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A comparative criteria method for telecommunications towers with different topological designs

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1. Introduction

A space truss is a freestanding framework structure consisting of one or more triangular sections constructed with straight members. These members are connected in joints that are referred to as nodes. The trusses are divided into pure trusses, where the nodal loads and axial forces (tension or compression) are generated and complex systems, where the individual members are subjected to member loads and, in addition to axial forces, shear forces and bending moments appear.

There are several different topological designs for truss towers. The optimum design for square, freestanding, communication towers has already been discussed [1], but only one topological design has been investigated and no assessment other than one based on structural criteria has been made. For the purpose of a comparison, six different planar- truss topological designs were investigated, where the influence of various loads on the structure was observed. The towers were designed for telecommunications usage and carry antenna loads.

The towers include vertical and diagonal bars as well as filling bars, aimed particularly at reducing the diffraction length and in this way reducing the bars cross section. All towers have the same basic dimensions: the height of the tower, the width of the base and the width of the tower top. Their top-view cross section has a square shape (Fig. 1). The antennas are mounted on the top of each tower at all four vertexes. The towers are made from standard L shaped steel profiles of different dimensions, according to DIN 1028. The dimensions of the profiles depend on the stress condition of each member for a certain topological tower design.

The towers are subjected to different load combinations, which are also dependent on the wind zones and the geographical characteristics of the building site. These loads are the self- weight, the telecommunications antenna load, the ice load and the wind load. All the towers are dimensioned to withstand the appropriate load combinations. When applying the wind load it is necessary to pay attention to the correct load distribution [2, 3] because the wind speed is dependent on the tower's height.

For the purpose of optimizing of a steel space truss different criteria have been examined. However, the problem occurs when having to decide on the optimization criteria. The minimum volume of a structure [4], the minimum element size [5] and the stability [6] are commonly used criteria, although some questions have been related to different criteria [7, 8].

In this article we investigate different topological designs of steel lattice towers and evaluate them on the basis of four comparison criteria.

The first criterion is based on the limit states. Limit states represent the criteria of the load capacity of cross-sections and the values must not exceed the designed loads. This criterion is commonly used and described in European codes [9] as well as being discussed in various papers [10].

The second criterion is the serviceability of the telecommunications tower, which depends on the angular rotations of the antennas mounting spots, because their operation depends upon these angles.

The third criterion of the comparison is the structural mass. Therefore, the dimensions and the length of each member are important. Besides the technical criteria, the towers also have to be compared on the basis of an economic evaluation, which includes the production processes from materials costs to the final product. The economic evaluation is made from four types of assessment, i.e. materials costs, production, storage, transport and mounting costs.

2. Research

The construction material used for the frame towers is steel quality S355, according to SIST EN 10025-2. The material characteristics are yield strength of 355 MPa and tensile strength of 510 MPa. However, any material nonlinearity affects the behavior of slender structures. These material nonlinearities include gradual yielding associated with flexural, torsion and axial stresses, as reported by Nishino and Tall [11].

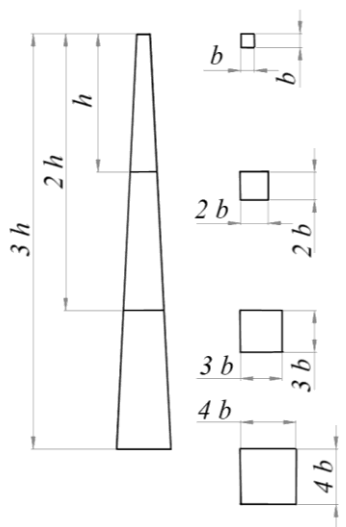


Fig. 1 Basic dimensions and stylization

The basic dimensions of the towers with different topological designs are the same (Fig. 1). The basic height of a tower is 30 m and the structural elements are designed to withstand the various load combinations. The width to height ratio of the towers is $b/h = 1/10$. If the lowest segment is removed, we have a tower of 20 m height, while the used structural members do not change. If both lower segments are removed, we have towers of 10 m height. At the top of the tower the width is 1 m; this is in order to ensure satisfactory antenna signal coverage.

The towers are affected by different loads, such as the dead weight of the structure, the useful load (the load of the telecommunications antennas), the ice load, the wind load and the various combinations of these loads. Two different useful loads have been investigated, i.e., antennas of 400 and 800 kg. A uniform ice thickness created by freezing rain on nonround structural elements must be taken into account [12]. The thickness of the ice envelope and the speed of wind depend on the environmental conditions of the building site. Two different ice thicknesses have been taken into account, i.e., ice envelope thicknesses of 18 and 30 mm. For the purposes of comparison, there are two possible wind zones: the zone with mean wind speeds up to 25 m/s and the zone with mean wind speeds up to 30 m/s. This is in accordance with the national annex for Slovenia [13]. These wind loads can occur in the head-on and diagonal directions and their impact can be increased as a result of the influence of the increased surface area due to the ice deposits.

