NUMERICAL SIMULATION OF WIND LOADS ON HIGH RISE BUILDINGS[1]

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ABSTRACT: *Article presents a methodology of the numerical simulation of the wind on high-rise buildings, which was developed by the Department of "Computer-aided design of structures" of the Ural Federal University named after the first President of Russia B.N. Yeltsin. Paper includes the results of researches on development of a technique of determination of wind pressure upon high-rise buildings by means of numerical modeling in an ANSYS package. The investigation was carried out within the grant of the Russian Academy of Architecture and Building Sciences. The results are applied to calculation of wind pressure upon a number of high-rise buildings under construction in Yekaterinburg City (Russia).*

Simulation is performed in the program ANSYS. The simulated building is placed in a domain that is the numerical analogue of wind tunnel. Domain sizes are chosen in such a way that simulated buildings do not affect the flow of air on its boundaries. Shear stress transport (SST) turbulence model has been used. This model effectively combines the stability and accuracy to the standard k-ω model in the areas, which are placed near the walls and the effectiveness of the k-e model at a distance from the walls with a smooth transition between them (input expansion functions). For the numerical solution of the governing equations the finite volume method was used (FVM). The scale of the turbulence is assumed to be 200-300m.

Use of the developed technique is shown on the example of calculation of wind pressure and wind velocities in pedestrian area for high-rise building under construction in the City of Ekaterinburg.

KEYWORDS: *high-rise building, wind impact, simulation, wind loads.*

1. INTRODUCTION

Wind loads on high-rise buildings have the great impact on their stress-strain state. Analysis of the standard values of wind pressures for buildings higher than 200 meters shows that the wind pressure can be more dangerous to the overall strength than the nine-point earthquake. Active codes of practice (SNIP 2001, Eurocode 1 1994, British Standard 1995, AIJ Recommendations 1996) do not sufficiently reflect wind effects on high buildings. In order to determine the wind loads both on the facade design and the framework of the building it is necessary to apply the experimental and numerical methods, which include: monitoring and field measurements, wind tunnel tests and numerical simulation.

In the recent 10-15 years computational fluid dynamics (CFD), technology of computations of wind loads on buildings and structures are rapidly developing at a steadily increasing power of computers. The creation of adequate computational models of high-rise buildings providing agreement between the numerical simulation and experimental data gives the possibility of the more accurate estimation of their stress-strain state and more accurate prediction of behavior of structures during their lifetime.

The purpose of the paper is to describe the procedure of determination of wind pressure on the walls and framework of high-rise buildings by numerical simulation. To create a computational model of the numerical analogue of wind tunnel the following steps are required: the choice of a mathematical model of the problem and model of turbulence; creation of the computational domain and finite volume rid; setting the boundary conditions.

2. MATHEMATICAL MODEL

The numerical model of incompressible air flow based on Reynolds equations was used for undertaking of numerical simulations (Loytsyanskiy 2003):

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Momentum equation

$$\rho\frac{dV}{dt}=-grad\left(p+\frac{2}{3}\mu_\Sigma divV\right)+2Div(\mu_\Sigma\dot{S}) \quad (1)$$

where ρ – density; V – velocity; p – static pressure; $\mu_\Sigma = \mu + \mu_t$, μ – molecular viscosity coefficient, μ_t – turbulence viscosity coefficient; $\dot{S}$ – deformation velocities tensor.

Continuity equation

$$div(V)=0 \quad (2)$$

To solve the differential equations the finite volume method is used. Computations are performed using methods and algorithms that are applied in the software package ANSYS. A "hybrid" model of turbulence SST (shear stress transport, transfer of shear stress) is used. The model effectively combines the stability and accuracy of the standard k-ω model in the near-wall regions and the effectiveness of k-ε model away from the wall with a smooth transition between them. This model corresponds to the world experience in solving the similar problems (Menter 2009).

