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Influence of wind load on connection system of temporary towers

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Abstract:

The objects of research are temporary demountable towers. When a wind load is applied to a structure at an angle, an uneven horizontal wind load occurs, which causes the structure to twist. For capital construction projects, due to the massiveness and greater rigidity of the nodes, this is not significant, but for light structures, accounting for this effect is very important. The purpose of the work is to study the connections of such towers and the influence of wind load unevenness on them. **Method.** Wind load studies are conducted, based on a model of a diving tower with the dimensions of the widest part 12 x 10 m and a height of 28 m. Different methods of calculation are taken into consideration, including the ones based on regulatory documentation and numerical modeling. Software packages allow calculating models with higher accuracy and less time, facilitating manual counting and reducing the probability of error. A gas-dynamic calculation is performed, as a result of which the aerodynamic coefficients are found. **Results**. A comparative analysis of two methods for calculating wind loads is carried out, after which measures are suggested to increase the load-bearing capacity of the structure.

1 Introduction

There is an arising need for temporary structures to use during cultural and entertainment events. Such structures should be easy and fast to install and demount, but also stable and resistant to wind. [1]–[3]. Demountable towers are widely used across the world [4]–[7]. Such structures work primarily on the perception of horizontal loads, the main of which is the wind load acting on the structure and equipment installed on it [8]–[10]. Horizontal impacts are also created by the tension forces of suspended antennas and wires [11]–[14].

A characteristic feature of tower-type structures is a big height with a relatively small base area. The tower consists of sections that have a lattice structure, the main elements of which are struts and diaphragms [15]–[17]. The placement of sports facilities on the city territory is also possible and relevant. Such facilities have a positive impact on the development and promotion of sports, as well as on the development and use of the territory [18],[19]. Modern development of construction technologies allows building and operating sports facilities in the city. Such structures do not have a negative impact on the urban environment [20]–[23].

One of the most widely used systems for temporary prefabricated structures is Layher Allround. When building structures with a mass stay of people from the Layher Allround modular wedge scaffolding system, additional requirements for reliability and safety are imposed. In this regard, the study of the actual operation of scaffolding in such structures is quite relevant [24]–[26]. These structures at the stage of construction and operation, due to their design features and the constant influence of man-made and natural factors, can undergo various types of deformation which lead to various changes in their spatial position. The wind load is one of the main ones, since the height of the structure exceeds its width and length at times [27]–[29]

Wind has the greatest impact on high towers. Wind occurs in the process of equalizing pressure differences in the atmosphere. The wind load on structures depends on their shape, position in space and the permeability of their fences. The current regulatory documents consider only examples of the influence of wind on rectangular buildings, so there is a need to study this effect on demountable towers to find the relevant aerodynamic coefficients and bending moments.

2 Materials and Methods

ANSYS Software Package gives an opportunity to create turbulence models that can be solved by different methods depending on their complexity. The design calculation is necessary to find the aerodynamic coefficients for the wind load when testing the structure with dimensions of 12 x 10 m.

In the calculation area, the dimensions of the area itself and the dimensions of the projected structure are set, i.e. the dimensions of the structure under study. The length of the wind flow entry zone is assumed to be 100 meters, and the length of the wind flow exit zone is assumed to be 300 meters. The object being studied is at an angle to the border of the wind flow entrance, since the wind load is applied at different angles with a step of 5 degrees to find the most "dangerous" angle of wind impact. Boundary conditions are also set for the calculated area: the input border, the output border, and two side borders.

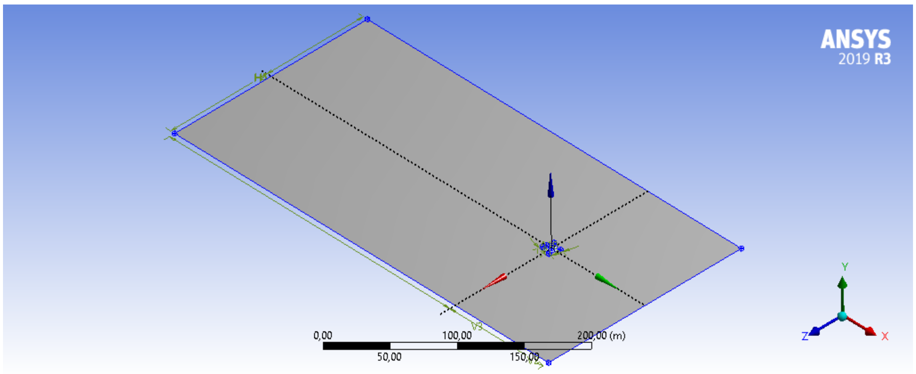

Fig. 1 - Design scheme of the structure in the Ansys SP

The mesh split step for the calculated area is 2 m. The mesh split step for the faces of the structure is 0.25 m. The mesh consists mainly of rectangular elements.