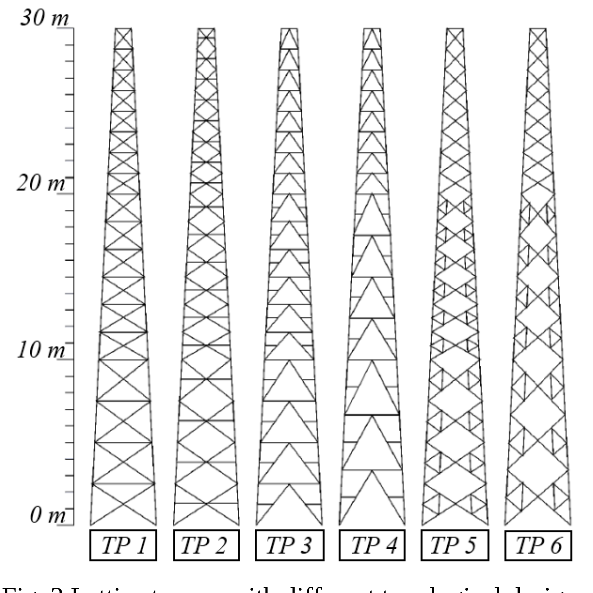


Fig. 2 Lattice towers with different topological designs

A total of 155 different types of antenna towers calculations were made. The stress calculations for the lattice towers were obtained from a linear elastic analysis, whereby the members are assumed to be axially loaded and, in the majority of cases, to have pinned connections. In comparison six different topological concepts were investigated (Fig. 2).

In the case of square towers two wind incidence angles that affect lattice structure and the telecommunications antennas are considered, i.e., 0 and 45° [14].

The towers with different topological designs were dimensioned according to strength and stability criteria in accordance with the valid European norms for designing steel structures [9, 15].

For reasons of clarity, each topological concept is labeled as TP X in Fig. 2, where X represents the sequential number of the design. The towers of the first two topological designs are made out of small numbers of structural beams that are relatively large scale. In the other topological designs there are a larger number of members. Filling beams are added to the designs in order to reduce the diffraction lengths. The effect of different diffraction lengths can be further observed as some of the tower designs differ in terms of the element lengths (case TP 3/TP 4 and TP 5/TP 6).

3. Loads

The loads are divided into four categories (Fig. 3): self-weight weight of the technological equipment, ice weight and wind loads. Many loads have an effect on each other, so the influence of the load also has to be considered. The result is nine different load cases for each steel lattice tower.

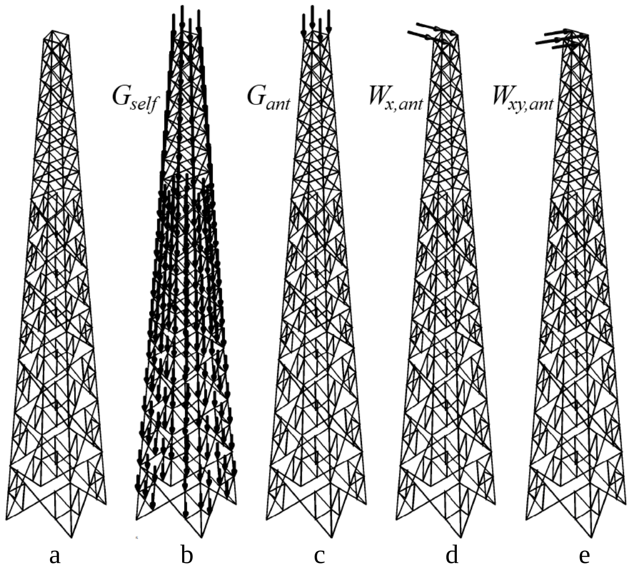


Fig. 3 Calculation model (a) and actions of the tower: self-weight (b), antenna self-weight load (c), wind antenna load (d, e)

Self-weight is the result of gravity's influences on the towers. It is applied to all the structural members (Fig. 3, b). This load is directly linked to one of the comparative criteria.

The useful load of a telecommunications tower is represented by the weight of the antennas that are mounted on the top of each tower (Fig. 3, c).

