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Methodology for Creating the Structural Shape of Steel Towers for Power Transmission Lines, Lightning Rods and Communication Towers

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Abstract: Transmission lines as part of the power grid infrastructure complex fulfil the function of ensuring uninterrupted power supply to consumers. An important link in the chain is the transmission line supports, as the safety of the entire line depends on the uninterrupted operation of each support. The trouble-free operation of the supports directly depends on three factors: the calculation of the justified design form, the correctly chosen mode of operation and the frequency of preventive maintenance. This paper presents calculation and analytical tools for selecting an effective structural form of lattice supports. By means of critical analysis of modern research in the field of calculation and design, data on the nature of damage and methods of strengthening of tower lattice supports in terms of the degree of elaboration of the research topic, the aim of the work and tasks aimed at its achievement, object and subject of the research are formulated. The results of modelling of geometrical dimensions of tower piers with one edge fracture are presented, characterizing the influence of geometry on the main design parameters of the structure, such as the first frequency of vibration, wind load and metal capacity of the structure. Based on the results of the computational and analytical study, a methodology for developing the structural form of steel lattice towers is summarized. The methodology can be applied equally to the design of transmission towers, lightning rod towers and cellular communication towers.

1 ITRODUCTION

Modern power grids are complex technical systems by their structure, organization of operation and management principles. The main task of power grids is to ensure continuous sustainable supply of electricity to consumers connected to the grid. Transmission line supports are components of power grids and the reliability of the entire power grid infrastructure depends on their trouble-free operation.

Lightning protection structures are an integral part of the system for ensuring the safety of key facilities of the energy sector. By protecting energy facilities from lightning strikes, these structures ensure uninterrupted operation of entire process chains, such as fuel and energy facilities - tanks and pipelines.

Radio and telecommunication systems for wireless data transmission are continuously improving. Fourth-generation communications are being replaced by fifth-generation communications, and research is underway to develop 6G communications from 2020. The requirements for antenna towers are increasing, which requires improvements in their design. Improving the design of tower towers is possible only with a full understanding of the interrelationship of the complex of factors affecting the structural form - the nature of the acting loads, the type of technological equipment and the way it is placed at the height of the structure, the design of means of access and maintenance of equipment and the load-bearing tower structure.

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The critical review presented in Section 2.1 showed that despite decades of experience in the calculation and design of lattice tower structures, no coherent methodology for creating the structural form is given in the scientific and regulatory literature.

Research goal: Development of a methodology for creating a structural form of steel lattice towers by systematizing the data accumulated by the authors and publicly available data on calculation, design, nature of damage and methods of reinforcement of lattice towers.

The list of issues has been solved within the framework of the conducted work:

– critical analysis of the researches of scientists in the direction of the chosen subject has been carried out;

– numerical and analytical models of the lattice tower line were developed, loads and forces in the model rods were calculated;

– the influence of changing the width of the supporting base in towers with one height fracture on the change of the main design characteristics of the structure was determined;

– the determining criterion of rod cross-section assignment was established by calculation;

– a methodology for creating the structural form of steel lattice towers was developed.

Research object: constructive form of lattice-type tower piers.

Research subject: the nature of changes in the stress-strain state of the main load-bearing structures for lattice tower trunk when the overall dimensions of the structure are varied.

2 MATERIALS AND METHODS

2.1 Review of Publications on the Topic of the Study

Analytical methods for calculating the load-bearing structures of tower structures are sufficiently developed in the works of domestic scientists, founders of schools for the improvement of high-rise structures such as A. G. Sokolov, N. P. Melnikov, Melnikov N. P., Pavlovsky V. F., Kondra M. P.

A significant contribution to the shaping of high-rise structures was made by scientists of the State Research Institute Ukrproektstalkonstruktsiya. Gordeev V.N., Grinberg M.L. and Kondra M.P. in the article (Gordeev, Grinberg, Kondra, 1969) gave practical recommendations on the selection of optimal outlines of lattice towers. O. I. Shumitsky developed the ideas of his predecessors in terms of improving the structural shape of welded steel television towers of great height. The systematization of the domestic experience of calculation and design of high-rise antenna structures was carried out by A.V. Perelmuter.

The study of the structural form of lattice supports is devoted to the works of scientists carried out under the guidance of E.V. Gorokhov, which resulted in a narrow-base lattice support with a cross-spring lattice. Methodological approaches to solving the problems of calculation and design of high-rise structures with a load-bearing metal frame are presented in the works of Gubanov V.V.