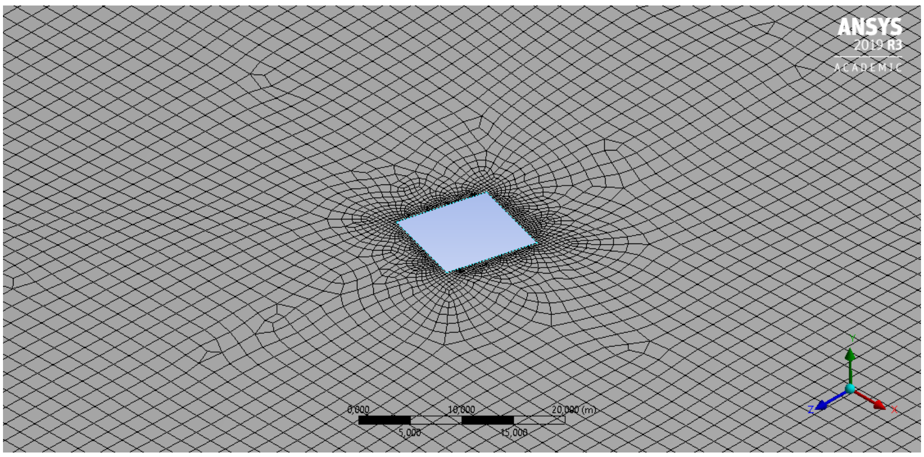

Fig. 2 - Design scheme and its mesh in the Ansys SP

To get a convergence graph, the number of iterations is set to 1000. The problem is solved with discrepancies less than 0.001, which is considered a success.

As an intermediate result, it is found that the wind pressure is positive on the windward side, and negative on the leeward side.

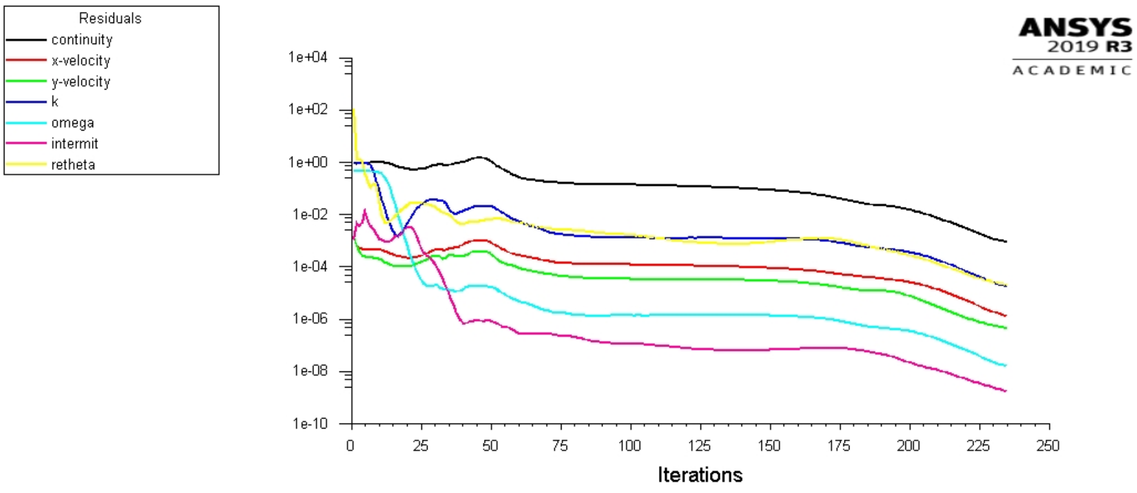

Fig. 3 - Convergence graph

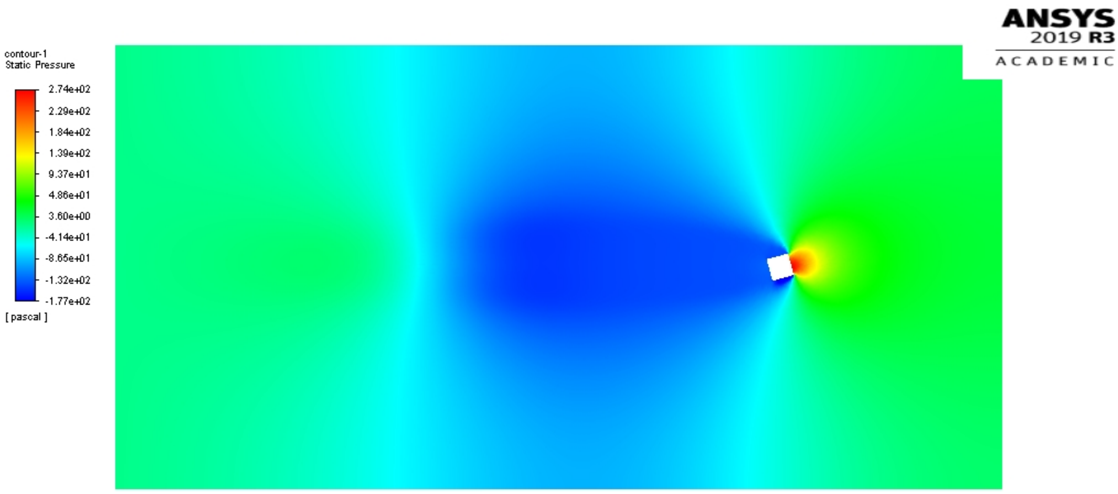

Fig. 4 - Static wind pressure around the design model

The static pressure value is necessary to know in order to find the aerodynamic coefficients defined for each boundary side of the structure.

