DOI: 10.23968/2500-0055-2024-9-2-79-85

RESULT VERIFICATION FOR NUMERICAL MODELING OF WIND EFFECTS ON UNIQUE BUILDINGS AND STRUCTURES

Olga Poddaeva

Research and Production Laboratory of Aerodynamic and Aeroacoustic Testing of Building Structures, Moscow State University of Civil Engineering, Moscow, Russia

E-mail: poddaevaoi@gmail.com

Abstract

Introduction: Despite the fact that wind tunnel testing is quite expensive and time-consuming, physical modeling in wind tunnels remains the primary method for determining wind effects on unique buildings and structures. Computational fluid dynamics (CFD) provides more variability, calculations are performed faster and at a lower cost. However, the issue of accuracy of integral characteristics obtained as a result of numerical modeling and, accordingly, verification procedure remains open. Currently, when using numerical modeling results in structural aerodynamics, it is mandatory to verify them with experimental data. In recent years, studies have explored the CFD potential for accurate wind load predictions, but there have not been studies presenting a comprehensive description and implementation of a verification and validation system to analyze wind effects on unique buildings and structures. The **purpose of the study** was to compare the CFD results with the wind tunnel test data for three different objects, analyze the results, and propose a method for verification and validation of CFD analysis of wind effects on unique buildings and structures. The following **methods** were used: physical testing of models of unique buildings and structures in a wind tunnel, including a detailed method of experimental studies to determine integral aerodynamic characteristics, as well as numerical modeling of wind effects using ANSYS. Numerical modeling was performed in two setups: with and without virtual wind tunnel modeling. As a **result**, it is shown that virtual wind tunnel modeling makes it possible to achieve better data consistency when verifying numerical modeling results with physical modeling data, and the proper use of numerical modeling technology can significantly reduce the time and cost of experimental studies in a wind tunnel and/or reduce the design time by decreasing the number of considered loading scenarios.

Keywords: verification; CFD; wind tunnel; integral aerodynamic characteristics.

Introduction

Experimental modeling in wind tunnels is the primary method of determining wind effects on unique buildings and structures, including facilities with a high criticality rating. This method is quite conservative and provided in the majority of regulatory documents pertaining to construction both in the Russian Federation and abroad. However, wind tunnel testing is expensive and time-consuming, which significantly complicates the design of unique buildings and structures (Kareem et al., 2013). Active development of software and computational capacities makes it possible to solve a number of problems using a more modern method — numerical modeling. Compared to wind tunnel testing, CFD ensures a higher variability of input data, calculations can be performed faster and at a lower cost (Galerkin et al., 2020). Compared to traditional tools, CFD has unique advantages, including: lower time- and cost-to-solution, greater flexibility in design parametrization, and access to flow conditions in the entire calculation domain (Blocken, 2014). At the same time, CFD is characterized by some difficulties mainly caused by the following factors: large Reynolds number, which requires fine grid resolution, complexity of flow field with impinging, sharp edges of a bluff body, flow obstacles at inflow and outflow (Murakami, 1998). At this stage of computational technology development, when using numerical modeling results in structural aerodynamics, it is mandatory to verify them with experimental data.

The integrated use of experimental and numerical modeling results makes it possible to obtain the most complete and reliable picture of wind effects on building structures.

The aerodynamic coefficients of external pressure on the surface of the facades and roofs of the facility under consideration represent a result of comprehensive computational and experimental studies of wind effects on building structures, in accordance with the requirements of regulatory documents. Studies are conducted for a representative set of wind flow directions. Usually, the model rotation step is 10–15°. Thus, as a result of the studies, it is possible to predict 24–36 different scenarios for loading the structure of the building under consideration with wind flow.

This information is redundant for a designer. In real design activity, it is sufficient to consider

For citations: Poddaeva, O. (2024). Result verification for numerical modeling of wind effects on unique buildings and structures. Architecture and Engineering, No 2 (9), pp. 79–85. DOI: 10.23968/2500-0055-2024-9-2-79-85.