Clarification of wind loads on lattice supports of overhead transmission lines is carried out in the study by Ye. Shevchenko, Ya. Nazim, A. Tanasoglo.

A review of modern trends in the development of cellular telecommunication towers and their alternatives is carried out in the work of Al-Jassani A.A.M..

The issues of redistribution of forces in the belts of lattice towers and ensuring their stability are devoted to the works by Y. V. Krasnoshchekov. Modern studies of stability of spatial rod systems are conducted by scientists Coşkun S.B. and Yoo C.H..

Research on the improvement of lattice tower structures is continued by the authors of this publication in the directions of searching for an effective structural form of various types of towers, in the study of the influence of the lattice type on the stress-strain state of the shafts, in the assessment of the character of damageability of tower shafts and in the development of methods for their strengthening.

A number of publications by modern authors are devoted to improving the efficiency of antenna-mast structures design in terms of metal intensity and specific construction cost, the issues of automation of cellular communication towers design based on the evaluation of structural solutions and some results of engineering calculations of tower structures. Separate studies are devoted to solving the issues of risk assessment of steel lattice towers restoration under the conditions of extreme impacts realisation. A detailed characterisation of the specifics of the development of design solutions for transmission line towers is given in the article by Orawski G.

General issues of optimization of technical systems are presented in the works of Wang Y., Sezer S. and Ohsaki M., and as applied to lattice systems - in the works of Tejani G.G., Fiore A., Jayaram M. A. and Akhtyamova L.Sh.. Modern research on optimising the shape of transmission line support structures is carried out by scientists such as Sousa de

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R.R., Chepurnenko A., Tsavdaridis K. D., and mast structures by Belevičius R.

Specialised software products have been developed by leading software developers in the field of structural design to accelerate and optimise the process of tower design. Such products include:

– «ReshK» plug-in package for automation of lattice structures calculation from SCAD SOFT Ltd;

– a line of RF-/TOWER modules for continuous design of lattice masts and towers in the RFEM and RSTAB structural calculation and design programmes from Dlubal.

There regularly appear highly specialised developments aimed at automating the calculation of tower lattice supports, such as the development of the Bryansk University of Engineering and Technology (BGITU) and the works of individual scientists, e.g. Roșca V. E.

The normative regulation of calculation and design methods for lattice steel structures of power transmission lines is reflected in the A.S.C.E standard.

Studies of the process of corrosion damage development in steel tower structures are carried out in the works by Chakraborty S. and Zhang J.

The accumulated rich experience of calculation, design of new towers and evaluation of the technical condition of the operating tower supports shows the necessity of development of the methodology of structural shaping of steel lattice towers, which allows not just to assign by experience, but to calculate and optimise in the process of design the silhouette and types of structural elements of towers, which will allow to obtain a tower support of minimum cost in the case.

2.2 Characterisation of the Object of Research

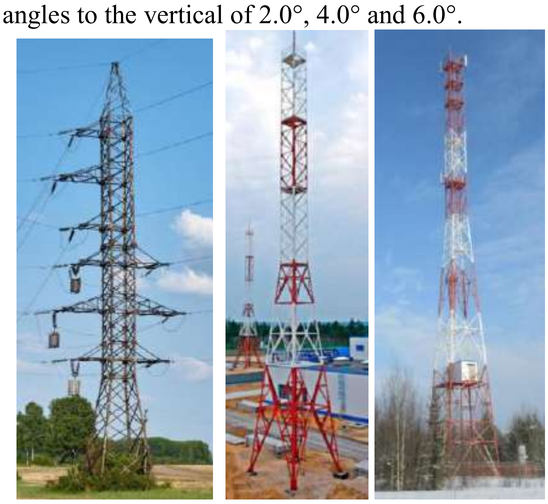
Power transmission towers, steel lightning rods and communication towers are related structures in terms of the type of structural solutions of load-bearing shafts. The vast majority of bearing shafts of these structures are made in the form of a lattice tower with a single height fracture.

The configuration of the most widespread type of steel lattice towers is shown in Fig. 1.

Structurally, the lattice shafts of the overwhelming majority of lattice towers of the research objects consist of two sections - a truncated pyramid at the base and a prism at the top. The scheme of a typical silhouette of tower trunks is presented in Fig. 2. An important task in assigning the geometry of the structure is the selection of the configuration of the support pyramid, the characteristic of which is the height and the angle of inclination of the belt to the vertical axis.

As an example, let us consider the results of calculation of a 48.6 m high tetrahedral lattice tower with one belt break. The tower is made of single equal-sided angle bars and is designed for installation in the first wind region. The scheme of the tower is shown in Fig. 3.