The calculation is performed with the wind flow blowing at following angles: 0; 5; 10; 15; 20; 25; 30; 35; 40; 45 degrees. When the wind direction is at an angle to one of the sides of a rectangular structure other than 0 and 90 degrees, a bending moment occurs. The angle at which the bending moment is applied is 20 degrees for this design of structure.

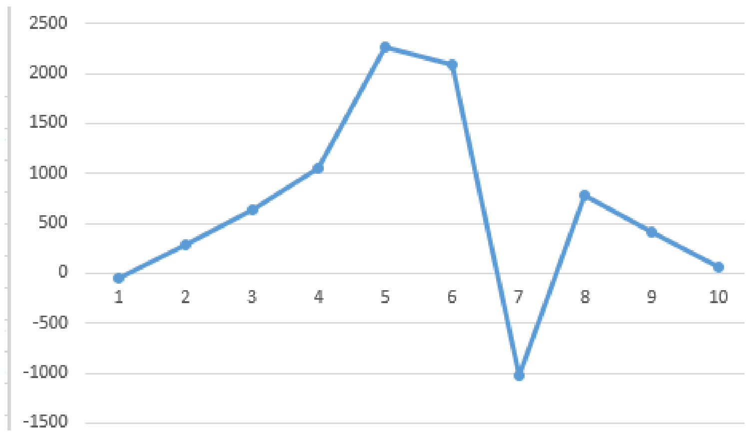

Fig. 5 - Graph of the bending moment depending on the angle of rotation of the structure

The study of stress-strain state of the tower under the action of a wind load that causes a bending moment is performed on the example of a demountable tower for diving. All elements of the tower structure are of Layher type. All design elements are modeled as rod elements, with shapes of cross-sections in the form of pipes: horizontal bracing – 48.3 x 3.2 mm, vertical bracing – 48.3 x 4.35 mm, in accordance with the structural elements of Layher. The design scheme of the structure is created in the LIRA Software Package, both the stiffness and load are also assigned there. The wind load is applied at a straight angle according to the regulatory documents and at an angle of 20 degrees, causing the largest bending moment, according to the results of previous gas dynamic calculation.

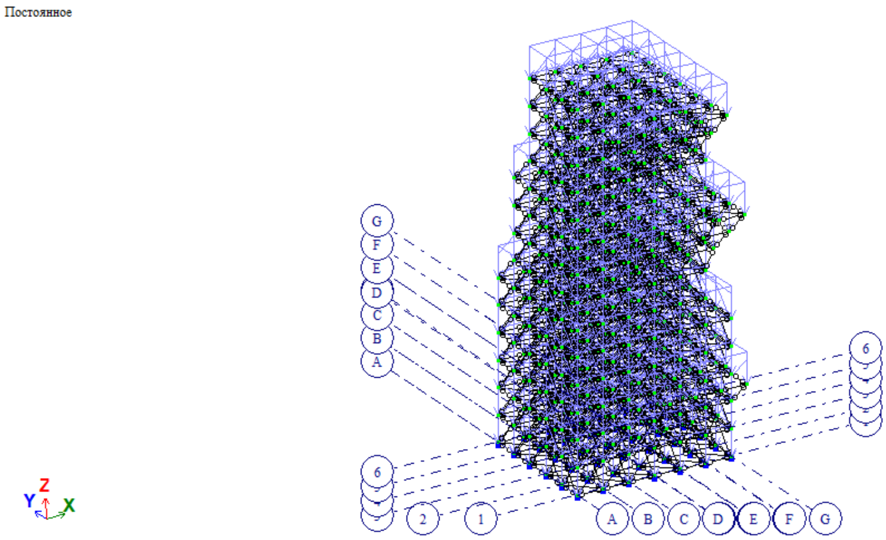

Fig. 6 – Design model of tower

3 Results and Discussion

The obtained maximum coefficients are averaged for each vertical element of the calculated tower, for further application of the wind load. For analysis, graphs of the bending moment at the ratio of the sides of the building are given for 1:1, 1:2, 1:4, 1:6, 1:8, and 1:10 at the angles of the wind flow direction to the building equal to 0, 15, 30, 45, 60, 75, 90 degrees.