3–4 most unfavorable cases. This brings up the following question: how to assess the need to take into account a particular loading scenario? The most obvious option is to estimate the total wind effect on the structure and the resultant aerodynamic force relative to the facility base.

The classical drainage aerodynamic experiment involves determining pressure at control points on the surface of the model. A system based on differential pressure sensors is used as a measuring system; special preparation of the model is required (pneumatic line routing in the intra-model space, sensor installation, etc.). To estimate the resultant aerodynamic force, it is necessary to sum up the values of wind pressure at control points, while taking into account the direction of the wind flow velocity vector and the orientation of the control point relative to that vector, which is a rather effort-demanding task that should be addressed for each model individually.

Therefore, in this case, it is recommended to perform additional tests using force-torque sensors, which make it possible to determine integral aerodynamic characteristics immediately and, based on them, easily calculate the resultant aerodynamic force. Such tests require fundamentally different model preparation. A single force-torque sensor is used, which is attached at the base of the model. It is necessary to prevent any model contact with the surrounding wind tunnel surface, etc. These factors do not allow for simultaneous measurement of pressure on the surface of the model and force-torque characteristics, and sometimes lead to the need to develop an additional model, which significantly increases the time and cost of experimental studies.

In this situation, mathematical (numerical) modeling can come to the aid. When performing CFD calculations in specialized software, an analyst can provide for any form of result output. Thus, in one calculation, it is possible to obtain both a pattern of pressure distribution over the surface of the model and integral characteristics of the wind effect for the relevant point.

The issue of accuracy of integral characteristics obtained as a result of numerical modeling and, accordingly, verification procedure remains open.

In recent years, some studies have explored the accuracy of predicting wind load on unique buildings and structures using CFD (Aboshosha et al., 2015; Ricci et al., 2018; Zhang et al., 2015). These studies show the CFD potential for accurate wind load predictions, but there have not been studies presenting a comprehensive description and implementation of a verification and validation system to analyze wind effects on unique buildings and structures.

Methods

This paper addresses verification of the results of experimental studies on integral wind loads using force-torque sensors with corresponding mathematical calculations in specialized ANSYS CFD software. Three structures of different types — a long low-rise building of an airport complex (Fig. 1), a high-rise residential complex (Fig. 2), and a chimney as part of a coke oven complex (Fig. 3) — were selected as objects of the study. All facilities selected for verification of numerical modeling are unique buildings and structures, which should have aerodynamic coefficients assigned according to the results of physical tests in wind tunnels.

The experimental studies were carried out with the use of a unique research setup — the Large Gradient Wind Tunnel, courtesy of the National Research University “Moscow State University of Civil Engineering”. For the experimental studies, models of the structures were made at the following scales: 1:200 — the airport complex (Fig. 4), 1:150 — the residential complex (Fig. 5), 1:125 —

Fig. 1. Long airport complex building

the chimney as part of the coke oven complex (Fig. 6). The models were used for both drainage tests and force-torque tests (after a complete retrofit to match the specifics of the measurement equipment).

The methodology for the *experimental studies* was described in detail by Poddaeva (2022). When experimental tests are conducted to determine integral aerodynamic characteristics, the measurement system includes force-torque sensors. During this study, Schunk FTD sensors with the following characteristics were used:

Measuring range Fx, Fy: ± 660 N;
Measuring range Fz: ± 1980 N;
Measuring range Mx, My, Mz: ± 60 N*m;
Measuring accuracy Fx, Fy: ± 0.125 N;
Measuring accuracy Fz: ± 0.25 N;
Measuring accuracy Mx, My, Mz: ± 0.008 N*m.

