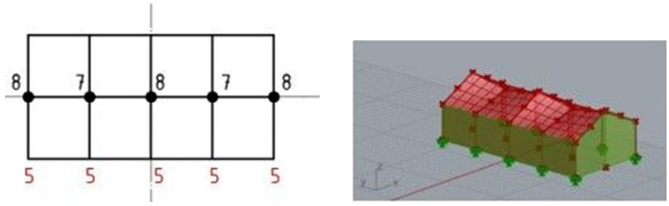

Fig. 5. Results of the second optimization: (a) obtained heights of frames and columns in meters presented (in red) on the plan of hall 2, (b) axonometric view of the hall 2

a) b)

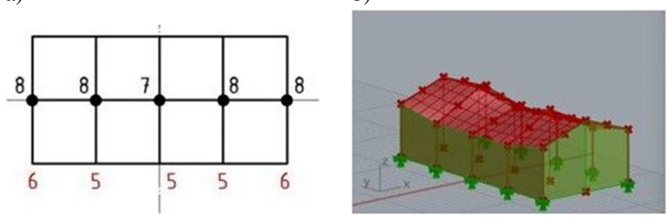

Fig. 6. Results of the third optimization: (a) obtained heights of frames and columns in meters presented (in red) on the plan of hall 3, (b) axonometric view of the hall 3

a) b)

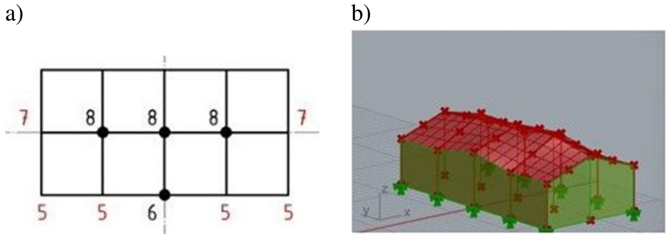

Fig. 7. Results of the third optimization: (a) obtained heights of frames and columns in meters presented (in red) on the plan of hall 4, (b) axonometric view of the hall 4

a) b)

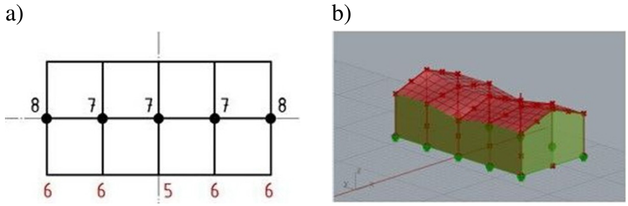

Fig. 8. Results of the second optimization: (a) obtained heights of frames and columns in meters presented (in red) on the plan of hall 5, (b) axonometric view of the hall 5

a) b)

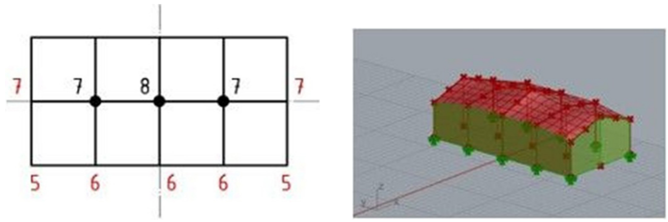

Fig. 9. Results of the second optimization: (a) obtained heights of frames and columns in meters presented (in red) on the plan of hall 6, (b) axonometric view of the hall 6

Geometries of hall structures obtained as a results of simulations were to be analyzed further. It is worth noting that the optimizations were performed for two different methods of dividing HP surfaces of roof modules, resulting in two distinct types of roof bar grids: type 1 and type 2, for each obtained frame system, Fig. 10.

a) b)

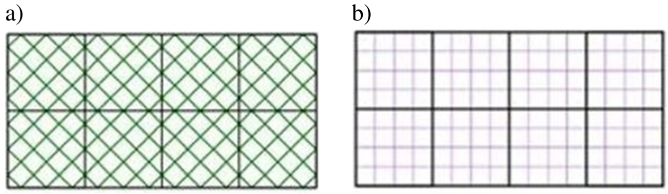

Fig. 10. Horizontal projections of roof structures with topology of: (a) type 1, (b) type 2

The type 1 bar grid had subdivisions that resulted in planar grid cells, while the type 2 bar grid was characterized by subdivisions that created non-planar grid cells.

