Assessment of the Possibility of using the Tensegrity System in the Steel Tower Structure

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Abstract. *Tensegrity structures, due to their lightness and high stiffness, have been popular among architects and constructors for many years. When designing building and engineering structures, the most important stage of designing is the selection of the appropriate structural system depending on the purpose and location of the designed facility. When selecting the load-bearing structure, designers are guided by the smallest possible weight of the structure, while ensuring the safe operation of the facility, meeting all strength conditions. The article presents an analysis of the effectiveness of using the tensegrity structure for the load-bearing structure of a tower in a steel structure. The assessment of effectiveness was carried out taking into account the economy of execution and the fulfillment of the ultimate and serviceability limit conditions of individual elements of the structure for the load-bearing system of the tensegrity structure. Numerical calculations and cross-section dimensioning were performed using the finite element method in RFEM, modeling the structure in 3D.*

Keywords

Tensegrity structure, tension structure, RFEM.

1. Introduction

When designing engineering structures, the first and most important stage is the selection of the appropriate structural system, adapted to the intended use and method of operation of the structure. When choosing the right solution, the most important factor is the safety during use and the cost of construction. By inventing new solutions, we strive to design effective structures that ensure the best weight-to-stiffness ratio [1], [2]. For decades, the concept of tensegrity has been very popular among scientists and engineers from such disciplines as civil engineering and architecture, but also aviation, biology and robotics [3], [4]. The tensegrity system is a spatial structure composed of struts and ropes, and the stability of the structure ensures integrity between the stretched ropes and the compressed struts. The word *tensegrity* comes from a combination of words *tensile* and *integrity*. A recently adopted and widely accepted definition of a tensegrity system was proposed in 2003 which reads as follows: "*A tensegrity is a system in stable self-equilibrated state comprising a discontinuous set of compressed components inside a continuum of tensioned components"* [5]. A tensegrity structure is an articulated structure in which there are compression elements (bars or struts) inside a network of tensile elements (ropes, cables or tendons) [6], [7]. A characteristic feature of steel is high tensile strength, so it is worth using it in structures where the load-bearing capacity is ensured by tensile elements, and such in tensegrites are in the form of ropes or cables. Whereas such structures have a large amount of lightweight tension cables, such structures have a high strength-to-weight ratio while providing high stiffness.

Tensegrity structures, due to their lightness, ease of assembly and stiffness, have been interesting for civil engineering designers for many years. The use of the tensegrity structure in civil engineering can be found in many cases, e.g. in bridges, where in the article [8] the authors presented a footbridge and conducted parametric studies, comparing various configurations, and as a result, an innovative tensegrity bridge was developed and the effectiveness of such a system was confirmed, provided it is properly designed. In turn, the tower in Rostock, Germany, designed by Schlaich, Bergermann and Partners, was built in 2003 and is probably the highest tensegrity tower with a height of 62.3 m [9]. The designed and constructed tower consists of six "simplex" modules, each 8.3 m high, and a spire 12.5 m high [10]. Schlaich in the publication [9], describing the conceptual and structural design of the tower, came to the conclusion that despite the high flexibility, the potential of the tensegrity structure is very large. In turn, the articles [11], [12] and [13] present an analysis of the use of the tensegrity structure, which showed that such systems are not only characterized by lower mass, but also lower stresses in individual bars than those that occur in traditional structures, and the computational examples show the effectiveness of using such solutions in engineering structures.

2. Tensegrity geometry

When choosing the right geometry of the tensegrity structure, there are many methods of searching for the tensegrity configuration and I am still looking for new ones. Tensegrity is a spatial lattice in which an infinitesimal mechanism occurs, which is balanced by a self-equivalent system of forces, i.e. stabilized by a self-stress state. Tensegrity trusses are therefore statically indeterminate, and the process of searching for such a node system is called tensegrity form-finding [14]. There are dozens of described tensegrity structures [15], and the authors in the article [16] presented one of the methods of determining the self-stress of tensegrity structures. However, this article analyzes one of the best known simplex tensegrity modules. It is a module based on the figure of a normal prism. In terms of the number of bars, the simplest version is a prism with a triangular base - the so-called three-struts module. In order to minimize the lengths of the diagonals of the side walls as a result of the rotation of the upper triangle in relation to the lower triangle, it has been shown that the diagonal reaches its minimum length with a rotation angle of 150° [15]. Fig. 1 shows the geometry of the simplex tensegrity form.