When performing the calculations, the width of the tower at the base was varied. The calculation was performed for base dimensions of 3.217 m, 5.088 m, 6.969 m, which corresponds to the belt inclination angles to the vertical of 2.0°, 4.0° and 6.0°.



a) b) c)

Figure 1: Examples of realization of the most common configuration of lattice towers: a) transmission line support; b) lightning conductor support; c) cellular communication support.

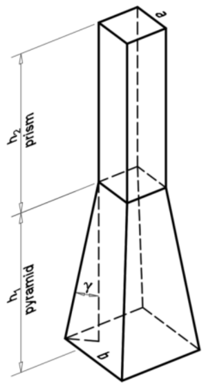


Figure 2: Geometric scheme of a typical silhouette of lattice tower trunks with one height break of the faces.

The load from the process equipment was applied on the upper section of the tower with a total

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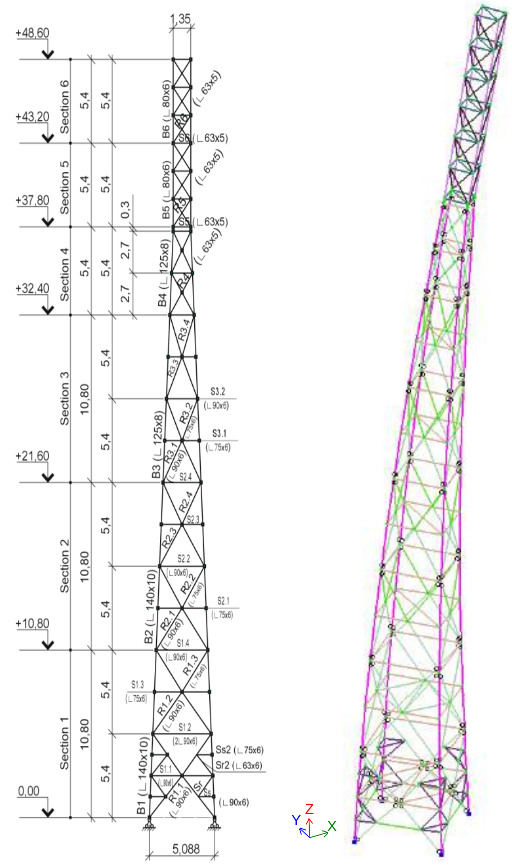
windward area of 2.0 m^2, the feeder path in height was 0.45 m2 per meter of height of the structure. When collecting the loads, the presence of stairs and platforms with fencing was taken into account.

The tower sections were calculated in compliance with the requirements of the normative documents for the bearing capacity and for the flexibility of the rods. Additionally, the horizontal displacement of the top of the structure was assessed.



a) b)

Figure 3: General view of a lattice tower: a) structural scheme; b) first form of vibration for tower's spatial design model.

The design model of tower was performed in the finite element analysis software Lira CAD in spatial formulation. For modeling of belt and lattice elements was used the finite element type FE 10 «universal spatial rod» with six degrees of freedom in nodes. The rods are hinged to each other. The tower is rigidly fixed to foundation. The joint operation of tower structure with foundation was not considered. Analysis was carried out in linear formulation without taking into account nonlinear properties of structural material according to the undeformed scheme.

2.3 Results of the Assessment of the Nature of Damage Development

For the development of an adequate methodology of structural shaping, the results of the assessment of damageability of lattice supports are of interest, which characterize the reliability of theoretical studies.

The results of inspection of lattice supports show that damage in the structures most often occurs as a result of the following factors:

– long-term operation without preventive maintenance, which leads to physical wear of rods and parts of nodal joints;

– ignoring the requirements for structural provision of sufficient cruelty of rods (see Fig. 4 a);

– placement of additional technological equipment without appropriate design justification.

a)

b)

Figure 4: Examples of damage to lattice support structures during operation: a) increased flexibility of lattice elements; b) loss of stability of tower rods as a result of violation of operating rules and excessive loads.

