IOP Conf. Series: Materials Science and Engineering **365** (2018) 052010 doi:10.1088/1757-899X/365/5/052010

Atypical structural systems for mobile communication towers

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Abstract. The improvement of the structural forms of mobile communication towers is an important and actual task in the modern world with growing needs in quality of mobile communication. The task of developing support structures for installation in a dense urban environment requires particular considerations, which must satisfy both the requirements for ensuring the reliability of structures and aesthetic requirements. Based on the results of the critical analysis of the design experience for supports, atypical structural solutions of the towers are proposed to cellular communication equipment. The prismatic towers are chosen for the study. The procedure for calculating towers is formalized in the form of a step-by-step system. For the uniform initial data on climatic and averaged technological loads for a given class of facilities, the loads on the towers were calculated; forces were determined; the cross-sections of tower elements in accordance with the requirements of two limiting states were received to be accounted for the effect of the most unfavorable design load combinations. The ranges of the stiffness characteristics variation are established for various types of towers structural solutions. The characteristics of the advantages and disadvantages are received for each constructive solution on the basis of the analysis of applicability of the existing and proposed towers structural solutions and evaluation of the stress-strain state performed. According to the criterion of metal consumption, the most economical version is chosen between the four towers structural solutions which include the triple leg frame system, the lattice tower of triangular cross-section (classical solution that has proved itself in practice), the spatial unflanged system and the cable system with the central trunk. The criteria for optimizing towers geometry and their elements are proposed and consist in simultaneously ensuring the requirements of limiting states. The new tower design solution in the form of the cable system with a central trunk has been worked out while varying the significant factors, such as the width of the base, the number of cable elements and the value of initial tension. Some dependencies have been proposed that are based on the numerical study results for the towers with a pre-stressed trunk and allow for regulating the stress-strain state and rigidity of the support at the design stage. The ways for improving tower structural form of structural solutions adopted are indicated. It is established that the unflanged system is inefficient as a support of small and medium height for the equipment for mobile operators.

1. Introduction

Massive use of cellular communication leads to the need to install in the city boundaries support structures designed to accommodate the equipment of mobile operators. Taking into account the dense building, the installation of masts with stays in the city area in the vast majority of cases is impossible or possible on flat roofs of buildings. Installation of equipment on the roofs and facades of existing buildings introduces unacceptable changes in the aesthetic forms and the appearance of streets. A suitable alternative to the masts is aesthetic forms of tower supports with a narrow base to allow for providing architectural expressiveness and unity of the city compositions.

Work goal: to perform the analysis of structural solutions and evaluate stress-strain state (SSS) of non-typical tower structures of prismatic form.

The problems are being solved in the study:
1) Offering support types for the placement of cellular communication equipment with non-typical design solutions of prismatic towers;
2) Evaluation of loads on the towers, determination the internal forces and design the cross-sections of the towers elements in accordance with the requirements of limit states;
3) Performing a comparative assessment of the bearing capacity and rigidity of the towers with various design solutions;
4) Comparison of the various structural solutions of the towers using the criterion of metal consumption;
5) Offering the measures for reducing the tower weights;
6) Outlining the ways for improving the structural form of tower with adopted structural forms.

2. The overview of the lattice tower design experience

As example of a high-rise construction with the frame system can serve the Eiffel's lighthouse that is located in Estonia on Ruhnu island and was built in 1877 (see figure1a).

The works of Russian scientists B Ostroumov [1,2], V Shukhov [6,7,8] are dealt with studying SSS of unflanged systems. The construction of two Shukhov's towers is shown in figure 1c. A large variety of unflanged systems was applied worldwide; examples of these are the works of Santiago Calatrava and Norman Foster [10].

The prismatic towers with triangular cross-section are the most common types of towers; their behavior has been thoroughly studied in the papers of such scientists as A Sokolov [15,16], M. Solodar [17]. An example of the tower is given at figure 1b.

The overview of the behavior of frame structures in the form of rigid struts for chimneys is performed in the paper [13].