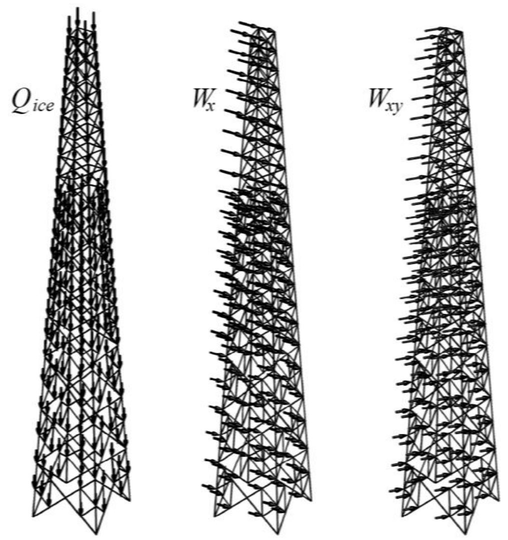
The influence of the wind on the antennas is considered to have an effect in two directions (Fig. 3, d and e). Wind speed is dependent on the terrain and its associated roughness length z_0. In our case we have an area with low vegetation and particular obstacles, such as trees and buildings, which gives us the terrain category II [16]. The influence of the terrain on the lattice structures (Table 1) is seen through the turbulence factor k_i, the terrain factor k_r as well as other influential factors and changes to the wind loads on the structures through the orography factor $c_0(z)$, the factor $c_e(z)$ and the change of the mean wind velocity $v_m(z)$.

Table 1

Terrain influence on the towers

$z_{0,\mathrm{II}}$, m	0.05	k_r	0.19
z_0, m	0.05	k_i	1
z_{min}, m	2.0	c_0	1

A consequence of the turbulence is that dynamic loading on a structure depends on the size of eddies that occur around the members. Slender structures (such as lattice towers in our case are) are sensitive to a dynamic response in line with the wind direction as a consequence of turbulence buffering. Therefore, the dynamical structural properties, characterised by natural frequencies, modal shapes, equivalent masses and logarithmic decrements of damping are important. The fundamental flexural frequencies of the towers are in the range from 1.70 to 1.85 Hz. When calculating the fundamental flexural mode for the towers the lattice tower factors have to be taken into account. The equivalent mass per unit length m_e depends on the tower design (Fig. 2); its value changes from 77 up to 194 kg/m. The logarithmic decrement of the damping δ depends on the logarithmic decrement of the structural damping, the logarithmic decrement of the aerodynamic damping for the fundamental mode and the logarithmic decrement of the damping due to special devices and its value depends on the height of the tower and the topological design.



a b c

Fig. 4 Ice (a) and wind (b, c) loads of towers

The peak pressure on the surfaces resulting from the wind forces does not appear simultaneously. Therefore, when calculating the wind force on the structure, the structural factor $c_s c_d$ should be taken into account. The wind force on the structure depends on the height of the tower. The wind force increment as a result of increasing tower height is clearly seen in Fig. 4, b and c.

$$F_{w,e} = c_s c_d \sum_{surfaces} w_e A_{ref}$$

Ice load is a consequence of freezing rain on the structural elements and is taken into account as an additional construction mass (Fig. 4, a). A uniform ice thickness is presumed for all the structural members [12]. The density of the ice envelope is determined as ρ = 7.0 kN/m^3. Ice load is determined as

$$F_{ice,vozl} = \frac{\sum \left(l_i \, n_i \, q_{i,ice} \right)}{n}$$

When applying the wind load the wind incidence has to be taken into account (Fig. 4). The actions associated with the ice should be considered in terms of their gravity effects and their effect on the wind actions. Therefore, when applying the wind load a magnified surface area due to ice deposits has to be considered.

When calculating the towers the equivalent static method [15] can be used if the stated criterion is satisfied. If not, more complex methods, such as the spectral analysis method, should be used.

$$\frac{7 m_t}{\rho_s c_{fT} A_T \sqrt{d_B \, \tau_0}} \left(\frac{5}{6} - \frac{h_T}{h} \right) < 1$$

At the same time a combination of loads affects the structures. Altogether, there are nine different load cases (Table 2):

1) structural self-weight,
2) useful weight (presents the antenna load),
3) ice load,
4) front wind,
5) diagonal wind,
6) front wind taking account the increased surface area due to the ice deposits,
7) diagonal wind taking account the increased surface area due to the ice deposits,
8) effect of front wind on the antennas,
9) effect of diagonal wind on the antennas.