Based on the test results, aerodynamic force and torque components along the X, Y and Z axes are determined. Based on the results of the tests to determine force-torque characteristics, aerodynamic coefficients are calculated according to the following equations:

$$C_x = \frac{F_x}{q_\infty S}; C_y = \frac{F_y}{q_\infty S}; C_z = \frac{F_z}{q_\infty S};$$

$$C_{Mx} = \frac{F_x}{q_\infty Sl}; C_{My} = \frac{F_y}{q_\infty Sl}; C_{Mz} = \frac{F_z}{q_\infty Sl}, \quad (1)$$

where C_x — drag coefficient; C_y — transverse force coefficient; C_{Mz} — torque coefficient; q_∞ — dynamic pressure; S — reference frontal area of the model; l — arm in the given coordinate system.

Forces and torques are measured relative to the zero point of the force-torque sensor.

Fig. 2. High-rise residential complex

Fig. 3. Chimney as part of the coke oven complex

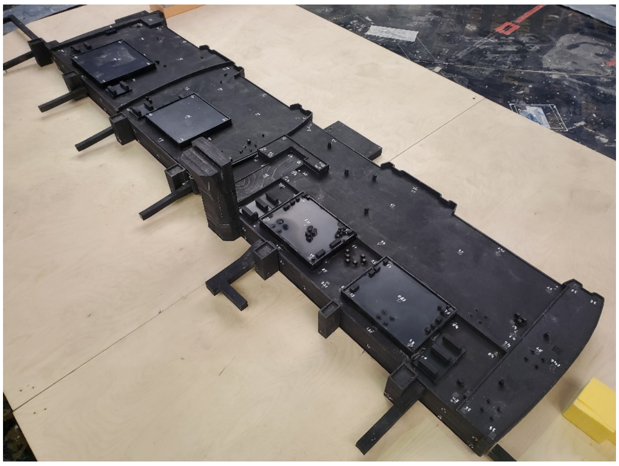

Fig. 4. Model of the airport complex, scale 1:200

Fig. 5. Model of the residential complex, scale 1:150

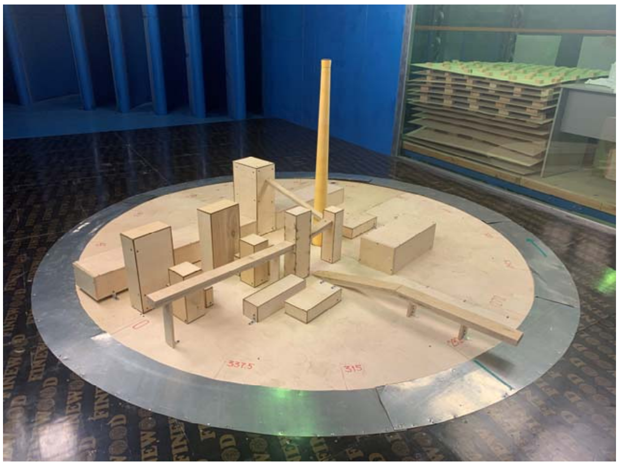

Fig. 6. Model of the chimney as part of the coke oven complex, scale 1:125

The force-torque sensors used must be graduated prior to testing. Graduation is carried out by conducting control tests. Control tests should be performed not earlier than 2 days before aerodynamic tests.

Equipment included in the National Register of Measuring Equipment and having a valid certificate of measuring instrument verification issued by an organization having accreditation for the right to perform works and (or) render services on verification and calibration of measuring instruments shall be used as control equipment during graduation. It is recommended to use a set of weights, class E2, with a weight range from 10 g to 10 kg, as a control device for load application.

To conduct control tests, it is necessary to follow and fix the following external parameters during verification:

- ambient air temperature — not lower than 20º (fixation);
- atmospheric pressure (fixation);
- it is not allowed to have heat sources near the system being verified and the reference equipment.

During graduation, a load of a certain value (minimum measuring range) is applied to the force-torque sensor via a suspension system using weights.

Scales readings at a steady load applied to them are saved (in N) with the help of the control software. The value of the control load is recorded in the appropriate column of the graduation report.

Using the set of weights, the load on the scales is modified according to the graduation method (minimum measuring range) with a given step.

As part of preparations, a control model point is selected relative to which measurements will be made.