The striking example of the cable system is the tower of an architect Donald Krohn in Australia Sydney Eye Tower height H=309 m (see figure 1d).

The main feature of the most structures built earlier is the presence of a pyramidal part that repeats the form of the bending moments diagram from the action of wind loads, which imposes restrictions on the use of such towers in dense urban buildings.

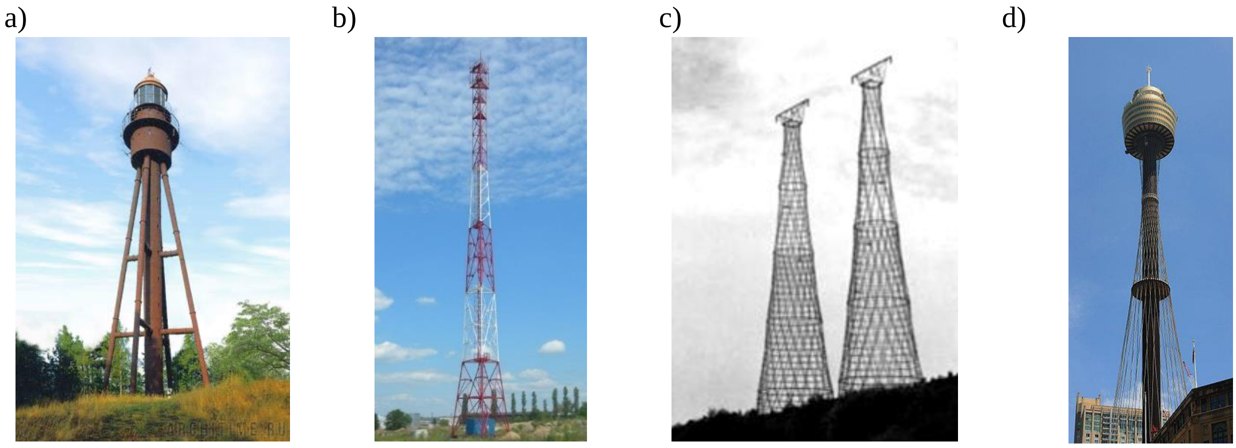

Figure 1. Examples of towers with different design solutions

Experimental researches of the lattice towers behavior under loading have been carried out by J Szafran, R Travanca, Y Zhuge in recent years [18-23].

Study of the equipment arrangement effect on the stress state of lattice towers is performed in the paper of S Sweety [24].

Research on various structural solutions of tower structures supporting wind turbines is performed by D Amlan, J Slobodanka, S Schafhirt [25-28].

3. Research objects and initial data

The object of study is non-typical towers of prismatic form. Constructive solutions of towers, calculation and SSS analysis of which are performed in the framework of this work:
– the three leg frame system (figure 2a, 3a);
– the lattice tower with a triangular body (figure 2b, 3b);
– the spatial unflanged system (figure 2c, 3c);
– the cable system with central trunk (figure 2d, 3d).

The calculatin of tower structures and SSS analysis is performed for uniform data – a shape, overall dimensions, design area, operating conditions (see table 1). The towers adopted are a height of 42.0 m, that corresponds to the average height of the equipment disposition for mobile communication facilities.

Non-typical constructive solutions applied to mobile communication objects are structural solutions towers a), c), d).

Table 1. Basic general geometric characteristics of towers and design assumptions.

Nomination	Designation	Value	Measurement units
Wind zone	3	0.38	[kPa]
Terraine type	A		
Height of structure	H	42.0	[m]
Design width of structure	b	2	[m]
Height of tower section	h	6.0	[m]
Structural form	prismatic		
Cross-sections of tower elements	pipes		
Limit deflection of the tower top under wind load	$\Delta_{horizont}$	420	[mm]

The loads on towers:
– self weight of the tower and weight of technological equipment;
– wind loads;
– initial tension in cable elements.

The loads from equipment:
– elevation 42.0 m – equipment with a total area of 2.9 m^2 and a total mass of 100 kg;
– along the trunk of a tower - six branches of feeders with a diameter of 32 mm (each branch) and three wires for the supply of lanterns.