3. THE COMPUTATIONAL MODEL AND BOUNDARY CONDITIONS

The high-rise building and surrounding objects are placed in the domain, which is analogous to a wind tunnel. Domain sizes are selected so that air flow on its boundaries are not affected by buildins placed in it. In the experience of testing in the wind tunnel it is assumed that the building height H affects up to a distance of 10 H. The size of the computational domain in the flow direction should be not less than 5H. The distance behind the building is recommended to be not less than 15 - 20 H. These recommendations correspond to thesis (Dubinsky 2010) and the work on experimental studies (Kozmar 2011, Plate 1982). The minimum sizes of the computational domain are shown in Figure 1 (Dubinsky 2010). The air flow must not be disturbed near the domain boundaries.

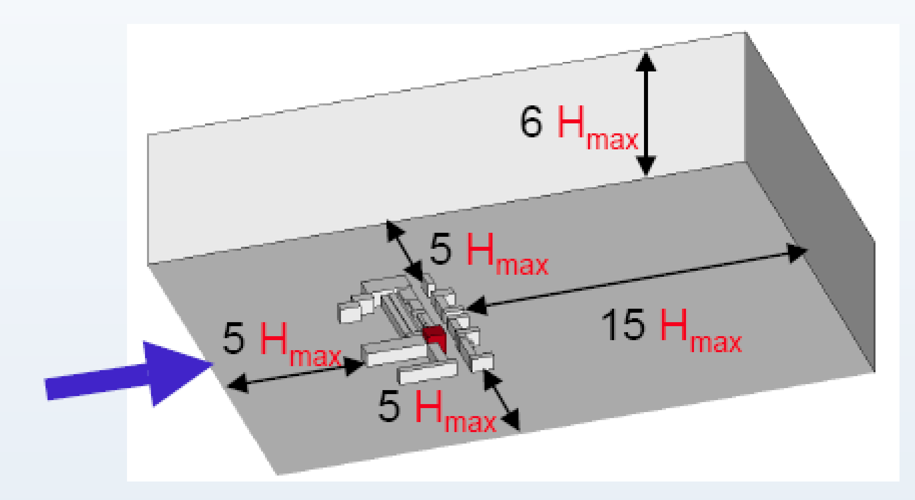

Fig. 1: The minimum dimensions of the computational domain for H-maximum height of the building.

Fig. 2 shows the domain for Iset Tower in which the objects are arranged. The top and side walls of domain are specified as «OPENING» - air flow can pass through the domain wall both inwardly and outwardly. The front of the domain is taken as «INLET» - air flow can be directed only into the domain. The opposite side surface - «OUTLET» - air flow can only be routed from the domain. The bottom surface of the domain and the surfaces of the buildings are taken as «WALL» - zero mass transfer.

The “no slip” condition is used in all boundary walls.

On the bottom boundary of the domain (type WALL) a roughness parameter can be specified which is determined by the characteristic height. This allows taking into account the objects on the ground which is not taken into account in the computational domain geometry (trees, no tall buildings). In urban areas it is recommended to take this option equal to 2 m (Simiu 1984).

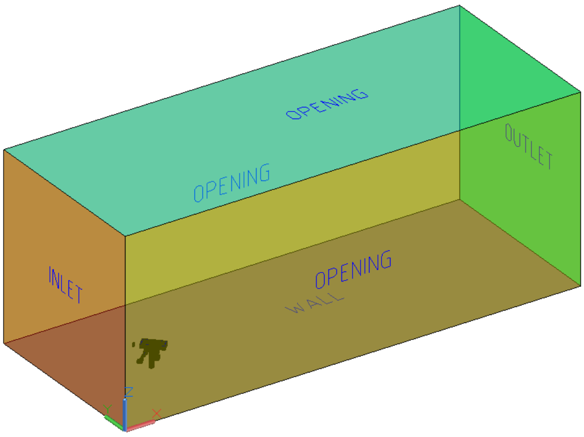

Fig. 2: Scheme of the domain.

On the front surface of the domain «INLET» the distribution of wind velocities on the basis of known meteorological data is given. During the calculation of high-rise buildings in the city of Ekaterinburg city (Russia) the initial distribution of wind speeds is taken as a power law (AIJ 1996):

$$V(z)=V_{ref} \cdot 1.7 \cdot (z / Z_D)^{\alpha}, \qquad (3)$$

where V (z) - wind velocity (m/s) at height z; V_{ref} - wind velocity at a height of 10 m; Z_D - a parameter depending on the height and density of buildings in the surrounding area. For the urban area of Ekaterinburg (V_{ref} = 23 - 13 m/s; α = 0,27; Z_D = 550) the distribution of wind velocities at a height corresponds to the Russian design standards (SNIP 2001).