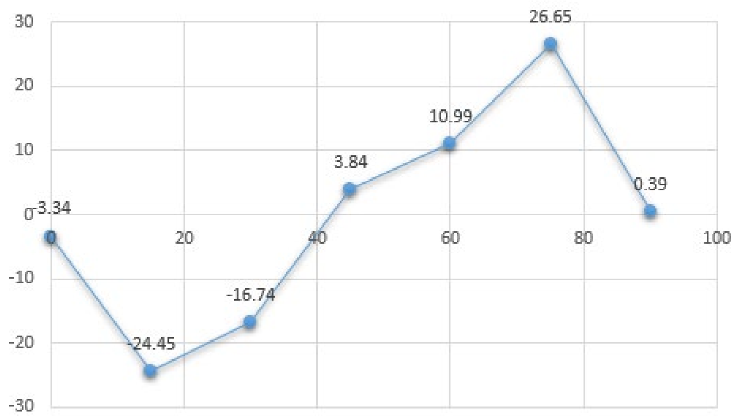

Fig. 7 - Graph of bending moment for the sides of the building with ratio of 1:1

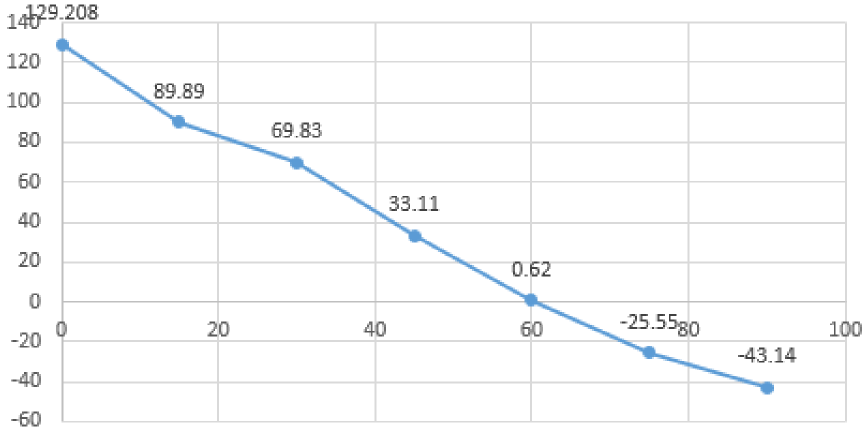

Fig. 8 - Graph of bending moment for the sides of the building with ratio of 1:2

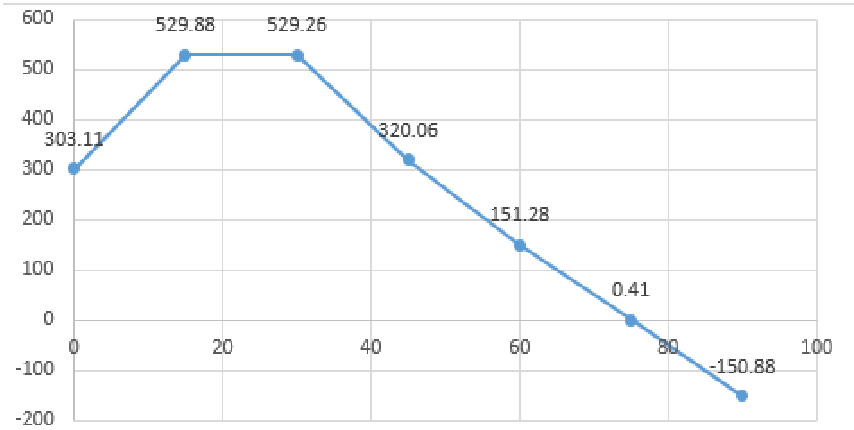

Fig. 9 - Graph of bending moment for the sides of the building with ratio of 1:4

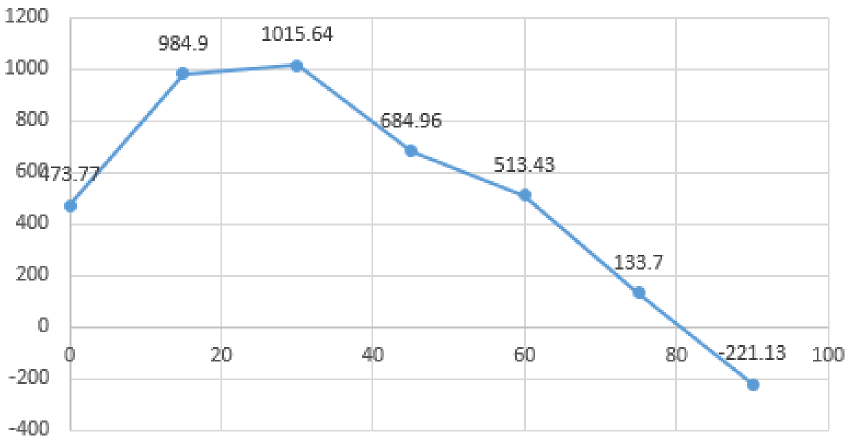

Fig. 10 - Graph of bending moment for the sides of the building with ratio of 1:6