During the calculations the towers were divided into 7 sections in height, within which the rigidity characteristics and distribution of loads were assumed constant.

The procedure for the tower calculating used in this work is a step-by-step process that includes:
– **step 1**: setting out the preliminary sizes of the cross-sections by the values of the initial parameters;
– **step 2**: performing the preliminary collection of loads; calculation of oscillation frequencies, design forces are determined for the design combinations;
– **step 3** correcting the previously adopted cross-sectional dimensions as to insure compliance with the limit state requirements;
– **step 4** the procedures described in steps 2 and 3 are repeated for the corrected cross-sections;
– **step 5** and the last steps are performing if the rigidity of the elements in the adjoining verification stages is more than 20% different.

The difference in the value of the wind loads for the towers of various design solutions due to the different windward area is shown at figure 4. The windward area of a particular tower section depends, in addition to an area of equipment, on the cross-sections of the elements of a tower, the mass and rigidity of the tower section and on rigidity of a tower in general.

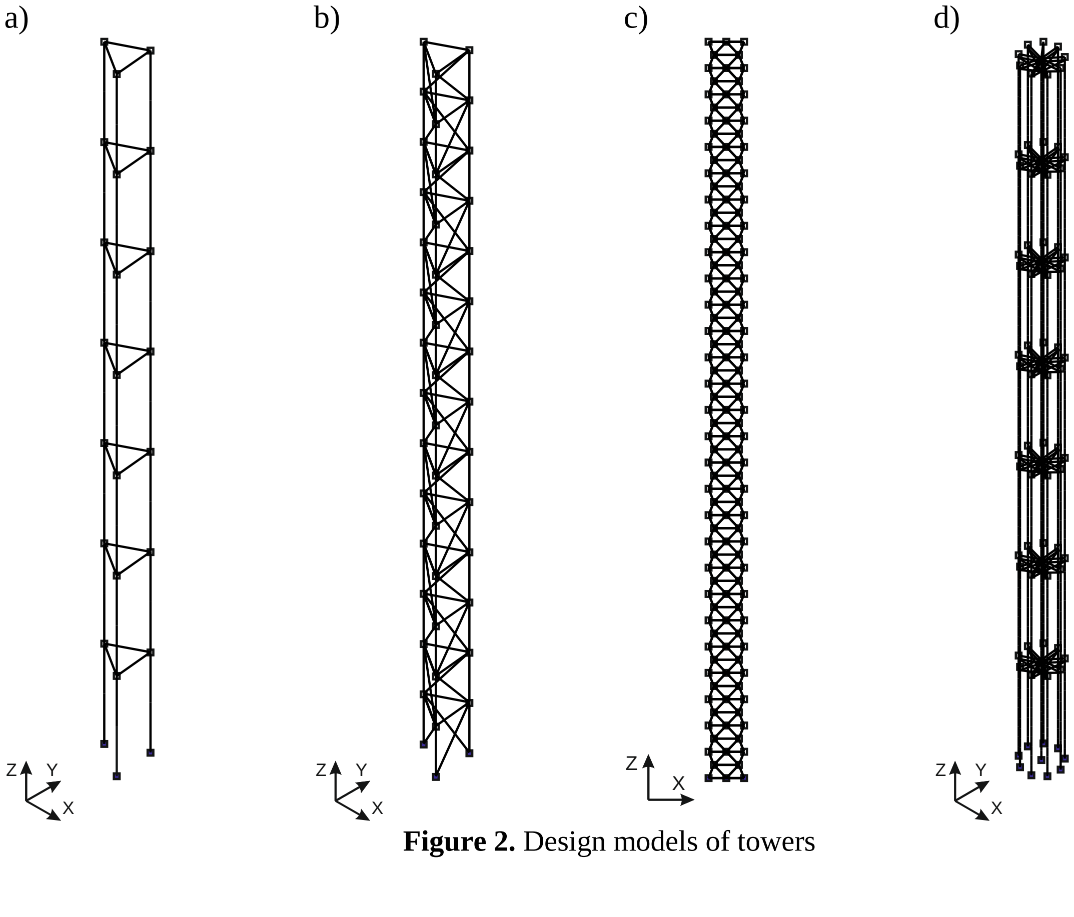

Figure 2. Design models of towers

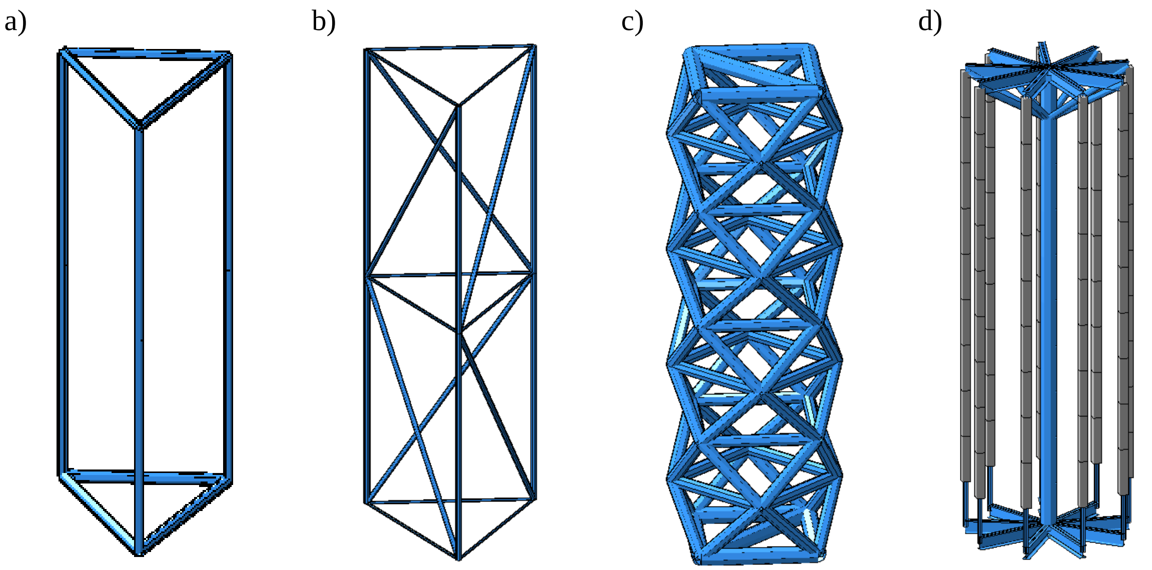

Figure 3. Fragments of the ordinary tower sections with different structural solutions

A sharp increase in wind loading in the seventh section (see diagrams at figure4) is caused by local concentration of equipment at the height of 42.0 m.

The determination of design forces in tower elements is performed according to the design combination of loads "tower weight + equipment weight + wind". For the structural solution tower d), the design load combination is "tower weight + equipment weight + pre-tension cable elements + wind".