Temporary law of wind oscillations is taken from (Dubinsky 2010)

$$V = V(z) \cdot (1+0.25 \cdot \sin(\omega \cdot t)), \qquad (4)$$

where the frequency $\omega = 2\pi / 5$, and 5 s - the time of one complete oscillation (obtained on the basis of numerical experiments). Total time for transient calculations was set to 100s, time step was about 1s.

Air parameters used in computations were taken as follows: temperature: 25 º C, the air density: 1.185 kg / m^3; air molar mass: 28.96 kg / kmol. As it was shown by the numerical computations the parameters at heights of buildings about 100 – 200 m varies slightly.

The geometry of the building is modeled precisely and the geometry of other objects included in the domain was modeled coarsely.

As an example the wind loads on 52th floor of the building "Iset Tower" are investigated. Area of high-rise building is 70600 sq.m., height – 209m. It consists of two main blocks: the living part (52 above-ground floors) and underground part (four floors) with parking and technical facilities. "Iset Tower" is a part of new business district "Ekaterinburg - City" that occupies a location in the heart of Ekaterinburg (figure 3).

The area of high-rise buildings is situated close to the river Iset. In the right part of the figure 3 the building of an existing hotel "Hyatt" is shown in the green. On the left side high-rise building complex "Iset Tower" is shown in the yellow. The blue color shows the Iset River. The surface of the circular high-rise building under construction is ribbed (figure 3) and the ribs height is 700mm (figure 4).

Experimental examination in the wind tunnel of the pressure on the building surfaces caused by wind was made by the company «WACKER INGENIEURE», Germany. The scale of the model was 1/380. Due to such a high scale of the model there were some questions about the distribution of wind pressure on the surfaces of the building and the mechanism of their transfer to the ceiling of reinforced concrete frame.

Fig. 3: "Ekaterinburg - City" area (project).

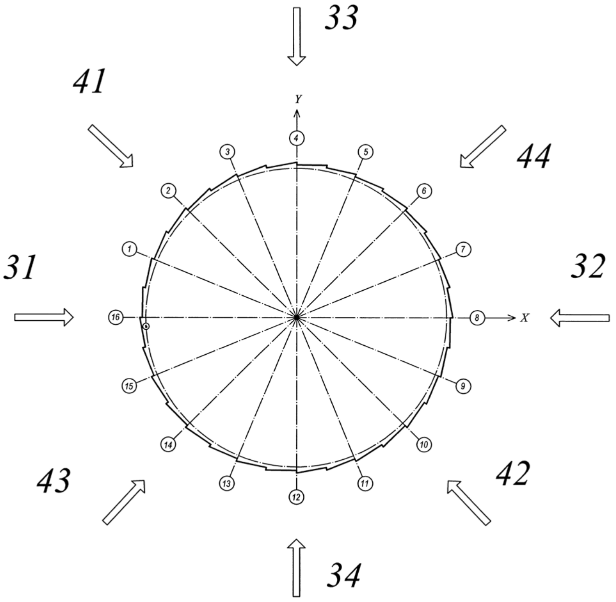

Fig. 4: Shape surface of the circular part of the building. The numbers and arrows show the direction taken in the calculation of the wind. The height of ribs on the facade is 700mm.

Finite volume mesh mostly consisted of the tetrahedral cells with prisms in the wall regions. The size of the cells was assumed to be near the boundaries of the domain - 100 meters, near the surface of the building - 0.5 meters. Figure 5 shows the finite element mesh in the boundary layer.