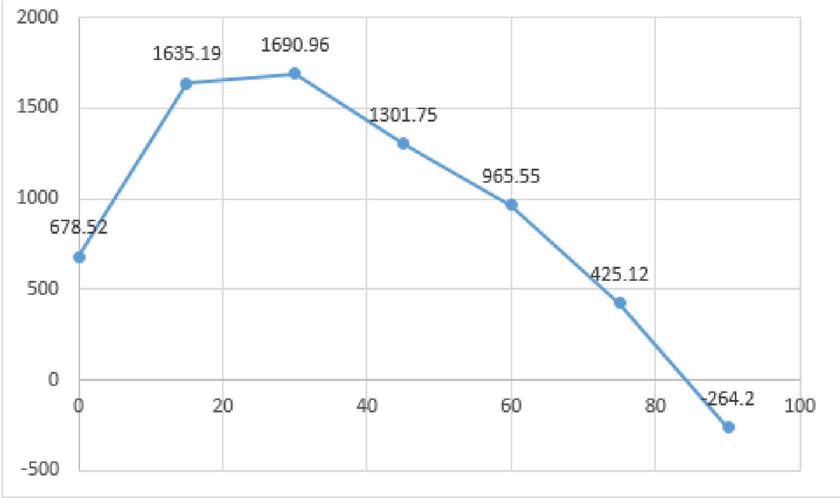

Fig. 11 - Graph of bending moment for the sides of the building with ratio of 1:8

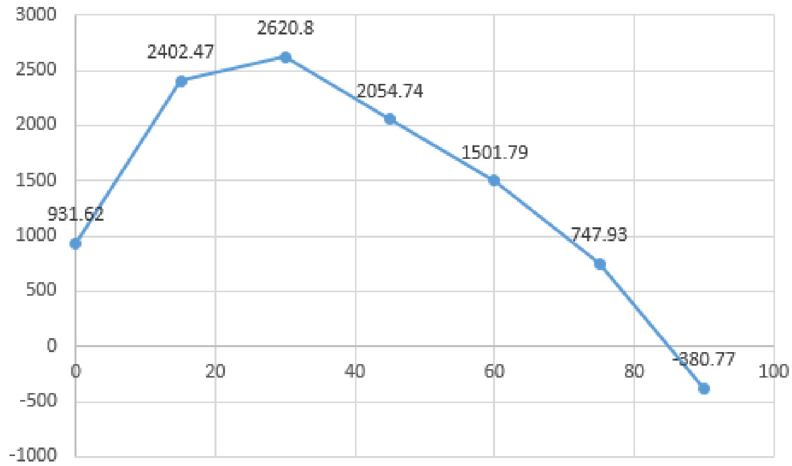

Fig. 12 - Graph of bending moment for the sides of the building with ratio of 1:10

The relative arm of the wind load is determined for each aspect ratio:

$$\Delta_i = \frac{M_{i\,max}}{\left(c_e + c_p\right) * b_i * \left(0.613 v^2\right)}, \quad (1)$$

where:

$M_{i\,max}$ – maximum bending moment;

$c_e; c_p$ - aerodynamic coefficients equal to 0.5 and 0.8, respectively (according to SP 20.1313330.2016 for the type of terrain B),

b_i – side of the object,

v - speed of the wind flow, 20m/s.

Based on the aerodynamic coefficients, it is shown that the uneven distribution of wind flow at different angles of application causes bending moments in the structure, which are not taken into account in the usual calculation in Russian regulatory document SP 20.13330.2016 "Loads and actions" [30] (https://docs.cntd.ru/document/456044318). In this regard, it is necessary to calculate the wind load taking into account the aerodynamic coefficients found for each building separately in order to avoid insufficient load-bearing capacity of the structure as a whole and avoid its collapse. It can also be concluded that when the ratio of wind sides of the tower increases, the arm of bending moment increases.

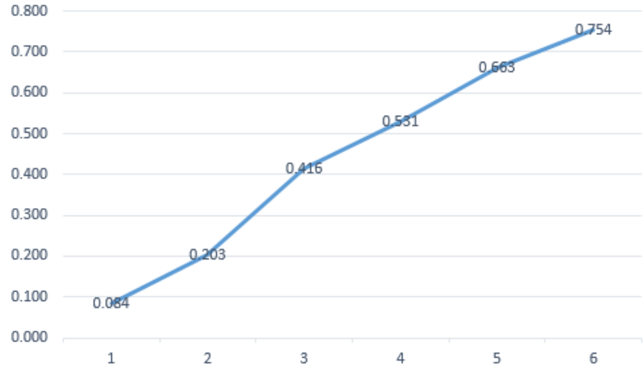

Fig. 13 - Graph of the bending moment’s dependence on the sides of the building ratio 1:1, 1:2, 1:4, 1:6, 1:8, 1:10