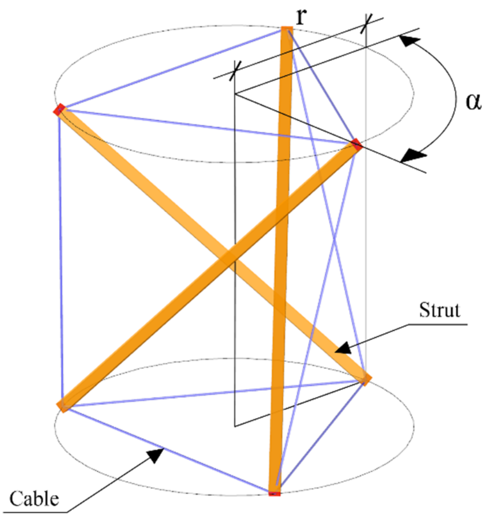

Fig. 1: The geometry of the tensegrity system - type simplex.

In engineering structures, multi-module structures, which consist of many modules of tensegrity structures, are much more applicable. There are two types of module connection:

- node-node connection,
- strut-tendon connection.

In the first of them, the modules are stacked on top of each other, connecting the nodes of the upper base of the lower module with the lower base of the upper module. This connection does not generate double knots or tendons, and the upper base of the lower module is the lower base of the upper module. To prevent the structure from twisting excessively in one direction under the influence of vertical action, successive modules can be alternately left-handed or right-handed. However, this structure loses the visual lightness associated with the presence of "airborne" struts. In addition, some tensegrity definitions say that there can only be one compression element at the nodes [15]. On the other hand, in the strut-tendon connection (Snelson tower), the lower nodes of the upper module hit the middle of the tendons of the lower module. In this case, the modules overlap and the nodes of the lower base of the upper module are not flush with the nodes of the upper base of the lower module. In this connection, additional ties are used that connect the lower base of the upper module to the upper base of the lower module. In such a solution, only one compressed bar reaches one node. Fig. 2 shows both types of tensegrity connections.

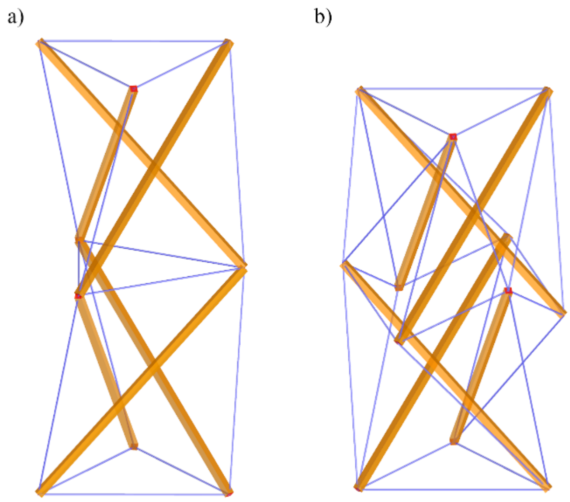

Fig. 2: Types of connection of tensegrity modules: a) node-node connection, b) strut-tendon connection.

The further part of the article presents the assessment of the possibility of using the tensegrity structure in the steel tower structure by performing the finite element analysis in the Dlubal RFEM program.

3. Computational model of tower structure in the tensegrity system

For the analysis, the construction of a tower consisting of simplex tensegrity modules was adopted, with the base described in the figure of a triangle, inscribed in a circle with a diameter of 3 m. The height of the tower was assumed to be 12 m, and the height of one module was assumed to be 3 m. The upper base of the module in relation to the lower base was turned by 150°. The tower consists of 5 modules overlapping each other by a distance of 1/4 of the module height. The tensegrity structure uses the opposite direction of twisting the base of the module compared to the previous one. The computational model with the geometry dimensions are shown in Fig. 3.