Table 2

Load combinations matrix with influential factors

Limit state	No.	G_{self}	G_{ant}	Q_{ice}	W_x	W_{xy}	$W_{x,ice}$	$W_{xy,ice}$	$W_{x,ant}$	$W_{xy,ant}$
ULS	1	1.10	1.10		1.40				1.40	
ULS	2	1.10	1.10			1.40				1.40
ULS	3	1.10	1.10	1.40			0.35		0.35	
ULS	4	1.10	1.10	1.40				0.35		0.35
ULS	5	1.10	1.10	0.70			0.70		0.70	
ULS	6	1.10	1.10	0.70				0.70		0.70
SLS	7	1.00	1.00		1.00				1.00	
SLS	8	1.00	1.00			1.00				1.00
SLS	9	1.00	1.00	1.00			0.25		0.25	
SLS	10	1.00	1.00	1.00				0.25		0.25
SLS	11	1.00	1.00	0.50			0.50		0.50	
SLS	12	1.00	1.00	0.50				0.50		0.50

The load case combinations are divided into the ultimate limit states (ULS) and the serviceability limit states (SLS). Every combination is determined as a concurrent effect of the loads with the compliance of influential factors [9], as described in Table 2.

Before the calculation of the towers is carried out the reliability level of the structures has to be determined. Different levels of reliability are adopted for the ULS verifications of the towers, depending on the possible economic and social consequence on their collapse. Therefore, a consequences class (CC) and a reliability class (RC) have to be determined.

Telecommunications towers have a medium consequence on economic and social life as they have a role in the information flow in modern societies. All the structures being calculated are in CC of CC2. The RC class of a structure is determined using the reliability index β, which is associated with CC; therefore the reliability class is RC2. This results in a partial factor for the permanent actions $\gamma_G = 1.1$ and partial factor for the variable actions $\gamma_Q = 1.4$. The reduction factor of wind pressure $k = 0.5$ (ice class G3) has to be accounted for when a combination of ice and wind loads is applied to the structure.

4. Comparison criteria

The comparison of the steel lattice towers with different topological designs was carried out on the basis of various criteria such as:

1) the criteria of ultimate limit states,
2) the criteria of applicability,
3) the mass criteria,
4) the economic criteria.

The ULS criteria present the criteria of the load capacity of the cross-sections. It is necessary to satisfy the condition of the axial, shear and bending load capacities and any possible combinations of these internal forces. The designed load capacity depends on the compactness class of the cross-section (in our case all the cross-sections are of 3rd class). The condition of Von Mises yield criterion must be satisfied

$$\left(\frac{\sigma_{x,Ed}}{f_y/\gamma_{M0}}\right)^2+\left(\frac{\sigma_{z,Ed}}{f_y/\gamma_{M0}}\right)^2+\left(\frac{\sigma_{x,Ed}}{f_y/\gamma_{M0}}\right)^2\times$$
$$\times\left(\frac{\sigma_{z,Ed}}{f_y/\gamma_{M0}}\right)^2+3\left(\frac{\tau_{Ed}}{f_y/\gamma_{M0}}\right)^2\le 1.0$$

Some structural members are affected by a combination load of compression with bending internal forces and have to satisfy the following criteria

$$\frac{N_{Ed}}{\frac{\chi_y N_{Rk}}{\gamma_{M1}}}+k_{yy}\frac{M_{y,Ed}+\Delta M_{y,Ed}}{\chi_{LT}\frac{M_{y,Rk}}{\gamma_{M1}}}+k_{yz}\frac{M_{z,Ed}+\Delta M_{z,Ed}}{\frac{M_{z,Rk}}{\gamma_{M1}}}\le 1.0$$

$$\frac{N_{Ed}}{\frac{\chi_z N_{Rk}}{\gamma_{M1}}}+k_{zy}\frac{M_{y,Ed}+\Delta M_{y,Ed}}{\chi_{LT}\frac{M_{y,Rk}}{\gamma_{M1}}}+k_{zz}\frac{M_{z,Ed}+\Delta M_{z,Ed}}{\frac{M_{z,Rk}}{\gamma_{M1}}}\le 1.0$$

The SLS are defined by the functional performance under designed loads where no plastic deformation occurs and they are a matter of structural application. The proper function of the antenna services of a telecommunications tower is affected by the rotation angle of the attached telecommunications antennas (the signal quality depends on these angles). Telecommunications technology advances, so it is advantageous to have versatile and adaptable towers. The minimization of the rotation angle provides an opportunity to adapt the tower to expansion and adaptation to different kinds of antennas. The rotations are checked at each point of the antenna mount and they occur in two directions, φ_x and φ_y. The angles of rotation are compared with each other:

$$\varphi_x;\quad \varphi_y;\quad \varphi=\sqrt{\varphi_x^2+\varphi_y^2}$$

The construction mass is important for any tower comparison because it effects the construction pricing as well as the transport and storage costs. As a result, we strive to minimize the construction mass. The mass of each tower is obtained by summing the mass of each structural member. The towers are divided into segments of different heights and the members are divided into vertical, diagonal and filling beams

$$m_{sum}=\sum_{i=1}^{n} m_{segm,i}=\sum_{i=1}^{n}\sum_{j=1}^{m} m_{el,j,i}=\sum_{i=1}^{n}\sum_{j=1}^{m}\left(l_{el,j,i}\ q_{L,el,j,i}\right)$$