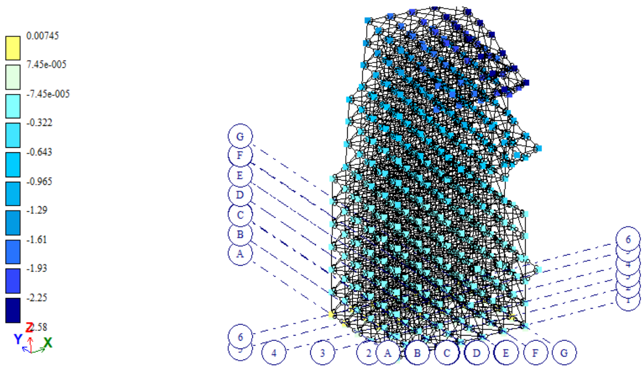

Fig. 14 - Mosaic of movements on Y without taking into account wind load unevenness

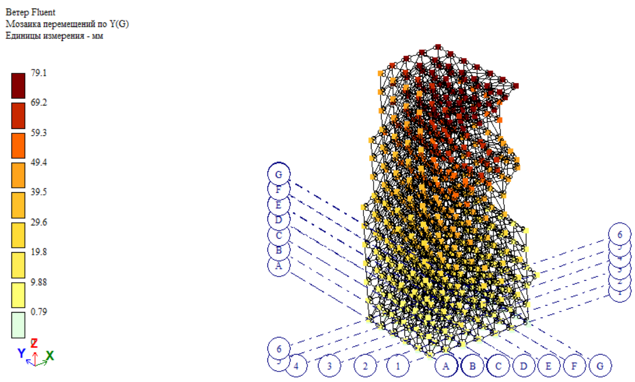

Fig. 15 - Mosaic of movements on Y taking into account wind load unevenness

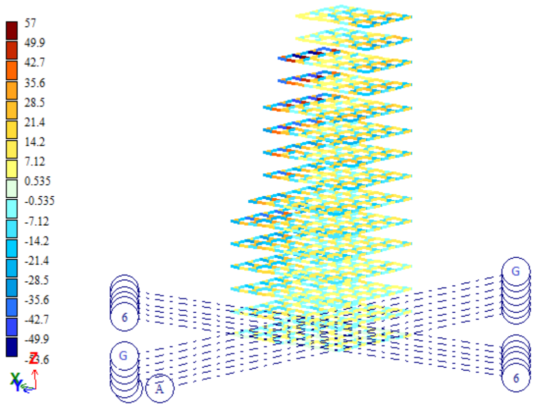

Fig. 16 - Mosaic of bending moments in the horizontal plane in crossbars in the absence of a system of horizontal braces

Uneven wind load causes torsion of the structure, which causes additional bending moments in the horizontal crossbars.

To ensure load-bearing capacity, the connection system must be installed as shown in the figure below (see Fig. 17). Horizontal braces must be set in the cells of the external contour, and the contour must be closed.

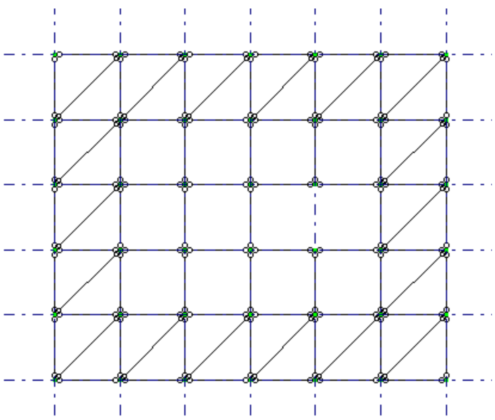

Fig. 17 - Scheme of installation of horizontal braces

According to the calculation, the load-bearing capacity of the crossbars, taking into account the horizontal braces in the cells, is sufficient.

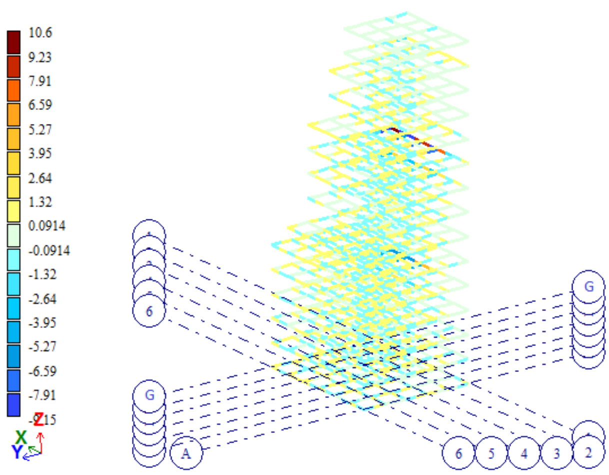

Fig. 18 - Mosaic of bending moments in the horizontal plane in crossbars in a structure with a system of horizontal braces

Using the example of a tower for diving, it is shown that taking into account uneven wind load causes additional forces in the elements of the structure, namely, the bending moment in the horizontal plane crossbars, which may lead to a failure to provide sufficient load-bearing capacity of the entire structure. For the perception of uneven wind load, a solution is proposed with the installation of horizontal braces in the cells of the external contour, while the contour must be closed.