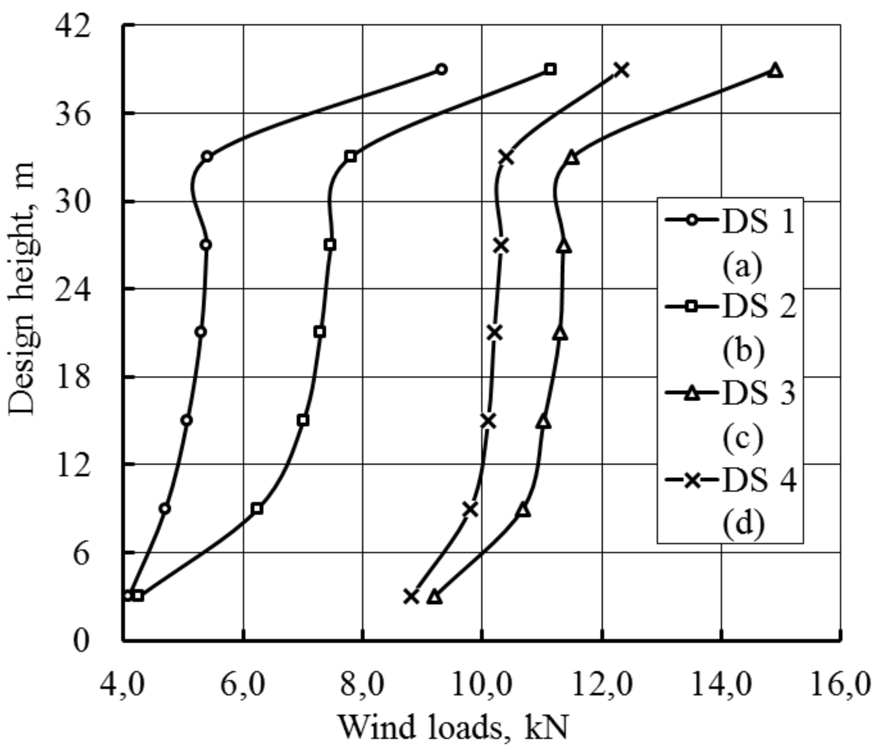

Figure 4. Distribution of design wind loads for various design solutions

The cross-sections of tower elements for different structural solutions are presented in table 2.

Table 2. Cross-sections of the tower elements

Structural element	Cross-section of elements at design solution, mm			
	Frame system	Triangular tower	Unflange system	Cable system
Struts, legs	Ø108x10 … Ø203x20	Ø76x3 … Ø180x7	Ø32x8 … Ø203x22	Ø180x7 … Ø351x18
Bracing members, cables	Ø114x14 … Ø203x12	Ø38x3 … Ø70x8	Ø32x8 … Ø168x12	Ø13 … Ø54

4. Main features and analysis of towers

The three leg frame system consists of three rigidly fixed pipes in the base. The pipes are united for conjoint behavior by beams rigidly fixed to the legs. The horizontal beams are provided with spacing of 6 m.

Advantages of the frame system: a small number of elements in the system.

Disadvantages of the frame system: increased flexibility in comparison with the triangular tower.

The triangular tower is a spatial truss of prismatic form. The bracing of the tower is single lattice with additional struts. The spacing of struts is about 3 m.

Advantages of the triangular tower: the small number of elements in the system that behavior mainly as the centrally compressed or tension members. This structural solution refers to the type of spatial trusses that have proved themselves in construction practice.

Spatial unflanged system is a three-dimensional bar system having inclined elements of the same length (braces). The tower of the adopted design has square cross-section with a side dimension of 1.4 m.

Advantage of the unflanged system: expressive architectural form.

Disadvantages of the unflanged system: increased flexibility in comparison with other forms of towers, significant metal consumption and labor costs.

The cable system with a central trunk is a spatial pre-stressed rod having a variable rigidity in height. The initial tension of cable elements is performed as step-variable.

Advantage of the cable system: sparse system; the cable elements carry only tensile forces, frequently located platforms, an expressive architectural form.

Disadvantages of the cable system: increased flexibility in comparison with the triangular tower; structural details are insufficiently worked out. This system may sustain loads effectively only in the presence of tensile forces in cables that ensures a uniform redistribution of bending moments between the cables. When the cable elements fall into the compression zone, the cables turn off from carrying loads, and the bending moment lever arm decreases significantly, which leads to an increase in the bending moment in the central trunk and tensile forces in the heaviest loaded cable element.

Based on numerical experiments on models of towers with a circular cable system, the deflection of the tower top was determined as a function of the initial tension in the cable elements. This relationship is shown in the graph (figure 5) and can be approximated by the following expression:

$$n = 1.368 \cdot 10^{-2} - 1.935 \cdot 10^{-4} \cdot T + 1.412 \cdot 10^{-6} \cdot T^2 \quad (1),$$

where T – initial tension in the cable element, expressed as a percentage of the maximum breaking force;

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n – relative deflection of the tower top.