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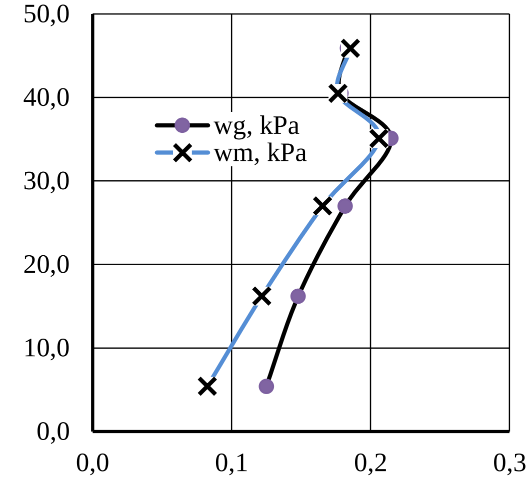
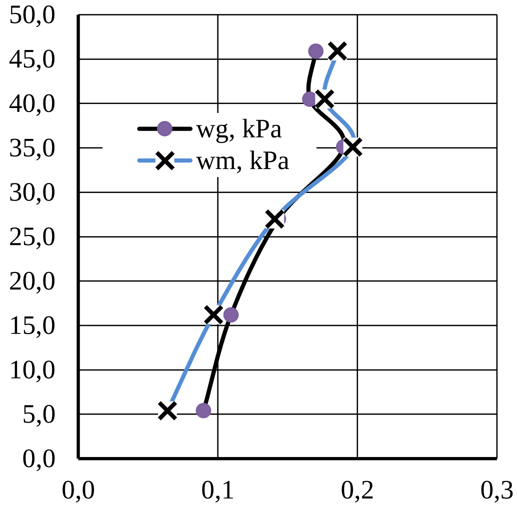
3 RESUTS AND DISCUSSION

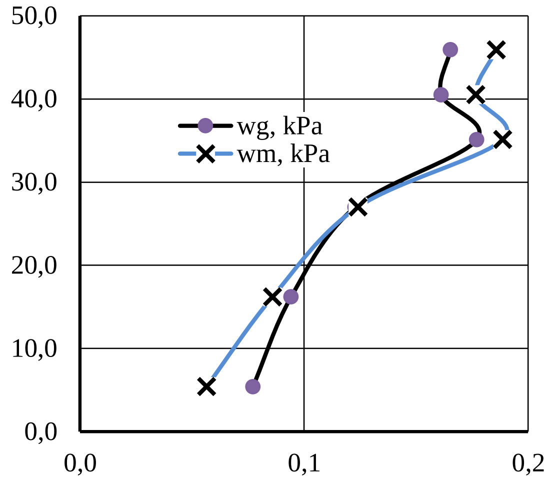
In the process of searching for an effective structural form, the thesis stated by A. V. Perelmuter that ‘the structural form actively influences the load’ was confirmed by analysis. An example of this, with respect to lattice towers, is the effect of changing the tower width on normative value of wind load (see Fig. 5) and effect of changing the vibration frequencies with changing the stiffness of structure on value of wind load (see Fig. 6 a).



a)

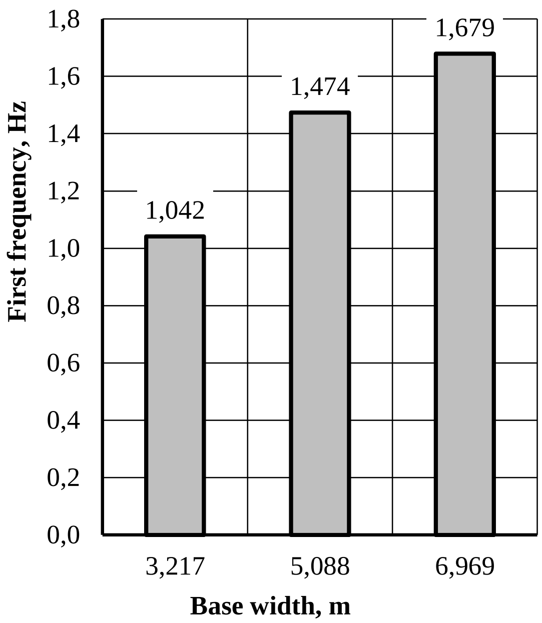


b)



c)

Figure 5: Effect of changing the tower width on the normative value of wind load: a) for a tower with a base width of 3,217 m; b) for a tower with a base width of 5,088 m; c) for a tower with a base width of 6,969 m.



a)