It was assumed that each roof consisted of eight grid and prefabricated HP modules with welded joints. Whereas each module was composed of three assembly elements. The elements were connected to each other with bolts and next screwed to the frame girders, ridge beams and edge beams of the hall. However, during performed simulations these connections were assumed as rigid.

3.2. Accurate static calculation and optimization

Due to the fact that the static analysis carried out using Karamba 3D should be considered as simplified and approximate, the structural models obtained as a result of simulations performed in Karamba 3D, were next subjected to a detailed static and strength analysis in Autodesk Robot Structural Analysis Professional. Each structural model was previously supplemented with gable wall columns and horizontal wall beams that were supposed to support the hall's casing. The analyzed six variants of structural models with roof bar grids of type 1 are shown in Fig. 11, however, the analyzed roof variants with roof type 2 are presented in Fig. 12.

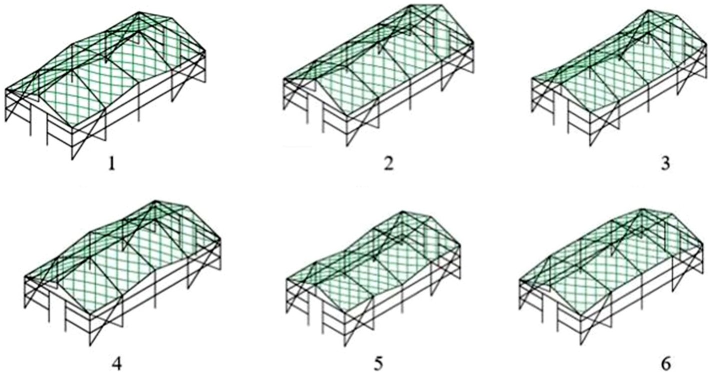

Fig. 11. Spatial hall models 1, 2, 3, 4, 5, and 6 with roof bar grid of type 1

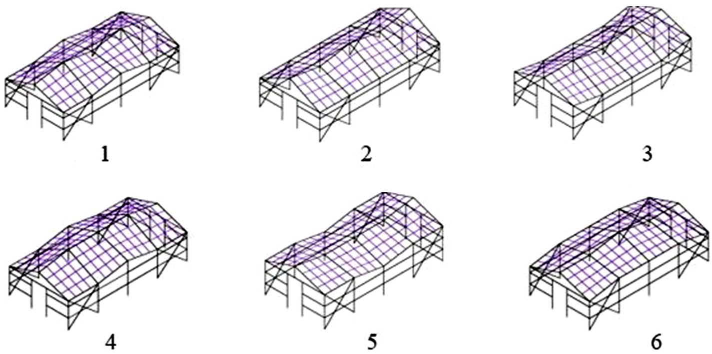

Fig. 12. Spatial hall models 1, 2, 3, 4, 5, and 6 with roof bar grid of type 2

According to the adopted assumptions, all the considered models of hall structures had the same dimensions in the horizontal projection, the same number and spacing of frames as well as the same total height. However, there were differences in the height of the columns and in the heights of the main load-bearing frames. Rigid connections were used, only the wall bracing was hinged. However, buckling length factors of the structural elements were determined equal to 2 for columns and equal to 1 for the rest of the structural members. To optimally dimension the structures and select the appropriate cross-sections, the groups of bars with similar structural functions were distinguished in each of the considered variants: longitudinal wall columns, main frame girders, roof module bar grids, gable wall columns, gable wall girders, ridge beams, edge beams, wall horizontal beams, and bracings. The next step was to introduce loads, such as in the previous analysis using Karamba 3D, i.e.: self-weight of the structure, including the weight of steel elements and the weight of the external hall casing – steel sheet (0.10 kN/m^2), and environmental loads as snow and wind one. The snow load equal to 1.20 kN/m^2 was assumed for the location of the city of Rzeszow, Poland, located in snow load zone III, taking into account both an uniform and non-uniform snow load distribution, as well as possibilities of the formation of snow pockets for some roofs, Fig. 13.

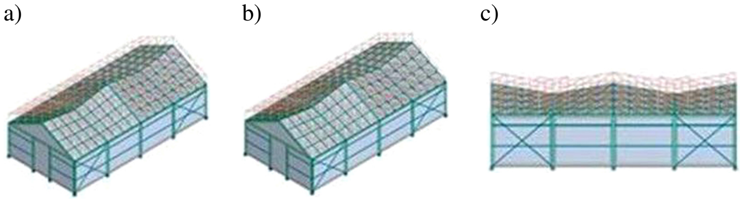

Fig. 13. Snow load cases: (a) uniformly distributed, (b) non-uniformly distributed, (c) formatting of snow pockets

Wind loads were generated automatically from three directions (due to the symmetries of the structures) for the location of the city of Rzeszow placed in the wind load zone I with base velocity pressure q_b equal to 0.30 kN/m^2, Fig. 14.