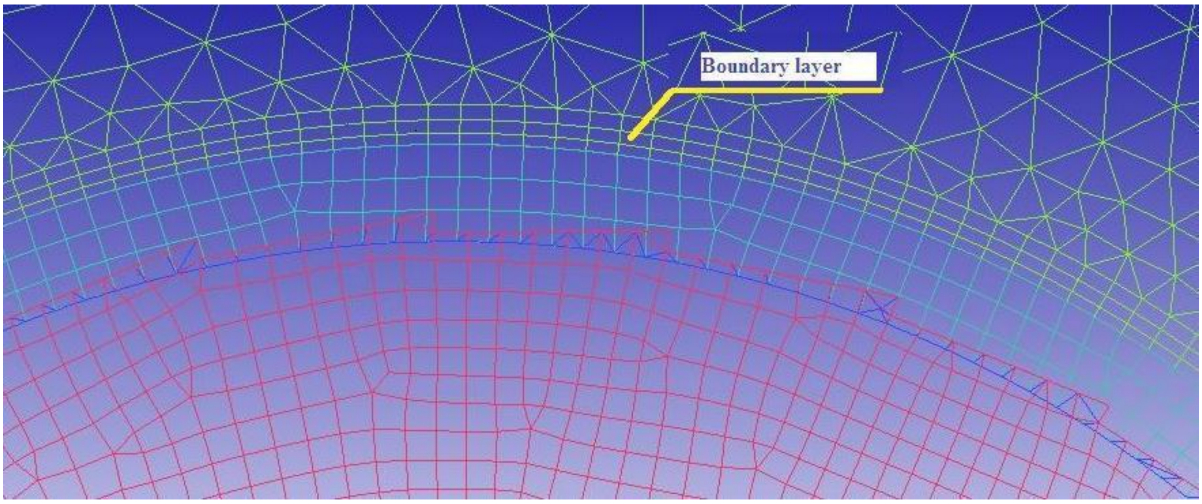

Fig. 5: The boundary layer.

The finite volume mesh size generally requires at least 2-3 finite elements on 1 meter of height. Cells on the surfaces of buildings were chosen mainly square. The triangular cells yield a square, as the square elements gives minimum errors due to averaging. The number and size of cells for the high-rise building satisfies this condition. It can be seen from Figure 6 that in the range of one floor there are 6 finite volumes 0.5 x 0.5 meters. Several theoretical models with different sizes of finite elements were built. In circumstances of the above mentioned recommendations for different grids the same results were obtained.

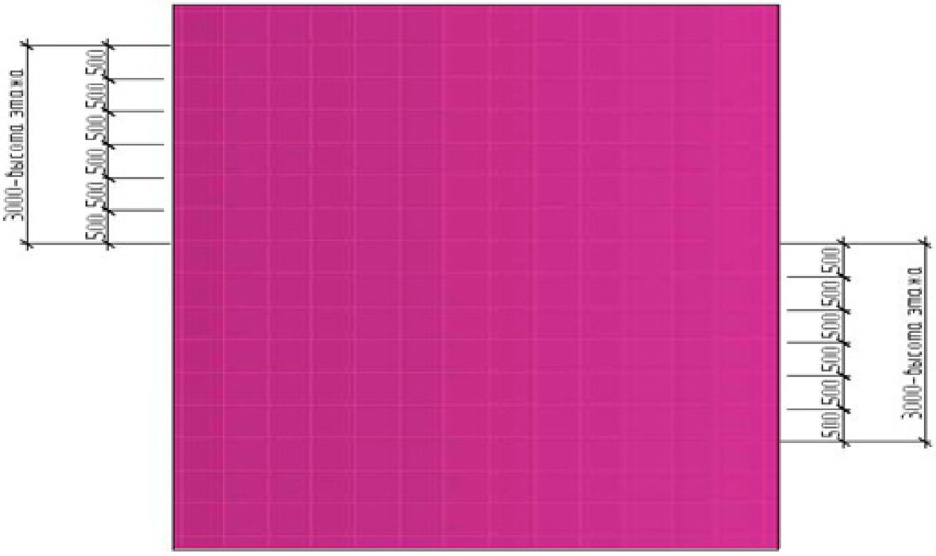

Fig. 6: The part of vertical wall of the building.

4. RESULTS OF COMPUTATIONS

The solution of the steady state problem is done, and the results are clarified by the solution of the trancient problem. Figure 7 shows the characteristic form of pressure distribution along the height of the building. Figure 8 shows the pattern of distribution of velocities at a height of 58.5 m.