The economic comparison of the towers is a criterion based on different costs. The cost of the material is directly linked with the construction mass. The cost of production depends on the topological complexity and the dimensions of the tower. Next are the cost of storage and transport. This criterion depends on the size of each tower segment as well as its geographical and orthographical location. In this case it has been assumed that no helicopter transport is required as this greatly increases the costs. The transportation is only by trucks and the transport distance is, in all cases, the same. Finally, the telecommunications tower has to be assembled and placed on the mounting location.

$$C=C_{mat}\left(\text{material}\right)+C_{prod}\left(\text{production}\right)+$$
$$+C_{st\&tr}\left(\text{storage/transport}\right)+C_{asm}\left(\text{assembly}\right)$$

It is assumed that that all the members of the antenna towers are made of the same material. The criterion of the material price therefore depends only on the construction mass. Some 10% of the used material represents production waste.The manufacturing costs are dependent on the complexity of the production processes and on the number of manufactured members and include the costs related to trimming, CN and CNC treatments and the procedures for weather protection (galvanizing and painting). The same production processes are used for all the towers. Therefore, the parameter of manufacturing costs is determined on the basis of the members and their characteristics.

The raw material has to be in storage prior to the production and after the various processes the members have to wait for transportation to the building site. The necessary complexity of the storage facility system is dependent on the number of different members, the length and the mass. The transport is dependent on the mass and the load dimensions (as well as the transport distance). The towers have appropriate dimensions for transport (it is not necessary to use large-scale transportation vehicles).

The antenna towers need to be assembled and placed on the placement location. It is necessary to pay attention to the tower's foundation in order to achieve the required construction conditions. The assembly cost is dependent on the time and the complexity. The assembly in the production facilities and at the building site is calculated separately. Some parts need additional machining before assembly.

5. Comparison based on criteria

The results of the comparison of the load combinations on the structures are presented in graphical form. The impact on the criteria for every topological design is clearly seen. During every comparison the results from different heights (10, 20 and 30 m) can be observed.

If the value of the limit states is less than 1.00, the towers are over dimensioned, which is favorable. This gives us the chance to mount additional telecommunications antennas on top of the towers (of course, in this case, the criterion has to be checked again). Another affect of smaller values is the opportunity to replace some of the structural members with beams of smaller cross-section. This positively influences the construction mass and the economic criteria, but has a negative influence on the angles of rotation (SLS). For the comparison, typical towers and constructions are dimensioned for a height of 30 m. However, when lowering the height used profiles of the construction elements do not change.

In the ULS comparison graph in Fig. 5 (the criteria of load cross-sectional capacity) it is clear that the towers with different topological concepts have a common property, i.e., when lowering the height of the tower the ULS values are reduced. The tower design TP 1 reaches the highest values at all heights. The TP 3 towers also achieve high values; therefore, both designs are not good for mounting additional antennas at a lower height. However, the designs TP 5 and TP 6 achieve the smallest values of the limit state for the lower heights.

A close look at the graph in Fig. 5 reveals a saw-shaped appearance for each topological design. This is mainly a consequence of the two different wind loads applied to the towers. It is clear that different wind speed has little impact on the tower TP 3 and a great influence on the tower TP 4.