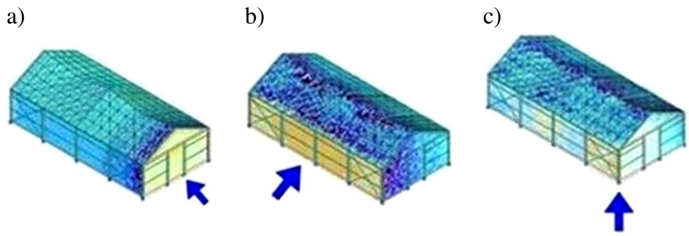

Fig. 14. Wind load generation from three directions: (a) perpendicular to the gable wall, (b) perpendicular to the side wall, (c) at a 45 degree angle to the gable and side wall

The structures were optimized and dimensioned for mass due to Ultimate Limit States (ULS) and Serviceability Limit States (SLS). The design process focused on obtaining the lowest possible total masses of the whole structures, while maximizing utilization of cross-sections. The optimizations were performed for twelve representative hall structure models (six models with roof type 1 and six with roof type 2. The first-order linear analysis was carried out assuming square and rectangular pipes as structural elements. The utilization of the bar cross-sections of the individual groups of bars was in the range of 80–90%. Thanks to it, the results obtained for the individual structures were comparable. The load-bearing capacity of the elements was also checked with respect to SLS. In no case the maximum deflections and displacements of the structural elements exceed the limit values, therefore the decisive criterion for dimensioning was ULS.

4. Results of the static-strength analysis and their evaluation

The structures with roof grid topology, both type 1 and type 2, were subjected to static calculations. As mentioned earlier, the type 1 bar grid had subdivisions that resulted in planar grid cells, while the type 2 bar grid was characterized by subdivisions that created non-planar grid cells. Some results of the structural analysis like total mass, values of the maximum deflections, values of the maximum normal stresses occurring in bars, maximum normal forces, and maximum bending moments are presented in Table 1 for the type 1 structures, Fig. 11, and in Table 2 for the type 2 structure, Fig. 12, respectively. However, due to the fact that the most important feature differentiating individual hall structures are their modular roofs, the comparative analysis and summary presented in Table 1 and Table 2 focused mainly on the internal forces and deformations of the grid modules obtained thanks to the calculations performed by Autodesk Robot Structural Analysis Professional (ARSA).

Table 1. Results of the structural analysis of the structures with roof bar grids of type 1, Fig. 11

Model number	**Total mass of the hall structure [kg]**	**Maximum deflection of roof bars (ridge/girder) [cm]**	**Maximum bar grid node dis-placement (ridge node) [cm]**	**Maximum normal stress in roof bars [MPa]**	**Maximum normal force in roof bars [kN]**	**Maximum bending moment in a roof module [kN · m]**	**Maximum bending moment in a bar grid [kN · m]**
1	12191	1.681	3.908	74.77	456.08	79.51	4.02
2	10401	1.607	4.652	70.14	324.05	27.33	3.73
3	12099	0.964	4.487	59.40	229.80	67.24	3.46
4	10839	1.505	4.146	81.09	216.52	33.21	3.94
5	11802	0.477	4.103	53.17	123.36	128.42	3.59
6	9820	1.666	4.683	34.24	73.97	52.46	3.15

Table 2. Results of the structural analysis of the structures with roof bar grids of type 2, Fig. 12

Model number	**Total mass of the hall structure [kg]**	**Maximum deflection of roof bars (ridge/girder) [cm]**	**Maximum bar grid node dis-placement (ridge node) [cm]**	**Maximum normal stress in roof bars [MPa]**	**Maximum normal force in roof bars [kN]**	**Maximum bending moment in a roof module [kN · m]**	**Maximum bending moment for a bar grid [kN · m]**
1	10558	1.310	4.225	17.39	57.51	98.16	6.07
2	10540	1.095	4.239	17.58	57.47	92.87	5.92
3	11865	0.901	4.080	17.96	60.85	98.62	4.62
4	10999	1.086	4.633	26.54	58.21	82.20	6.10
5	11779	1.340	4.518	15.82	58.23	105.99	6.57
6	13827	1.156	4.716	34.24	73.97	24.75	6.82

Based on the obtained results, the considered structures were compared and their efficiency was determined. Based on the data in Table 1 and Table 2, the normal forces in the bars of type 1 roofs are generally higher than those in type 2 roofs. While the values are similar within the type 2 group, they vary more in type 1 roof structures. The bending moments in the grid bars are small for both roof types, but they are smaller in type 1 roofs.