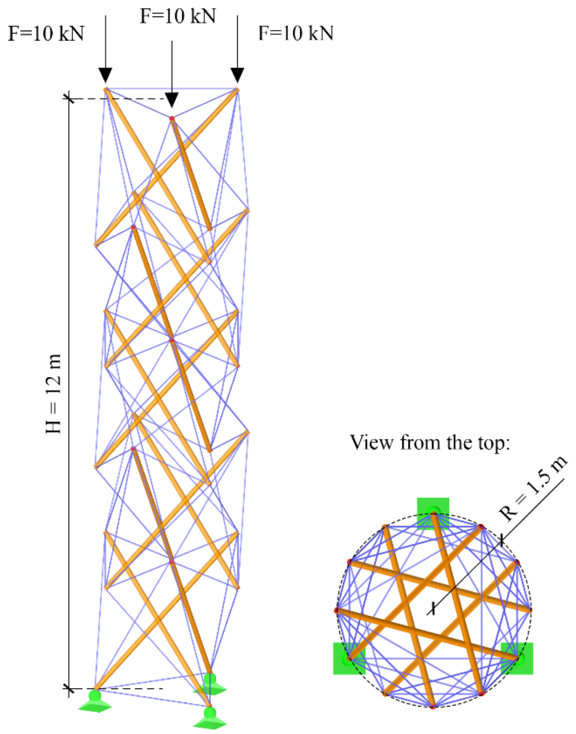

Fig. 3: Calculation model in Dlubal RFEM program.

The tower model was modeled in Dlubal RFEM, assuming steel grade S235 and modulus of elasticity 210 GPa for all structure elements. In order to compare the displacements of the upper nodes of the tower, three initial stresses of the tension tendons were assumed, with the values of 25 kN, 30 kN and 35 kN. At the highest nodes of the tower, an operational vertical load of 10 kN was assumed at each node, so the total vertical load on the tower is 30 kN. Additionally, the self-weight of the structure was taken into account, and horizontal loads due to the action of wind on the structure. Wind loads were collected on the basis of Eurocode 1 [17] assuming the location of the tower in Poland in the first wind zone, assuming the base wind speed $v_{b,o} = 22$ m/s, for a height above sea level A < 300 m. Wind loads were modeled as a continuous load horizontal on the bars. A round tube was assumed for the compressed bars (struts), while for the tension cables, a steel full bar was assumed, and the supports were assumed to be articulated.

In the next stage, calculations with the finite element method were performed and the optimization of individual elements of the structure was performed due to the fulfilled of the ultimate limit state conditions based on Eurocode 3 [18]. The resistance of the members in compression, taking into account the buckling, was calculated on the basis of the formula:

$$N_{b,Rd} = \frac{\chi \cdot A \cdot f_y}{\gamma_{M1}} \tag{1}$$

where χ is the reduction factor for the relevant buckling mode, A is the cross-sectional area of the member in compression in (mm^2), f_y is a yield strength in (N·mm^{-2}), γ_{M1} partial factor for resistance of members to instability assessed by member checks, which is equal to 1. When determining the buckling factor, the bar fixing factor was adopted $\mu = 1$, because the tensegrity rods are mounted articulated. On the other hand, the load capacity of the tensile elements was calculated on the basis of the formula:

$$N_{pl,Rd} = \frac{A \cdot f_y}{\gamma_{M0}} \tag{2}$$

where A is the cross-sectional area of a bar in tension in (mm^2), f_y is a yield strength in (N·mm^{-2}), γ_{M0} is a partial factor for resistance of cross-sections, which is equal to 1. One type of cables and one type of struts were adopted in order to differentiate the number of elements in one structure as little as possible. The further part of the article presents the analysis of the results of numerical calculations and cross-section optimization.

4. Results and discussion

As a result of the FEM analysis, optimization of the structure elements was performed by selecting the smallest possible cross-sections meeting ULS conditions for three cases of initial stress. Table 1 shows the maximum forces occurring in individual elements, the selected cross-section, the ultimate limit state, vertical displacement of the upper nodes and the total weight of the structure.

Tab.1: Results of numerical calculations of the analyzed tower for different prestressing forces.

Rod	*Length [mm]*	*Cross section*	**Initial compression – 25 kN**		**Initial compression – 30 kN**		**Initial compression – 35 kN**	
			Force [kN]	*ULS [%]*	*Force [kN]*	*ULS [%]*	*Force [kN]*	*ULS [%]*
Struts	4171	RP 76.1x5.0	**– 69.79**	95	**– 73.21**	99	**– 74.73**	101
Diagonal cables	3099	∅16	26.79	57	32.17	68	37.55	79
Shorter diagonal cables	2380	∅16	25.00	53	30.00	64	35.00	74
Cable internal base	1677	∅16	40.73	86	42.94	91	43.60	92
Cable external base	2598	∅16	33.75	71	40.50	86	47.65	101
Vertical displacement of the upper nodes			18.8 mm		16.7 mm		16.0 mm	
Horizontal displacement of the upper nodes			18.8 mm		17.0 mm		15.9 mm	
Total mass of construction			880.33 kg					

* the sign "-" means compression of the bar.