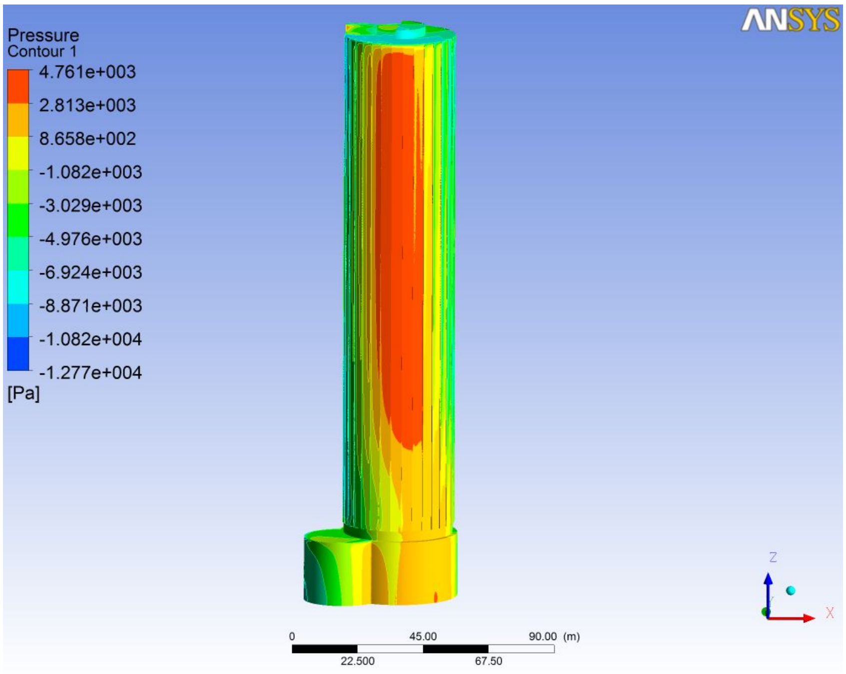

Fig. 7: The distribution of pressure to the building.

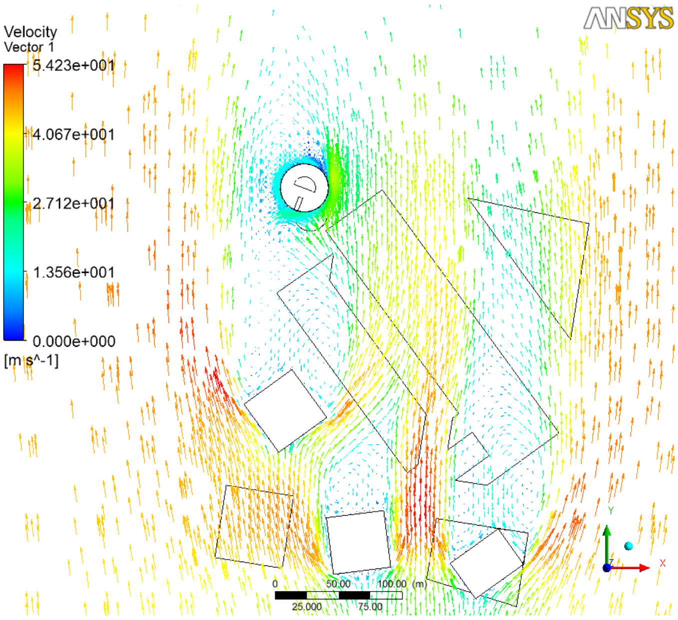

Fig. 8: The distribution of velocities at a height 58.5 m.

The resulting pressure on the surface of the building was transformed with the help of specially designed computer programs to average pressures in the level of floors and was applied to a computational model of the building framework (Figure 9). The development of two computational models of the building was caused by the lack of resources of used computers because automatic transfer of pressure to the computational model of the building is possible only for a solid model using three-dimensional finite elements. The computational model of the framework was created using the core and shell finite elements.