Small bending moments arise due to the characteristics of the hyperbolic paraboloid, which resemble those of minimal surfaces. For models 1–5 of both structure types 1 and 2, the ridge beams experienced the largest deflections and node displacements. However, in model 6, the girder beams showed the greatest deflections, while the ridge beams had the highest nodal displacements for both structure types 1 and 2, as illustrated in Fig. 15.

a) b)

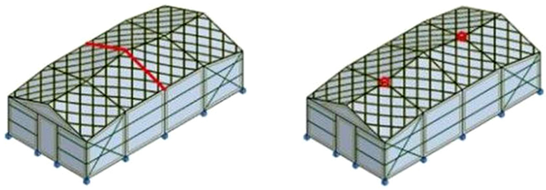

Fig. 15. Model 6 of type 1 with: (a) girders where the greatest deflections occur, (b) ridge nodes of the biggest displacements

In the group of hall structures with roof type 1 the model 6 is the most effective. It is characterized by the lowest total mass equal to 9820 kg, making it the most economical solution. It also has the lowest normal stresses in the group of the considered structures. However, analyzing the structures of both types 1 and 2, it can be stated that although model 6 for the type 1 bar grid topology has the lowest mass, for the type 2 topology it reaches the highest mass. The difference in mass for both types is as much as 4000 kg.

In the group of hall structures with roof of type 2, the most economical solution is model 2. This is the model with the lowest total mass equal to 10540 kg, and with low normal stresses. A comparable model to model 2 in the considered group is model 1 with a mass of 10558 kg. However, model 2 deserves special attention. Upon examining the data in Table 1 and Table 2, it is evident that model 2 is the most versatile option. This is because it maintains a comparable mass for both type 1 and type 2 topologies, with only a 140 kg difference. Consequently, the geometry of model 2 exhibits minimal sensitivity to variations in the roof bar grid topology regarding the structure's mass. However, significant differences are observed in the normal stresses in the roof bars for both topologies, as illustrated in Fig. 16.

a) b)

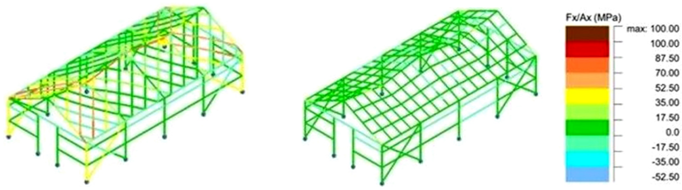

Fig. 16. Maps of normal stresses on bars for model 2; a) type 1, b) type 2

Additionally, there are notable differences in the bending moments for the roof bar grid, as shown in Fig. 17.

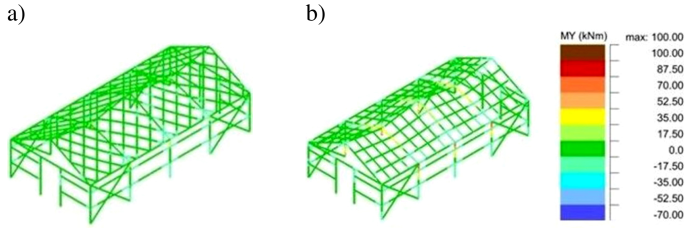

Fig. 17. Maps of bending moments on bars for model 2; a) type 1, b) type 2

It is important to highlight that model 2 features columns of uniform height, resulting in HP surface modules with a single horizontal edge. Additionally, the roof structure consists of a single type of module, which is also mirrored, enhancing the repeatability of the modules. Given that the type 1 roof structure can be covered with flat panels, calculations were performed assuming a load of glass panels. The results, as shown in Table 3, indicate that the internal forces and stresses in the bars remain largely unchanged, while the mass of the structure increases by over 300 kg.