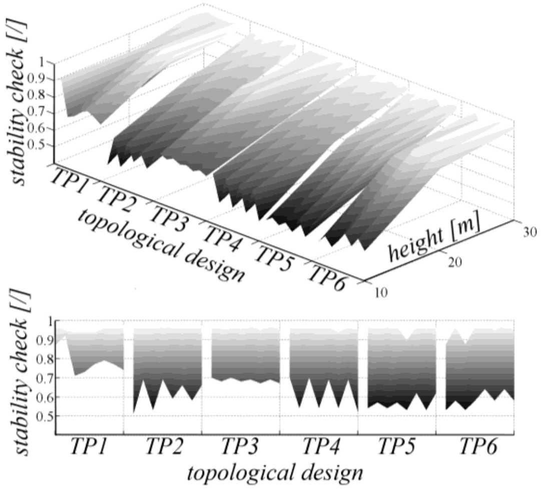


Fig. 5 Comparison of stability check during ULS

When comparing the tower designs to the ultimate limit states criteria we seek to maximize the reduction, because it affects the usefulness of the structure. In Table 3 the average reduction of the criteria (when compared to the values at 30 m) is seen as a percentage. The towers of different topological designs do not experience similar reductions when lowering the maximum height. Thus, for a height of 20 m a reduction occurs in the range between 4 and 16%, for a height of 10 m, this difference is even more pronounced, the reduction in the area ranges between 17 and 41%. It turns out that the TP 1 tower design has the smallest drop of criteria (unfavorable); meanwhile, the TP 5 tower achieve the biggest drop of criteria (favorable) and, therefore, they can be adapted.

Table 3

Lowering of the limit states criteria with a reduction in the height of the tower

Ultimate limit states criterion		Topological design					
		TP 1	**TP 2**	**TP 3**	**TP 4**	**TP 5**	**TP 6**
30 m height	average value	0.958	0.974	0.969	0.964	0.965	0.948
20 m height	average decline, %	7.0	14.504	10.4	13.9	16.3	4.4
	average value	0.891	0.833	0.866	0.830	0.808	0.905
10 m height	average decline, %	17.4	37.0	29.0	36.2	41.4	38.6
	average value	0.791	0.614	0.684	0.615	0.565	0.583

The angle of rotation of the antenna was observed. It mainly depends on the wind's effect on the structure, which impacts in different directions. The wind velocity is dependent on the height of the tower and therefore with lower towers there is an impact of lower wind velocity. A comparison based on the criteria of angular rotation is shown in the graph in Fig. 6. In the case of the rotations of telecommunications towers at the antenna mounts, this presents the serviceability of the structure. When reducing the height of the tower the rotation angles also decrease a great deal. It is clear that the TP 2 towers reach the highest values of rotation for all heights. On the other hand, the tower designs TP 4 and TP 6 have small angular rotations.

When constructing a tower, control of the SLS values is necessary. In our case the telecommunications antennas have a maximum allowed rotation φ_{max} = 0.75° at a maximum wind speed of v_{max} = 120 km/h to ensure sufficient data transmission.

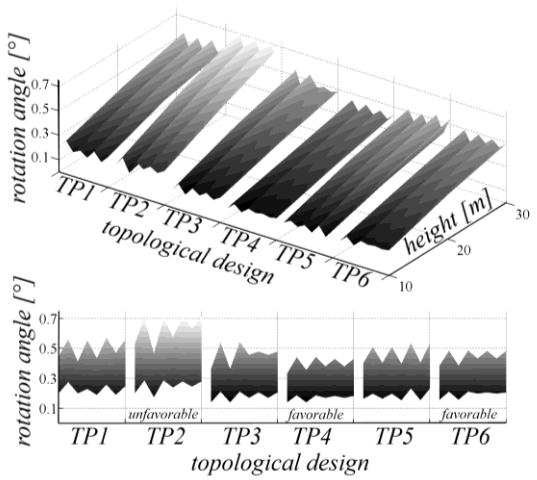


Fig. 6 Comparison of angular rotations

During a comparison of the towers in terms of the size of the angle of rotation, it is favorable to achieve minimal rotation angles in order to ensure better signal dispersion from the antenna. Towers with different topological designs achieve similar reductions of angular rotation when lowering the height from 30 m (Table 4). Thus, at a height of 20 m a drop of 25% (± 3%) occurs, and at a height of 10 m the size of the drop is 59% (± 3%). But there is a difference in the values of the angles of rotation when comparing topological designs. The TP 4 towers stand out because they achieve small angles of rotation (which is favorable for the operation of telecommunications antennas) while the TP 2 towers reach the highest values of rotation (unfavorable). In all the tower designs, the size of the angular rotation is reduced by lowering the height of the towers.

Table 4

Lowering the angular rotation by lowering the height of the tower

Angular rotation		Topological design					
		TP 1	**TP 2**	**TP 3**	**TP 4**	**TP 5**	**TP 6**
30 m height	average value, °	0.507	0.638	0.465	0.402	0.468	0.450
20 m height	average decline, %	23.7	28.4	27.8	27.0	25.0	25.4
	average value, °	0.387	0.458	0.336	0.294	0.352	0.336
10 m height	average decline, %	56.1	61.4	61.3	58.2	60.6	57.5
	average value, °	0.222	0.247	0.180	0.168	0.185	0.191