The relative deflection of the tower top is determined by the formula:

$$n = \Delta / H \quad (2),$$

where Δ – horizontal deflection of the tower top, mm;
H – the tower height, mm.

The influence of the value of initial tension in the cable elements on the bearing capacity of the cable system (poles and cables) is nonlinear, as evidenced by the type of dependencies represented by the graphs at figure 6.

As a result of the calculations carried out, it is determined that the most economical solution according to the criterion of minimum metal consumption is the classical solution in the form of a triangular lattice tower (see the data at figure 6). The comparison of the weight of towers with different design solutions is performed for two conditions: the first condition is the first limit state to be met (I LS marking at figure 6), the second - when the requirements of the second limit state are met (marking II LS at figure 7).

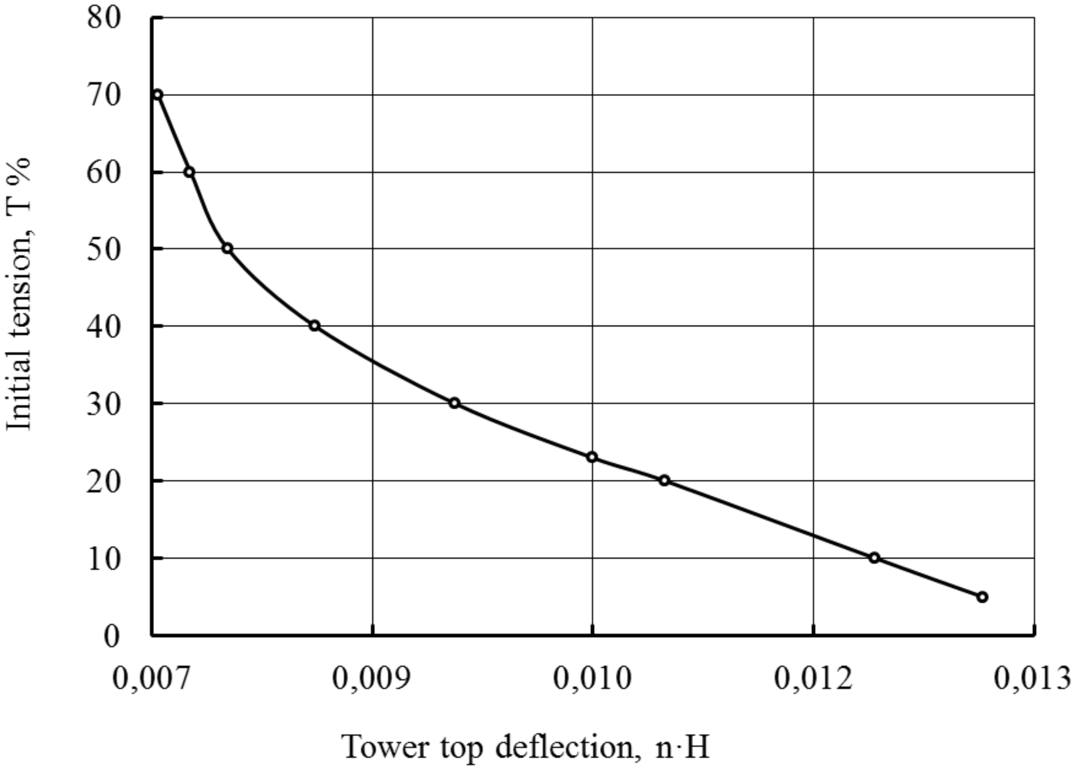

Figure 5. The plot of end deflections against a value of the initial tension

The basic parameters of the tower SSS with various structural solutions are summarized in Table 3. It is noteworthy that for most design solutions of towers the second mode of the tower's vibration is the flexural-torsional mode, which indicates the low rigidity of towers in torsion.

