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Skeleton tensile structure as a single-family house project

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ABSTRACT:
In designing building structures, the most important stage is the selection of appropriate construction solutions, depending on the architectural design, purpose of the facility and the conditions in which the designed facility will be located. When choosing the type of materials from which single-family houses are erected, traditional solutions, such as concrete and brick building elements, are most often chosen. Traditional construction solutions for houses, however, do not always allow for the construction of buildings with sophisticated architecture or in particularly demanding places, e.g. in a seismic zone or in a mining area. In this case, skeletal steel structures can help, because when properly designed they are able to ensure safe operation in these areas. This paper presents an analysis of the use of a skeleton steel tensile structure in a single-family house design.

KEYWORDS:
steel structure; tensile structure; house project, designing

1. Introduction

Reinforced concrete is the most commonly chosen construction material in low-rise buildings due to its economy. In the case of high-rise buildings, due to the significant self-weight loads, greater stiffness and difficulties in setting up the formwork, it is no longer as economical as compared to steel structures. The use of steel structures has a much greater effect in seismic zones where forces are transferred to structures in direct proportion to the weight of the structure. Steel structures are characterized by a high strength to weight ratio and can undergo significant plastic deformation before failure. Steel structures have higher stiffness and ductility, and are also economically viable, and as such, are used for various structures such as skyscrapers, bridges, towers, industrial plants, buildings, etc. The weight of steel structures is much lower than that of reinforced concrete structures, which translates into a reduction in the cost of the foundation [1]. The selection of an appropriate foundation is crucial due to the safety of the facility's operation and must be designed in such a way that the ground does not exhibit any deformations as a result of transferring loads from the building, which makes it much easier for lighter structures [2].

At the material selection stage, the designer strives to reduce the weight of the elements as much as possible while maintaining the appropriate strength properties. One of the systems with such features is cold-rolled section structures [3]. Houses in steel structure are more and more often built of light, thin-walled load-bearing structures with various external and internal coating solutions that ensure appropriate technical requirements of partitions [4, 5]. In such structures, walls are the main structural elements, carrying horizontal loads such as wind and earthquakes [6, 7]. Properly designed connections in the steel structure transfer loads to individual elements of the structure very well [8]. The production of hot-rolled steel profiles has

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a negative impact on the environment, and cold-formed steel profiles are easier to manufacture and all kinds of sections can be designed, resulting in more effective designs [6]. Through the use of appropriate systems of reinforcement in diagonal walls made of steel thin-walled elements, these structures are perfect for seismic areas, as shown in the research presented in the article [9]. More and more often, modular steel structures are used for buildings used temporarily or in crisis situations, such as the COVID-19 pandemic [10]. Modular structures made of steel elements are characterized by good strength and rigidity of the structure while maintaining a low weight. Prefabrication of building elements on the production line significantly speeds up the execution of such objects, and ready-made buildings can be easily and quickly assembled on the construction site. The analysis of the conceptual design is presented in the article [10].

The cost of building a facility is a key factor when choosing between a steel or reinforced concrete building. Nowadays, customers always choose the cheapest option. The cost of a steel structure is lower than that of a reinforced concrete structure as it does not require formwork, the construction of the facility is much faster and the axial reactions and forces are ultimately lower, which generally reduces the cost of building steel structure buildings [1]. The following part of the article presents an analysis of the execution of a single-family house in a skeleton steel tension structure.

2. Calculation model of the design of a round single-family house in a steel frame structure

For the analysis, the design of a round, two-story single-family house was adopted. The shape of the house was based on a circle with a diameter of 12 m, the height of one story was 3.5 m, and the total height of the building was 9.5 m. The slope of the roof was assumed to be 25%, and the length of the protrusion was 1 m, so the outer diameter of the roof was 14 m. The load-bearing structure of the house was modeled in the steel structure, while the roof contained a wooden roof truss. The house plan was modeled in RFEM, the calculation model is presented in Figure 1. Two models were made, without tendons and with tendons – diagrams of the load-bearing structures are shown in Figure 3. The load-bearing structures are positioned every 60 degrees around the central column (the core of the building), and the top plan view of the building is shown in Figure 2. The models were loaded according to the Eurocodes [11-13] own weight, live load, snow and wind. Then, FEM calculations were performed and individual sections of steel load-bearing elements were dimensioned in accordance with the Eurocode [14] due to ULS and SLS. The analysis of the calculation results is presented in the next part of the article.