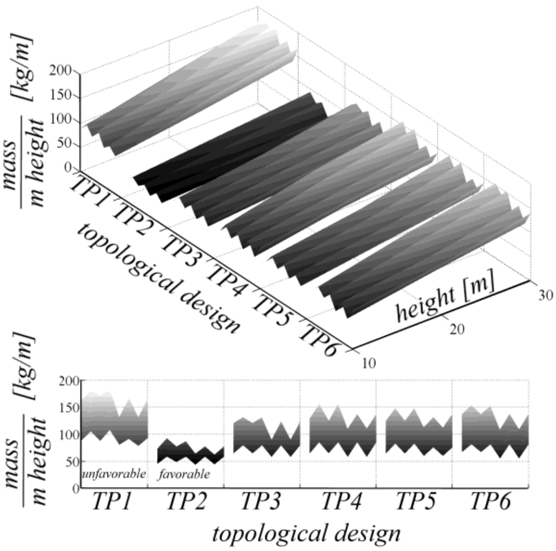


Fig. 7 Construction mass comparison

The mass of the tower depends on the number of used members and their dimensions. It is presumed that the towers of smaller height have smaller construction masses. This is a positive effect, as mass influences the material, transport and storage costs. Structural beams of smaller cross-sections can also have a negative effect because the angles of rotation at the top may increase and the tower could become unusable for the purpose of telecommunications usage (SLS).

For the tower-mass comparison presented in Fig. 7 it is clear that the structural mass is reduced by reducing the height of the towers (this is because less material is used for the construction of smaller towers).

Towers with the design TP 1 achieve the highest masses at all heights, despite the sharp decrease in mass from 30 to 20 m. On the other hand, the TP 2 towers have the smallest masses at all heights. At the same time, they achieve the smallest reduction with a lowering of the height of the tower. The towers with other topological designs achieve comparable structural masses for all heights, except for the TP 3 towers, which have slightly smaller masses at greater heights.

The graph in Fig. 7 shows the impact of different loads on the construction. A different antenna load changes the appearance of the graphs and gives us distinctive saw-shaped graphs for each topological design.

During a comparison of the towers, depending on the structural mass, it is favorable to have the minimum masses per meter height for all heights. The towers with different topological designs have similar reductions in of masses as a result of lowering the tower height, except for TP 1 and TP 2. Thus, at a height of 20 m a drop in mass of 20% (± 4%) occurs, and at a height of 10 m the reduction is 40% (± 8%), as seen in Table 5.

The tower design TP 2 stands out because it has the lowest masses per meter of height for all heights (favorable) and at the same time it has the smallest reduction in construction mass. On the other hand, the TP 1 towers have the highest structural masses per meter of height at all heights. The masses of the other topological designs are somewhere in between, at low heights the masses are similar (except for TP 2), whereas at greater heights the differences between the topological designs are clearly seen.

When looking at the economic criteria of the lattice towers it is expected that structures with a lower height are more favorable, because less material is being used and fewer logistic capacities and a smaller work force is needed in order to construct the tower. Economically favorable designs mean a smaller price per meter of height.

Table 5

Change in the construction mass per meter of height

Construction mass		Topological design					
		TP 1	**TP 2**	**TP 3**	**TP 4**	**TP 5**	**TP 6**
30 m height	average value, kg/m	164.0	77.4	118.0	134.4	132.0	135.7
20 m height	average decline, %	22.0	16.3	21.1	20.8	25.2	23.8
	average value, kg/m	128.0	65.0	93.0	106.6	98.3	103.5
10 m height	average decline, %	44.1	33.0	40.2	45.8	46.5	47.7
	average value, kg/m	91.5	51.8	70.0	73.0	70.5	71.1

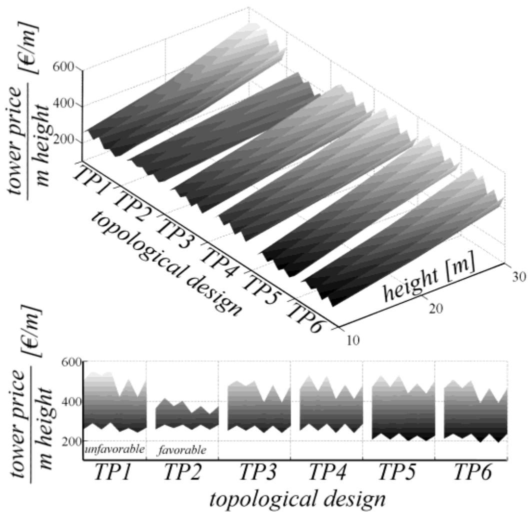


Fig. 8 Comparison of economical criteria

For the tower comparison based on the economic criteria presented in Fig. 8 it is clear that the tower's price per meter of height increases when the height of the towers is increased. The TP 1 towers have the least favorable economic evaluation. On the other hand, the TP 2 tower has the most economical most favorable design. Despite having a good economic evaluation for low heights, the tower designs TP 5 and TP 6 appear to lose their advantage at greater heights.