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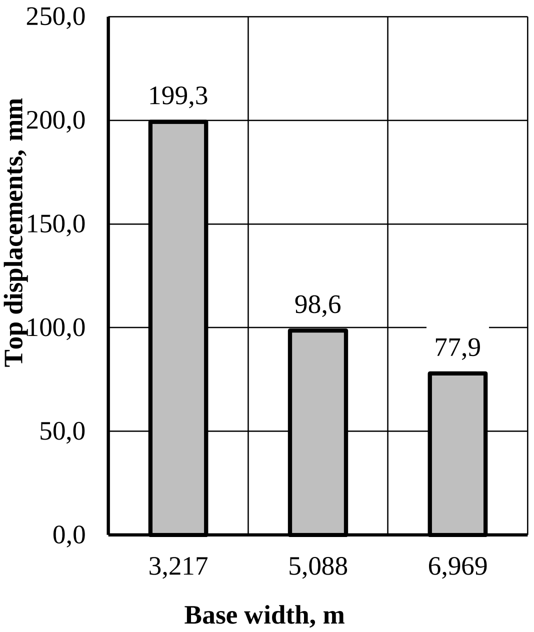

b)

Figure 6:. Effect of changing the width of the tower on the main parameters of the structure: a) the nature of the change in the first frequency; b) change in the deformations of the top of the structure.

It is noteworthy that for towers of the same height and adopted configuration (silhouette), changing the width of the base of the pyramidal part of the tower has almost no effect on the bending moment at the embedment due to the change in the frequency of vibration and hence the dynamic response of the structure. The resulting bending moment in the embedment for the three adopted design schemes is close in value and is about M_{op} = 1550 kN×m. When varying the geometry of the structure, considering the fulfilment of the requirements of normative documents in terms of ensuring the bearing capacity and stiffness of the structure, there is a complex change in the main parameters of the structure: the size of the cross-section of the belts and lattice elements, as a consequence, the mass and frequency of vibrations and, consequently, deformations of the top.

The complex interrelation of the design parameters of the structure when varying the geometry explains the weak variability of the metal intensity of the structure (see Fig. 7). It should be noted that the dimensions of the tower elements in the upper third of the structure are practically unchanged when varying the overall geometry of the structure and are selected mainly from the structural requirements, based on the requirements for the stiffness of the rods.

A significant part (from 25 to 60%) of the wind load is due to technological equipment distributed in height, for example, for cellular towers in the form of feeder routes and stair elements, and concentrated at design technological levels.

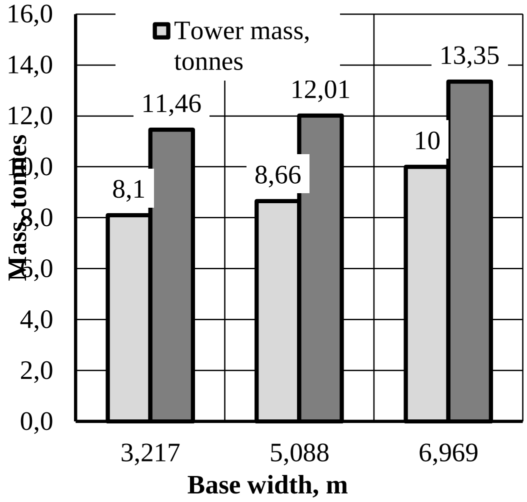

Figure 7: Effect of changing the width of the tower on the metal intensity of the structure.

Practical analysis of lattice towers show that for small process loads (in particular, insignificant windward area of the equipment) for the upper third of the structure, the decisive influence on the choice of sections is not the requirements to ensure the load-bearing capacity of the elements, but the guidelines to ensure the required stiffness. The selection of the cross-section of the lattice struts for this part of the tower is based on structural considerations and on the condition that the flexibility limits are not exceeded (see Table 1).

This peculiarity is characteristic to some extent for the upper sections of all types of lattice tower configuration, which in practice is compensated by the use of combined type towers with stepwise changing geometry with the transition from lattice construction at the base to solid sections in the upper part of the structure.

Table 1: Defining criterion for assigning cross-sections to tower bars*.

plot no.	**Section centre mark, z(e)**	**Type element**	**γ =°2°**			**γ =°4°**			**γ =°6°**		
			***δ_σ*, %**	***δ_λ*, %**	***K***	***δ_σ*, %**	***δ_λ*, %**	***K***	***δ_σ*, %**	***δ_λ*, %**	***K***