4 Conclusions

1. Gas-dynamic calculation of rectangular buildings with aspect ratios from 1:1, 1:2, 1:4, 1:6, 1:8, and 1:10 is carried out. As a result of the calculation, aerodynamic coefficients and the angles of wind flow at which the maximum bending moment occurs are determined.

2. Based on the corresponding values, a graph of changes in the relative wind load's arm from the building's side ratio is provided. As the side ratio increases, the relative wind load's arm also increases: with a 1:1 aspect ratio, it is 6%, and with a 1:10 ratio, it is 75% of the size of the larger side.

3. The calculation of the stress-strain state of the tower for high diving events is also carried out. As a result of the calculation, it is determined that an uneven wind load causes twisting of the structure, resulting in additional bending moments in the horizontal crossbars, thus the sufficient load-bearing capacity of the structure is not provided.

4. A scheme for installing horizontal connections that provides the bearing capacity of the structure under wind load that causes twisting is proposed. The system of connections consists of installing additional horizontal braces in the external cells of the structure, thus forming a rigid contour with the crossbars.

References

1 Mendis, P., Ngo, T., Haritos, N., Hira, A., Samali, B. and Cheung, J. (2007) Wind Loading on Tall Buildings. *Electronic Journal of Structural Engineering*, **7**. https://doi.org/10.56748/ejse.641.

2 Mikheev, P., Okorokov, R., Sidorenko, G. and Timofeeva, A. (2020) Determination of Energy Costs of Wind Farms at All Life Cycle Stages. Advances in Intelligent Systems and Computing. https://doi.org/10.1007/978-3-030-19756-8_22.

3 Zu, G. and Lam, K.M. (2018) Simultaneous Measurement of Wind Velocity Field and Wind Forces on a Square Tall Building. *Advances in Structural Engineering*, **21**. https://doi.org/10.1177/1369433218770822.

4 Lam, K.M. and To, A.P. (1995) Generation of Wind Loads on a Horizontal Grandstand Roof of Large Aspect Ratio. *Journal of Wind Engineering and Industrial Aerodynamics*, **54–55**. https://doi.org/10.1016/0167-6105(94)00054-H.

5 Killen, G.P. and Letchford, C.W. (2001) A Parametric Study of Wind Loads on Grandstand Roofs. *Engineering Structures*, **23**. https://doi.org/10.1016/S0141-0296(00)00069-9.

6 Letchford, C.W. and Killen, G.P. (2002) Equivalent Static Wind Loads for Cantilevered Grandstand Roofs. *Engineering Structures*, **24**. https://doi.org/10.1016/S0141-0296(01)00085-2.

7 Overend, M. and Zammit, K. (2006) Wind Loading on Cladding and Glazed Façades. *Proceedings of the International Symposium on the Application of Architectural Glass (ISAAG)*. https://www.semanticscholar.org/paper/Wind-loading-on-cladding-and-glazed-façades-Overend-Zammit/d84f051514a4f7acc5003a555304e3132c542b77.

8 Liu, C., He, L., Wu, Z. and Yuan, J. (2018) Experimental and Numerical Study on Lateral Stability of Temporary Structures. *Archives of Civil and Mechanical Engineering*, **18**. https://doi.org/10.1016/j.acme.2018.06.002.

9 Chandrangsu, T. and Rasmussen, K.J.R. (2011) Structural Modelling of Support Scaffold Systems. *Journal of Constructional Steel Research*, **67**. https://doi.org/10.1016/j.jcsr.2010.12.007.

10 Cao, Z., Su, N., Wu, Y. and Peng, S. (2018) Gust Response Envelope Approach to the Equivalent Static Wind Load for Large-Span Grandstand Roofs. *Journal of Wind Engineering and Industrial Aerodynamics*, **180**. https://doi.org/10.1016/j.jweia.2018.07.014.