It is advantageous to achieve the lowest ratio of tower price per meter of height. For all the tower designs this increases with an increase in the height. However, the towers with different topological designs do not exhibit similar increases. Thus, at a height of 20 m there is an increase in the range between 11 and 30%; at a height of 10 m, this difference is even more pronounced, i.e., the increase ranges between 28 and 55% (Table 6).

For greater heights the best economic assessment goes to the TP 2 towers, but at smaller heights the TP 5 and TP 6 towers have the lowest tower price per meter of height. On the other hand, the TP 5 towers also have high costs at greater heights (unfavorable). Therefore, in an economic comparison there is no clear winner when it comes to the most suitable design for the tower.

The comparison of the economic criteria showed that there are similarities between the mass comparison and the economical comparison when observing towers with a low height. At greater heights the overall cost of the structure is influenced by the cost of man hours and the processing technology, which also has an influence on the complexity of the production. This effect is revealed as an increased structural (topological) complexity of the tower's design and its influence increases with the height of the tower.

Table 6

Change in the price of the tower per meter of height

Economical evaluation		Topological design					
		TP 1	**TP 2**	**TP 3**	**TP 4**	**TP 5**	**TP 6**
30 m height	average value, €/m	506.89	375.41	467.54	474.72	488.76	460.81
20 m height	average decline, %	29.5	11.7	22.0	24.2	28.2	29.4
	average value, €/m	356.92	330.89	363.74	359.40	350.40	324.95
10 m height	average decline, %	47.6	27.9	43.9	43.8	55.5	52.5
	average value, €/m	264.54	270.07	261.32	266.17	217.65	218.69

6. Conclusion

In this paper the differences between the topological designs of lattice towers for telecommunications purposes on the basis of comparative criteria have been explored. It has been shown that each topological design has its advantages, as well as its disadvantages, depending upon the discussed criteria.

For instance, towers with topological designs that seemed to be a good solution with regards to the displacement angles of rotation achieved only an average economic evaluation (case TP 3 and TP 4). And the results appear in a similar pattern if we change the order of the criteria (case TP 1). Towers of design TP 4 and TP 6 were shown to be good designs as their results achieved a fair evaluation. A comparison of the towers for telecommunications usage was carried out. The analysis show that the TP 2 towers achieved a good economic evaluation, but they also have large angular rotations and therefore they do not represent a good design for a telecommunications tower.

There is a clear connection between the tower's mass and the economic evaluation. For greater tower heights the effect of the topological complexity of the design and, consequently, the production complexity has an increasingly significant impact on the economic evaluation.

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LYGINAMŲJŲ KRITERIJŲ METODAS SKIRTINGOS TOPOLOGIJOS TELEKOMUNIKACIJOS BOKŠTAMS PROJEKTUOTI

R e z i u m ė

Straipsnyje aprašomas skirtingos topologijos plieninių santvarų panaudojimo telekomunikacijų bokštams tyrimas, kai antenos yra montuojamos bokšto viršūnėje. Bokštai yra veikiami įvairių krūvų: savojo svorio, vėjo, ledo ir jų kombinacijų (apledėjus bokštams padidėja jų paviršius ir sustiprėja vėjo poveikis). Krūvio poveikio rezultatai yra palyginti tarpusavyje naudojant lyginamuosius kriterijus, tokius kaip ribinis padėties kriterijus, antenos posūkio kriterijus, konstrukcijos masės kriterijus ir konstrukcijos ekonominis įvertinimas. Palyginimas atskleidė keletą kiekvieno topologinio projekto konstrukcinių ypatumų.

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A COMPARATIVE CRITERIA METHOD FOR TELECOMMUNICATIONS TOWERS WITH DIFFERENT TOPOLOGICAL DESIGNS

S u m m a r y

This paper presents an investigation of different topological designs of steel-frame towers for the purpose of telecommunications usage, where the antennas are mounted at the top of the tower. The towers are subjected to different loads, such as self-weight, antenna loads, wind loads, ice loads and their combination (wind has an effect on iced towers because of the increased surface area). The results of the load impacts are compared to each other on the basis of comparative criteria, such as the criteria of ultimate limit states, the criteria of angular rotation at the antenna mounting, the structural mass criteria and economic evaluation of the structures. The comparison revealed some of the structural features of each topological design.

Keywords: comparative criteria method, telecommunications tower, topological designs.

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