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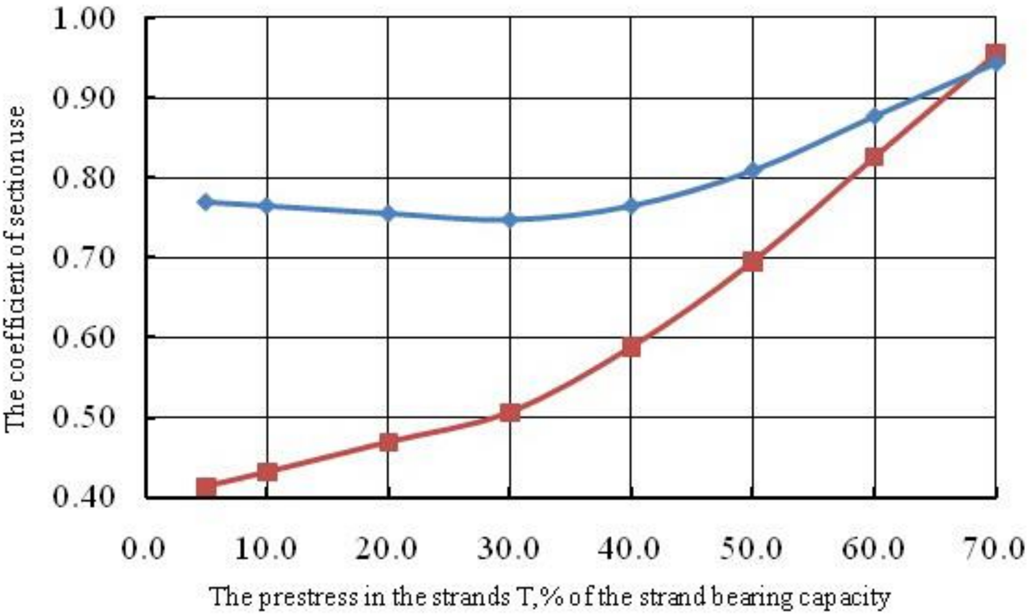

Figure 6. Dependences of the element bearing capacity in a cable system on the value of the cable element pre-stressing*

* red graph – for pole, blue graph – for truss.