11 Yuan, X., Anumba, C.J. and Parfitt, M.K. (2016) Cyber-Physical Systems for Temporary

Structure Monitoring. *Automation in Construction*, **66**. https://doi.org/10.1016/j.autcon.2016.02.005.
12 Hu, H., Yang, Z. and Sarkar, P. (2012) Dynamic Wind Loads and Wake Characteristics of a Wind Turbine Model in an Atmospheric Boundary Layer Wind. *Experiments in Fluids*, **52**. https://doi.org/10.1007/s00348-011-1253-5.
13 Ahmad, S., Muzzammil, M. and Zaheer, I. (2011) Numerical Prediction of Wind Loads on Low Buildings. *International Journal of Engineering, Science and Technology*, **3**. https://doi.org/10.4314/ijest.v3i5.68567.
14 Sauca, A.C., Milchiș, T. and Gobesz, F.-Z. (2019) Wind Loading on Solar Panels. *Műszaki Tudományos Közlemények*, **10**. https://doi.org/10.33894/mtk-2019.10.10.
15 Wang, F., Lam, K.M., Zu, G.B. and Cheng, L. (2019) Coherent Structures and Wind Force Generation of Square-Section Building Model. *Journal of Wind Engineering and Industrial Aerodynamics*, **188**. https://doi.org/10.1016/j.jweia.2019.02.019.
16 Van Uffelen, G.M. (2009) Wind-Induced Building Interference: Increase of Wind Loads on Existing Buildings after Erection of New High-Rises. 5th European and African Conference on Wind Engineering, EACWE 5, Proceedings. https://iawe.org/Proceedings/5EACWE/114.pdf.
17 Chekalin, A. V., Andreev, V.M., Ascheulov, Y. V. and Chumakov, Y.S. (2019) Aerodynamics for CPV: Investigating the Efficiency of Using Air Fairings on Solar Trackers. AIP Conference Proceedings. https://doi.org/10.1063/1.5124195.
18 Petersen, W., Øiseth, O. and Lourens, E. (2020) Investigation of Dynamic Wind Loads on a Long-Span Suspension Bridge Identified from Measured Acceleration Data. *Journal of Wind Engineering and Industrial Aerodynamics*, **196**. https://doi.org/10.1016/j.jweia.2019.104045.
19 He, Y.C., Lin, H.B., Fu, J.Y., Chan, P.W., Zheng, Q.X. and Deng, T. (2021) Dependence of Wind Load on Air Density for Highrise Buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, **211**. https://doi.org/10.1016/j.jweia.2021.104558.
20 Salehinejad, M.M. and Flay, R.G.J. (2021) A Review of Approaches to Generate Equivalent Static and Synthetic Wind Loads on Tall Buildings for the Preliminary Stage of Design. *Journal of Wind Engineering and Industrial Aerodynamics*, **219**. https://doi.org/10.1016/j.jweia.2021.104823.
21 Li, Y., Tian, X., Tee, K.F., Li, Q.S. and Li, Y.G. (2018) Aerodynamic Treatments for Reduction of Wind Loads on High-Rise Buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, **172**. https://doi.org/10.1016/j.jweia.2017.11.006.
22 Stathopoulos, T. and Alrawashdeh, H. (2020) Wind Loads on Buildings: A Code of Practice Perspective. *Journal of Wind Engineering and Industrial Aerodynamics*, **206**. https://doi.org/10.1016/j.jweia.2020.104338.
23 Elshaer, A., Gairola, A., Adamek, K. and Bitsuamlak, G. (2017) Variations in Wind Load on Tall Buildings Due to Urban Development. *Sustainable Cities and Society*, **34**. https://doi.org/10.1016/j.scs.2017.06.008.
24 Dagnew, A.K. and Bitsuamlak, G.T. (2013) Computational Evaluation of Wind Loads on Buildings: A Review. Wind and Structures, An International Journal. https://doi.org/10.12989/was.2013.16.6.629.
25 Zang, C., Gong, B. and Wang, Z. (2014) Experimental and Theoretical Study of Wind Loads and Mechanical Performance Analysis of Heliostats. *Solar Energy*, **105**. https://doi.org/10.1016/j.solener.2014.04.003.
26 Guo, J., Zhu, M. and Hu, C. (2020) Study on Wind Load Shape Factor of Long-Span Stadium Roof. *Advances in Structural Engineering*, **23**. https://doi.org/10.1177/1369433220908111.
27 Kwon, D.K., Kareem, A., Stansel, R. and Ellingwood, B.R. (2015) Wind Load Factors for Dynamically Sensitive Structures with Uncertainties. *Engineering Structures*, **103**. https://doi.org/10.1016/j.engstruct.2015.08.031.
28 Natalini, B. and Natalini, M.B. (2017) Wind Loads on Buildings with Vaulted Roofs and Side Walls – A Review. *Journal of Wind Engineering and Industrial Aerodynamics*, **161**. https://doi.org/10.1016/j.jweia.2016.12.004.
29 Xu, J., Xu, H., Zeng, C., Xie, C. and Guo, J. (2020) CFD Simulation Study on Wind Load of Perforated Traffic Sign Board. *PLoS ONE*, **15**. https://doi.org/10.1371/journal.pone.0240927.
30 SP 20.13330.2016 Loads and Actions. https://docs.cntd.ru/document/456044318.