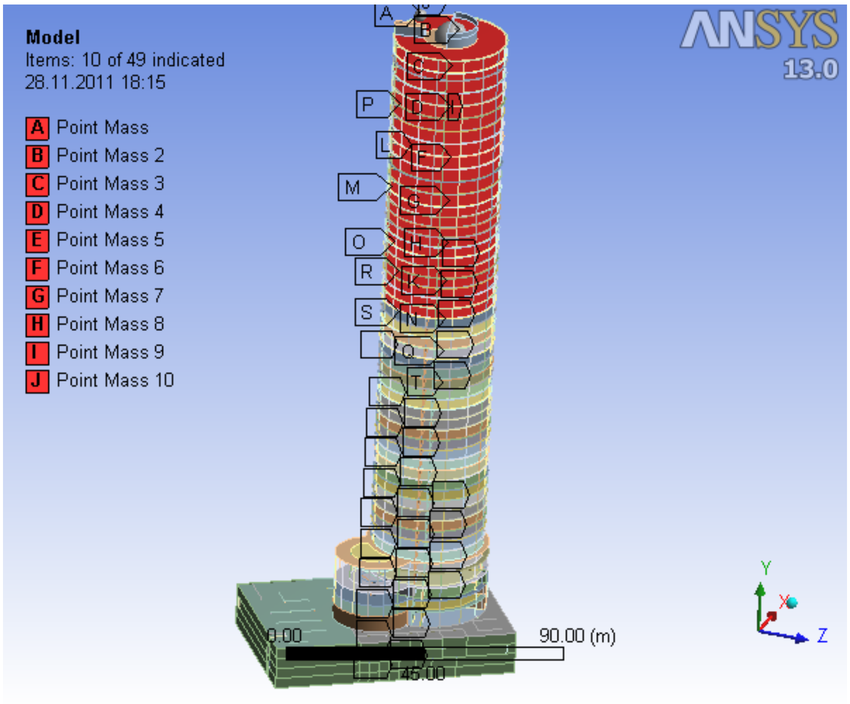

Fig. 9: The computational model of the building framework

Figure 10 shows typical graphs of the mean and fluctuating components of wind pressure in points on the surface of the building.

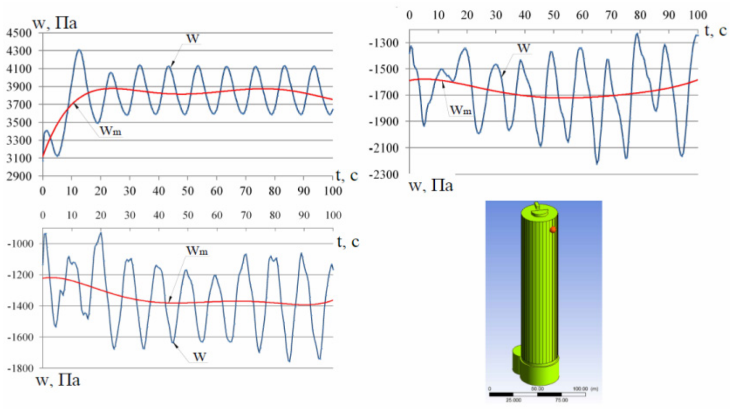

Fig. 10: Graphs of the total wind pressure and the mean component in the point marked in red on the facade of the building.

The obtained results were compared with experimental data: the values of the total force of wind loads acting in the center of gravity of the upper round part of the building.

The numerical method of simulation of aerodynamics of high-rise buildings has been applied to a number of objects under construction and planning in Ekaterinburg (Russia).

The analysis of experience led to a more reasonable calculation in order to determine maximum loads on the structure of buildings. The authors believe that the ultimate test of the correctness of calculations is the coincidence of numerical and experimental data. An experimental model does not fulfill all the requirements of the similarity theory (Plate), and numerical models require experimental verification.

5. CONCLUSION

Numerical analysis showed:

- The numerical estimation of the frequency of natural oscillations of the building design models presented in the paper are quite close to the experimental data.

- The maximum total force of wind loads acting in the center of gravity of the upper round part of the building determined from the simulations for different directions of the wind are close to the experimentally obtained values.

- The difference of values of the wind pressure are due to different structural models of buildings that were used in experimental studies and calculations, as in the numerical analysis the computational model of the building was constructed according to the working draft.

Above considered calculations show qualitative agreement with experimental results.

According to the results of numerical simulation of wind effects it can be concluded that in the design both aerodynamic experiments and numerical analysis are needed. If there is coincidence of experimental and numerical results then they can be used to calculate the skeleton of the building.

6. ACKNOWLEDGEMENTS

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