When analyzing the results presented in Table 1, it can be seen how important it is to properly optimize the prestressing force in the tension members of the tensegrity structure. Additionally, as part of the analysis, calculations were made for other values of prestressing forces, namely for 15 kN, 20 kN, 40 kN, etc. For forces below 25 kN, the system was unstable and showed significant displacements, while by increasing the force to more than 30 kN, the displacement decreased, but the ultimate limit state for individual members was not satisfied, therefore the cross-section should be increased, and therefore the eigen mass of the structure would increase. As a result of optimization in terms of the ultimate limit state of the load capacity, a round tube 76.1×5.0 mm was selected for the struts, and a solid bar with a diameter of 16 mm for the cable members. For the sections used while meeting the ultimate limit state conditions, the optimal prestress force in the tendons is the force of 30 kN, because the vertical displacement of the upper structure nodes was 16.7 mm, and the horizontal displacement of the upper structure nodes was 17.0 mm, i.e. less than for the force of 25 kN, for the same sections. By increasing the force to 35 kN, the vertical displacements decreased to 16.0 mm, and the horizontal displacement of the upper structure was 15.9 mm, while the ultimate limit state was exceeded in the struts and the intermediate and external cables.

Moreover, knowing the optimal prestressing force in the tensile cable of the structure, a comparative analysis was additionally carried out for a tower consisting of a different number of modules, i.e. for 3 and 4 modules, for the same loads and the same selected sections for individual elements of the tensegrity structure. The calculation results are presented in Table 2.

Tab.2: Results of numerical calculations of the analyzed tower consisting of a different number of modules of the tensegrity structure.

Rod	**Tower consisting of 3 modules overall height – 7.5 m**		**Tower consisting of 4 modules overall height – 9.75 m**		**Tower consisting of 5 modules overall height – 12 m**	
	Force [kN]	*ULS [%]*	*Force [kN]*	*ULS [%]*	*Force [kN]*	*ULS [%]*
Struts	**– 63.86**	87	**– 66.77**	91	**– 73.21**	99
Diagonal cables	32.01	68	32.14	68	32.17	68
Shorter diagonal cables	30.00	64	30.00	64	30.00	64
Cable internal base	37.24	79	38.11	81	42.94	91
Cable external base	30.00	64	30.00	64	40.50	86
Vertical displacement of the upper nodes	8.7 mm		13.2 mm		16.7 mm	
Horizontal displacement of the upper nodes	5.6 mm		7.9 mm		17.0 mm	

* the sign "-" means compression of the bar.

Analyzing the calculation results presented in Table 2, it can be seen that the forces occurring in individual bars slightly increase as the number of tower modules increases, because the increase of forces results from the increase only of the self-weight of the structure. The greatest forces are in the bottom module because it has to carry the weight of the modules above it. Horizontal and vertical displacements also increase with increasing number of tensegrity modules. The vertical displacements obviously result from an increase in the self-weight, but also from the sum of the displacements of individual modules, which in turn results in greater displacements for the tower, which consists of a greater number of tensegrity modules. The horizontal displacements increase due to the overall height of the structure, and thus due to the higher wind loads resulting from the difference in tower height and the number of structural elements that must transfer the wind actions.

When analyzing the results of forces and displacements, it can be seen that the use of tensegrity in the tower structure is an interesting alternative to standard solutions. In addition, it is worth noting that the analysis carried out in this paper shows that when designing, the tensegrity structure is an interesting and effective structural solution for a steel tower, which is worth paying attention to.

5. Conclusion

The article presents the tensegrity structure as an interesting solution in the mechanics of structures in engineering facilities. The uniqueness of such a system is determined by the self-stress state and the infinitesimal mechanisms that stiffen it. Due to the axial distribution of forces in individual elements of the structure, some of them can be replaced with light cables, which significantly contributes to reducing the weight of the structure. It is worth noting, however, that in the tensegrity structure there is a risk of failure of the entire structure as a result of damage or tearing of one of the elements, and this may lead to the destruction of the entire structure and is disadvantageous from the point of view of the reliability of the structure. However, as a result of the analysis carried out on the basis of the modeled, loaded and dimensioned tower model, it can be concluded that the tensegrity structure for the tower structure is an interesting solution that is worth considering when designing.

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