Table 3. Results of the structural analysis of model 2 with roof type 2 covered by metal and glass

Type of covering material	**Total mass of the hall structure [kg]**	**Maximum deflection of roof bars [cm]**	**Maximum bar grid node dis-placements [cm]**	**Maximum normal stress in roof bars [MPa]**	**Maximum normal force in roof bars [kN]**	**Maximum bending moment in a roof module [kN · m]**
glass	10725	1.316	4.664	70.31	324.83	33.34
metal	10401	1.607	4.652	70.14	324.05	27.33

5. Conclusions

A new approach to shaping steel halls with modular curved roofs using genetic algorithms has been presented. This method involves developing a script that parametrically defines the structure's geometry and enables genetic optimization to minimize the structure's mass under a given load, selecting the optimal parameters for the structure's geometry. The key advantage of this approach is its multidisciplinary nature, considering not only aesthetics but also functional and economic criteria related to minimizing the amount of material used. A static analysis of 12 steel hall structures with modular roofs was carried out using ARSA software, while additional analyses were conducted using Rhinoceros 3D and Karamba 3D software. The analysis was detailed, focusing on different topologies of the roof bar grid and the effect of the geometry of the roof modules on internal forces. Comparative evaluation of multiple HP roof module configurations can guide the design of similar structures. Additionally, the research identified the most efficient structure, which proved to be the most resistant to topology changes. For this structure, the difference in mass for the entire hall structure when changing the topology of the roof bar grid was only 139 kg.

Moreover, the study demonstrated that genetic algorithms can be a valuable interactive engineering tool for designing efficient structures at an early stage. The authors note that while the amount of structural material is a key factor in efficiency, technological aspects also play a significant role. However, due to structural similarities, it is assumed that these aspects are consistent across all structures. Therefore, mass was used as a comparative parameter for the analyzed hall structures. Future research will expand to include other factors affecting structural efficiency, such as technological aspects related to the method of roofing installation.

Acknowledgements

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Parametryczne kształtowanie konstrukcji hal stalowych z modułowymi, krzywoliniowymi dachami – wstępna analiza porównawcza

Słowa kluczowe: algorytmy genetyczne, hale stalowe, konstrukcje modułowe, konstrukcje prętowe, paraboloida hiperboliczna, parametryczne kształtowanie

Streszczenie:

Konstrukcje hal z dachami o krzywoliniowych kształtach zyskują na popularności w nowoczesnej architekturze przemysłowej. Dachy te nie tylko nadają budynkom wyjątkowy wygląd, ale również mogą przynosić pewne korzyści funkcjonalne. Badania koncentrowały się na porównawczej analizie efektywności stalowych hal o ramowych układach konstrukcyjnych z dachami krzywoliniowymi, które składają się z modułów paraboloidy hiperbolicznej (HP). Przy zastosowaniu programu Rhinoceros 3D i jego nakładek do generatywnego modelowania i analizy konstrukcji opracowano skrypt definiujący modele konstrukcji w sposób parametryczny. Wstępnie określono obciążenia konstrukcji i przeprowadzono symulacje, aby w ustalonym zakresie zmiennych parametrów wyznaczyć optymalne geometrie konstrukcji przy zminimalizowanej masie. Jako zmienne parametry zastosowano wysokości poszczególnych słupów, wysokości całkowite ram portalowych, szerokości ram, ich rozstaw oraz rozstaw siatki prętów kształtujących dach. Parametryczne modelowanie geometrii pozwoliło na wygenerowanie wielu wariantów konstrukcji hal jednonawowych z pięcioma układami ramowymi oraz dwoma rodzajami siatek prętów kształtujących moduły dachowe. W celu przeprowadzenia analizy porównawczej założono, że wymiary wszystkich hal w rzucie prostokątnym wynoszą 12×24 m, a maksymalna wysokość 8 m. Kolejnym krokiem była dokładna analiza statyczna konstrukcji o wygenerowanej geometrii w programie Autodesk Robot Structural Analysis Professional; optymalizacja ze względu na masę oraz wymiarowanie. Konstrukcje przebadano pod kątem możliwości zastosowania pokrycia z blachy, jak również możliwości zastosowania płaskich paneli, co wiązało się ze zmianą topologii siatki prętów dachowych. Wybrano optymalne warianty pod względem efektywności i funkcjonalności. Przeprowadzone badania pokazały, że parametryczne kształtowanie hal stalowych może stanowić skuteczne narzędzie inżynierskie na wczesnym etapie projektowania. Natomiast wyniki przeprowadzonych analiz mogą stanowić pewne wytyczne do kształtowania hal z dachami złożonymi z modułów HP.

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