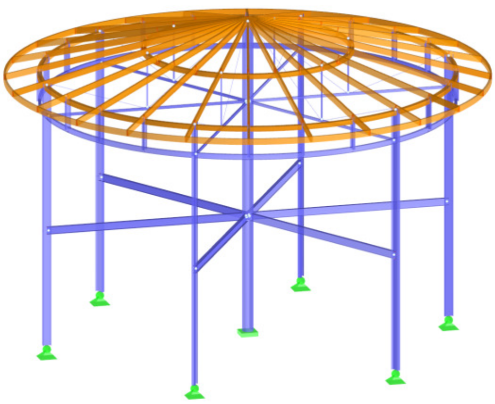

Fig. 1. 3D model of a circular building in the RFEM programme

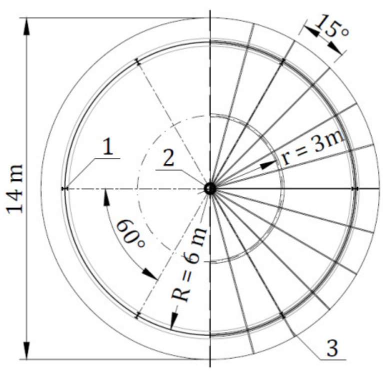

Fig. 2. Top view of the house: 1 – external columns; 2 – central column (building core); 3 – roof rafters

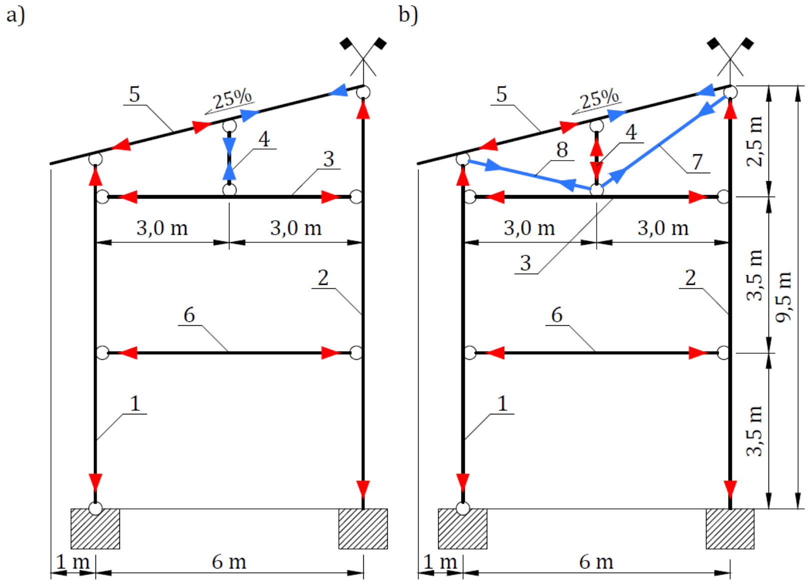

Fig. 3. Static diagrams of the analyzed load-bearing structure of the house design: a) scheme A: without additional tendons; b) scheme B: with additional tension tendons; 1 – external column; 2 – central column (building core); 3 – support beam; 4 – the column supporting the roof truss; 5 – roof rafter; 6 – ceiling beam; 7, 8 – tension tendons

3. Results

The FEM calculations were performed in RFEM. In the model, all steel profiles were adopted from S235 steel and after performing static calculations, optimization of individual sections was performed due to the ULS and SLS conditions, while maintaining the lowest possible weight of the structure for both variants. The obtained values of the maximum normal forces N are shown in Figure 3, and the values of the maximum bending forces M_y are presented in Figure 4.

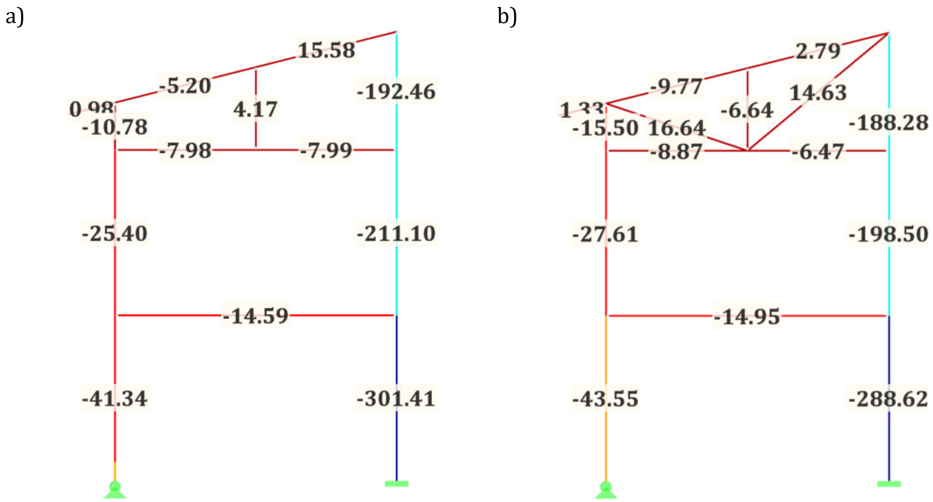

Fig. 3. Calculation results, values of maximum normal internal forces in kN in individual bars; a) scheme A: without additional tendons; b) scheme B: with additional tension tendons