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6	45.90	Raskos Belt	83.0 82.9	10.0 5.1	λ λ	83.0 83.4	10.0 5.1	λ λ	83.0 83.6	10.0 5.1	λ λ
5	40.50	Raskos Belt	71.8 42.7	10.0 5.1	λ λ	71.8 44.6	10.0 5.1	λ λ	71.8 45.3	10.0 5.1	λ λ
4	35.10	Raskos Belt	45.7 53.0	19.7 9.6	λ λ	47.3 60.1	17.0 9.4	λ λ	47.9 64.6	14.0 9.1	λ λ
3	27.00	Raskos Belt	31.9 3.6	18.2 9.6	λ σ	41.3 28.8	15.7 9.4	λ λ	44.8 41.9	11.0 9.1	λ λ
2	16.20	Raskos Belt	10.7 5.0	12.0 19.0	σ σ	18.3 34.3	4.4 18.9	λ λ	60.2 16.8	15.8 9.1	λ λ
1	5.40	Raskos Belt	67.3 6.4	20.7 46.0	λ σ	69.0 37.3	7.7 45.9	λ σ	73.4 25.5	5.0 39.4	λ σ

*Notes to Table 1:
δ_σ – reserve for bearing capacity;
δ_λ – flexibility reserve;
K – defining criterion for assigning a section to the rod.

According to results of performed complex for calculation-analytical studies and generalizations, the methodology of creating the structural form of steel lattice towers of power transmission lines, lightning rods and communication towers, consisting of the following stages, is compiled:

1) assignment of the preliminary configuration of the structure based on the purpose (according to the technological task);

2) preliminary simplified calculation of the tower as a conditional cantilever rod of variable height stiffness:

- To simplify the height calculation, the tower is divided into 6 to 10 sections, within which the configuration (average width and type of lattice) and loads are assumed to be conditionally constant;
- the tower mass distribution by height is taken according to analogue designs or simplified empirical relationships;
- the average wind load component is determined at the design sections (on the lattice tower structure, access means and process equipment) in the direction of wind action on the tower face and on the rib;
- the design scheme of the tower in the form of a cantilever rod of variable height stiffness is prepared;
- the pulsation component of the wind load is calculated analytically or in the software system;
- analytically or in the software system, the forces (M, N, Q) in the support sections of each design section of the tower are determined, considering the increasing coefficient for the wind load transition from the 'on edge' direction to the 'on rib' direction;
- using analytical methods provided in reference and regulatory documents, the tower rod cross-sections are calculated in the design (support) sections of each design section of the tower;
- in accordance with the selected efficiency criterion (as a rule, according to the criterion of unity of the design section of the tower belt in height), the geometry of the structure is adjusted (width of the design sections and the number of broken edges in height);

3) analysis of the tower as a spatial truss:

- for the adopted configuration, a spatial design scheme of the structure is drawn up in the environment of the software package;
- load 'own weight' is created, loads from the weight of the tower and the weight of access means (stairs, transition platforms and fencing) are set;
- the load 'weight of process equipment' is created;
- loadings of the average component of the wind load (considering the wind on the lattice tower structure, access means and technological equipment) are created in the direction of wind action 'on the edge' and 'on the rib' of the tower (and for three-sided towers in the direction along the edge);
- the pulsation component of the wind load is calculated in the software system environment;
- loads 'load from the weight of ice deposits' and 'ice-wind load' are created;
- RCS and RCN are created, materials and additional characteristics of structural bars are set, structural and unified elements are assigned, deflection bracing is set;
- the final automated calculation and checking of sections of rods in the environment of the software system is performed;
- based on numerical analysis results are performed the final assignment of sections and section typing within the tower's design sections;
- calculation of beam cages of technological platforms is performed;

4) the calculation of the tower core mating nodes is performed: the support node, the mating nodes of the sending girdle grades, the mating nodes of struts and struts with the girdles.

For the convenience of calculation, it is advisable to collect loads on the tower shaft separately for the tower, access means and technological equipment, which allows to quickly adjust the accepted structural form of the structure and, accordingly, the metal capacity of the structure.

4 CONCLUSIONS

1) By critically analyzing the research of scientists in the direction of structural shaping of steel lattice towers of power transmission lines, lightning rods and communication towers, the aim and objectives of the research are defined.

2) The developed numerical and analytical models of lattice towers allowed to obtain statistical material, processing and interpretation of the results of which allowed to obtain regularities characterizing the influence of stiffness changes on the main design parameters of the structure.

It has been established that for small process loads, the average width of the tower should be the minimum permissible width. This will make it possible to adopt cross-sections based on load-bearing capacity rather than on structural requirements. The proposed approach will allow to reduce the metal intensity of structures.

3) As a result of systematization of data on calculation and design of new supports, processing of data from a series of verification calculations of operating supports, as well as systematization of data on the nature of damage and methods of reinforcement, a methodology for design of steel lattice towers was developed, allowing the engineer to regulate the steel capacity of the structure at the stage of pre-design decisions.

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