The force-torque sensor model is selected based on the weight of the model and preliminary calculation of the maximum possible load.

When placing the model in the operating area of the wind tunnel, it is necessary to provide a gap of 1–2 mm between the object under study and the components of the surrounding buildings not involved in the determination of the load, to prevent their contact.

After placing the model, a pressure-sensitive element tube is installed in the operating area to control flow velocity and perform aerodynamic coefficient calculations.

After preparations, the measuring system is energized and zero (in the absence of flow) readings of the force-torque sensor are taken, which is necessary to take into account initial displacement due to the sensor loading by the weight of the model structure.

In the tube, the flow rate corresponding to the experimental conditions is set and the data recording protocol is enabled. During the specified time, the force-torque sensor readings are being taken and two files are being recorded: load readings with a frequency of 1000 Hz and averaged load readings for the entire period of the recording program operation.

Rotation of the model in the tunnel is carried out with a step corresponding to the experimental conditions. The force-torque sensor readings are taken for each angle. Rotation of the model is carried out up to 360° to take control readings and then compare them to the zero readings.

Based on the results of the tests to determine force-torque characteristics, aerodynamic coefficients are calculated according to equations (1).

Mathematical modeling was performed in specialized ANSYS fluid dynamics software. The turbulent motion of the air medium near a body is described by a system of Reynolds equations closed using additional differential relations of a two-parameter dissipative turbulence model. The calculations were performed using the FLUENT computational technology (control volume method, interpolation of convective terms using the MARS scheme, implicit time step scheme, internal iterative PISO algorithm, k-w SST turbulence model).

An example of a three-dimensional computational domain with multi-scale unstructured grids with thickening in the vicinity of the building for the high-rise residential complex is shown in Fig. 7.

Discussion

Based on the data obtained from numerical and experimental modeling, verification of the studies was conducted for three objects of different types in two different numerical modeling setups: with and without virtual wind tunnel modeling. The verification results are shown in Figs. 8–10.

Based on the obtained data, it can be stated that the convergence of the results of experimental and mathematical modeling in determining the integral components of the average wind load is achieved

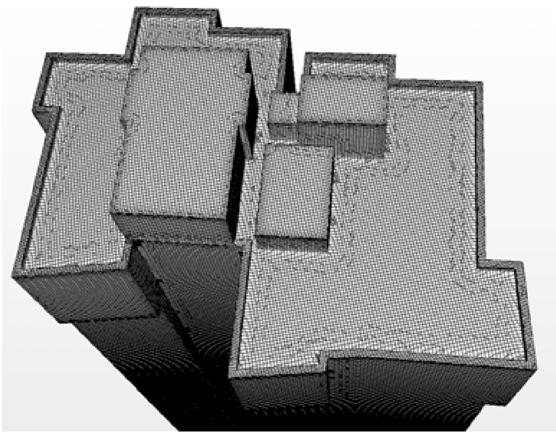

Fig. 7. Fragment of the computational grid in the vicinity of the residential complex building

with an error of no more than 20 % under the condition of virtual wind tunnel modeling. In a setup where the wind tunnel is not modeled, the error is up to 30 %. The obtained results suggest that it is possible to use numerical modeling when selecting critical wind flow directions, which should be taken into account in the analysis of load-bearing structures of construction facilities, and virtual wind tunnel modeling makes it possible to achieve better data consistency when verifying results with physical modeling data.

Thus, the proper use of numerical modeling technology can significantly reduce the time and cost of experimental studies in a wind tunnel and/or reduce the design time by decreasing the number of considered loading scenarios.