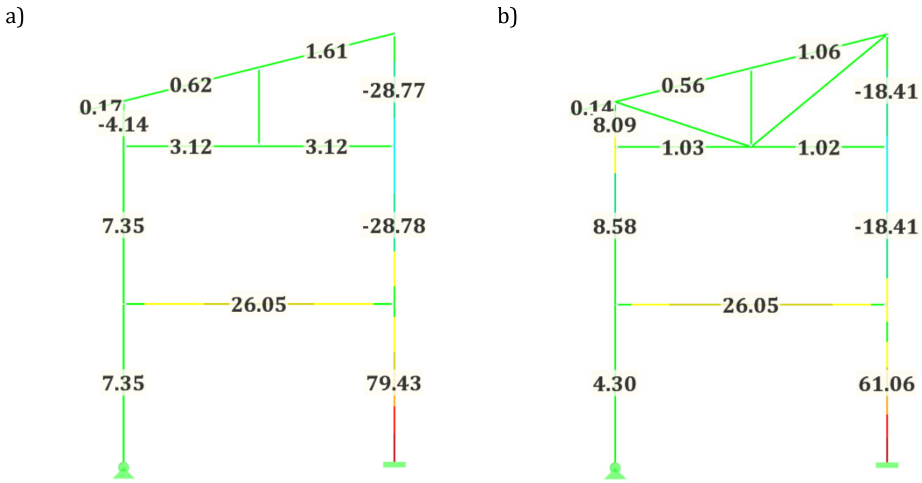

Fig. 4. Calculation results, values of the maximum bending moments M_y in kNm in individual bars: a) scheme A: without additional tendons; b) scheme B: with additional tension tendons

4. Discussion

Table 1 shows the cross-sections for the individual bars of the load-bearing structure of the house along with the obtained ULS load-bearing capacity conditions. Analyzing the results, it can be seen that for the load-bearing structure with additional tension members, the normal forces and bending forces are better redistributed throughout the structure, which in turn allows for the selection of appropriately smaller sections, and also ensures the safe operation of the object at lower production costs. The use of additional tendons (bars 7 and 8) reduces the bending moment transmitted to the support by the building core, which greatly facilitates the implementation of the foundation and also reduces costs. The bar (4) in diagram A is in tension, i.e. the wooden structure supports the transom (3), while in diagram B, the column (4) is compressed and transfers the loads from the roof truss, and then these loads are appropriately transferred by the tendons (7 and 8). Therefore, the bar (4) for scheme B has a greater stress than in scheme A. The weight of the steel structures themselves was 3.2 tons for structures without tendons and 3.0 tons for structures with tendons. Comparing the weight to reinforced concrete structures, the weight of the steel structure is several times lower while maintaining the same load capacity.

Table 1
ULS calculation results for sections for individual bars. The bar numbering was adopted according to the diagrams in Figure 2

Bar No.	Scheme A: without additional tendons		Scheme B: with additional tension tendons	
	Cross-section	ULS, %	Cross-section	ULS, %
1	IPE 220	65 ↑	IPE 220	63 ↓
2	RO 355.6x6 ↑	93 ↑	RO 323.9x6 ↓	81 ↓
3	IPE 100 ↑	65	IPE 80 ↓	78
4	RK 40x4	5 ↓	RK 40x4	15 ↑
5	70/180	79 ↑	70/180	69 ↓
6	IPE 220	98	IPE 220	98
7	–	–	Bar ϕ10	90
8	–	–	Bar ϕ10	79

5. Conclusions

The article presents an analysis of the design of a single-family house using a steel structure comparing two variants of load-bearing structures. When choosing the type of materials for a given object, the key factor influencing their choice is cost. The cost of steel structures compared to reinforced concrete structures is much lower, as the weight and labor intensity is much less. Steel structures do not require formwork, and individual elements can be made in the workshop. Analyzing various construction schemes, it can be noticed how important a role is played by the appropriate system for a given type of building. The use of additional tendons significantly improved the uniform redistribution of forces in individual bars, which allowed for the optimal selection of sections that meet the ULS and SLS conditions, while maintaining a low weight of the structure.

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Szkieletowa konstrukcja cięgnowa jako ustrój domu jednorodzinnego

STRESZCZENIE:
W projektowaniu obiektów budowlanych najważniejszym etapem jest dobór odpowiednich rozwiązań konstrukcyjnych w zależności od projektu architektonicznego, przeznaczenia obiektu oraz warunków, w jakich będzie się znajdował projektowany obiekt. W przypadku doboru rodzaju materiałów, z jakich są wznoszone domy jednorodzinne, najczęściej wybierane są tradycyjne rozwiązania, takich jak betonowe i murowane

elementy budynku. Tradycyjne rozwiązania konstrukcyjne domów jednak nie zawsze umożliwiają wykonanie obiektów o wyrafinowanej architekturze lub w miejscach szczególnie wymagających, np. na terenie znajdującym się w strefie sejsmicznym lub w obszarze górniczym. W takim przypadku z pomocą przychodzą szkieletowe konstrukcje stalowe, ponieważ, odpowiednio zaprojektowane, są w stanie zapewnić bezpieczną eksploatację na tych terenach. W pracy przedstawiono analizę zastosowania szkieletowej stalowej konstrukcji cięgnowej w projekcie domu jednorodzinnego.

SŁOWA KLUCZOWE:
konstrukcje stalowe; konstrukcje cięgnowe; projekt domu, projektowanie