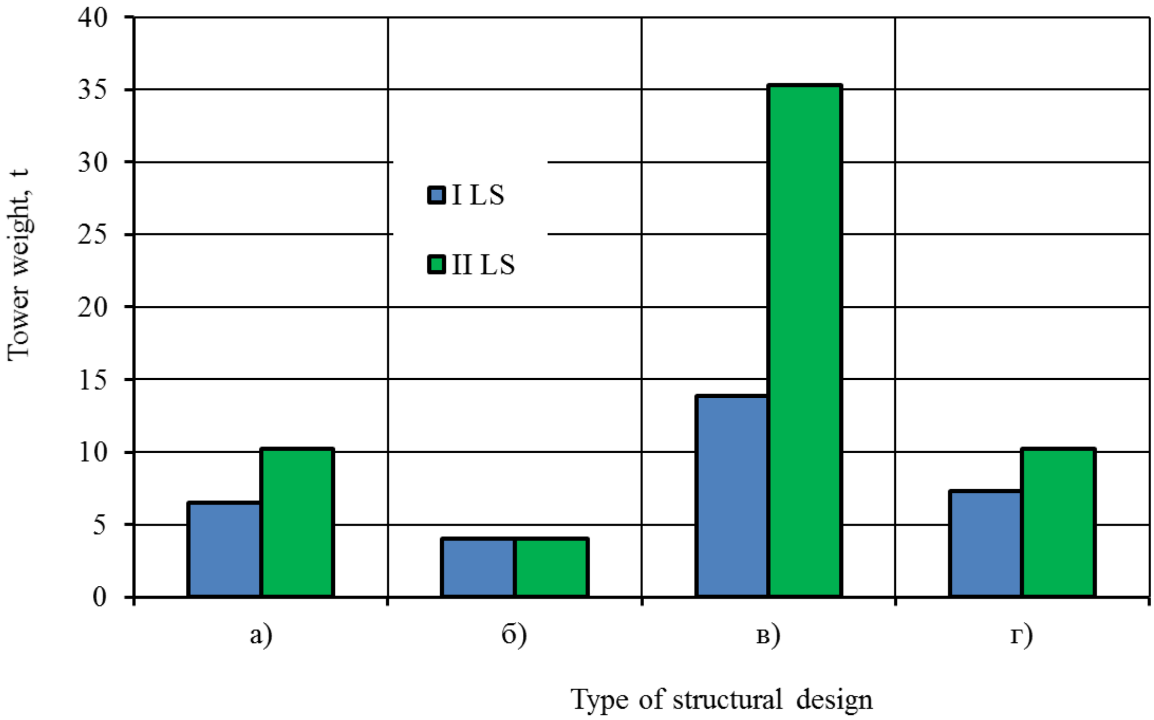

Figure 7. Weights of towers: I LS – by the criterion of the satisfaction requirements for the first limit state (strength), II LS – by the criterion of the satisfaction requirements for the second limiting state (deflections)

Table 3. Main parameters of towers with a different type of structural design.

№	Design solution of tower	Performing limit states requirements	Rigidity		Oscillation frequencies, Hz			Reserve bearing capacity, %	Deformation from the normative loads, mm	Tower weight, t
			EI, $kN*m^2$	EA, kN	f_1	f_2	f_3			
1	Space frame	I – satisfied, II – not satisfied	$1*10^6$ – $3*10^6$	$1.6*10^6$ – $4.5*10^6$	0.771	1.692	1.831	2-10	640	6.5
		I – satisfied, II – satisfied	$1.3*10^6$ – $4.8*10^6$	$1.9*10^6$ – $7.1*10^6$	0.756	1.648	1.732	24-49	419	10.2
2	Triangular tower	I – satisfied, II – satisfied	$2.8*10^5$ – $1.6*10^6$	$4.3*10^5$ – $2.4*10^6$	1.398	4.428	5.737	4-11	400	4.0
3	Unflanged system	I – satisfied, II – not satisfied	$1.1*10^5$ – $2.2*10^6$	$2.3*10^5$ – $4.5*10^6$	0.574	1.974	4.551	3-8	1021	13.9
		I – satisfied, II – satisfied	$2.5*10^5$ – $5.1*10^6$	$5*10^5$ – $1.1*10^6$	0.656	2.35	5.303	55-66	420	35.3
4	Cable system with central pole	I – satisfied, II – not satisfied	$2.2*10^5$ – $2.2*10^6$	$1.7*10^5$ – $8.2*10^6$	0.634	1.27	1.310	1-8	538	7.3
		I – satisfied, II – satisfied	$5.8*10^5$ – $2.4*10^6$	$2.6*10^5$ – $1.1*10^6$	0.762	2	2.097	13-65	420	10.2

5. Conclusions and provisions for improving tower design:

1) The towers a), b), d) with a width b = 2.0 m are characterized by increased flexibility while satisfying the requirements of the first limit state. The geometry of the tower can be adopted rationally, for which the rule is realized that the requirements of the second limit state are justified necessarily provided that the requirements of the first limiting state are met.
2) The most economical solution by the criterion of minimum metal consumption is a structural solution having form of a prismatic lattice tower with a triangular cross-section.
3) To reduce the weight of the towers with the structural solutions a) and d) is necessary to increase the base dimensions of the two lower sections, that slightly affects the increase in wind loads, but at the same time increases the rigidity of the structure and allows for reducing metal consumption and horizontal deflection due to increasing the bending moment lever arm.
4) The structural shape of the unflanged system is inefficient as a support of small and medium height for the placement of mobile operators equipment.

6. The prospects for further research:

– determination of the rational dimensions of towers with structural solutions a), c), d) in order to exclude the increase in cross-sections of elements due to the need for limiting horizontal deflections;
– to perform numerical researches of towers and their elements exposed to load combinations "tower weight + equipment weight + weight of ice deposits + wind in ice", and to determine the degree of effectiveness of the considered design solutions in terms of material consumption and minimization of operating costs.

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