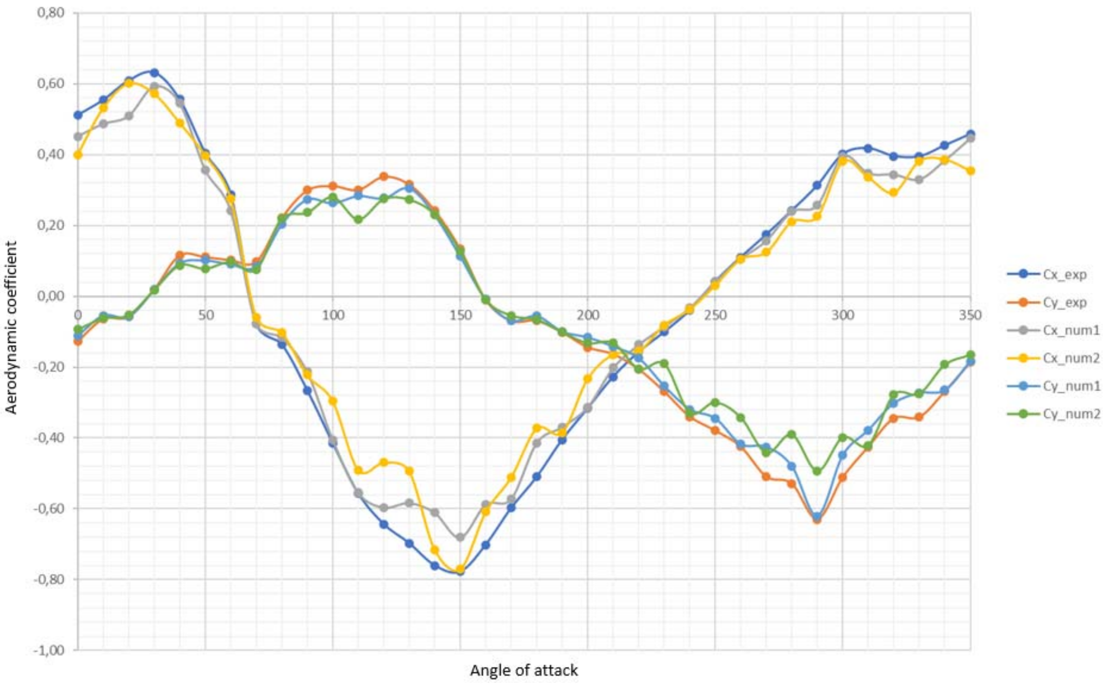

Fig. 8. Results of the verification studies for the airport complex

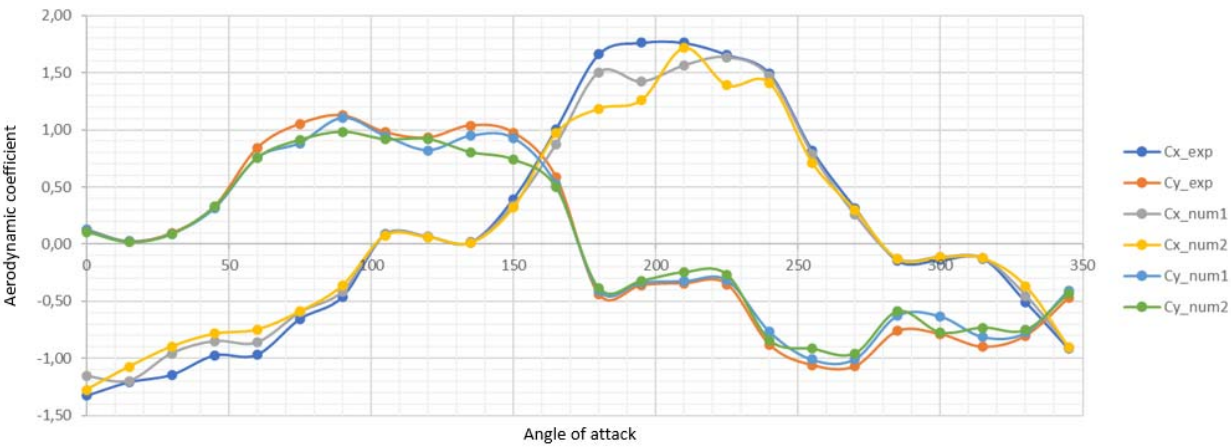

Fig. 9. Results of the verification studies for the high-rise residential complex

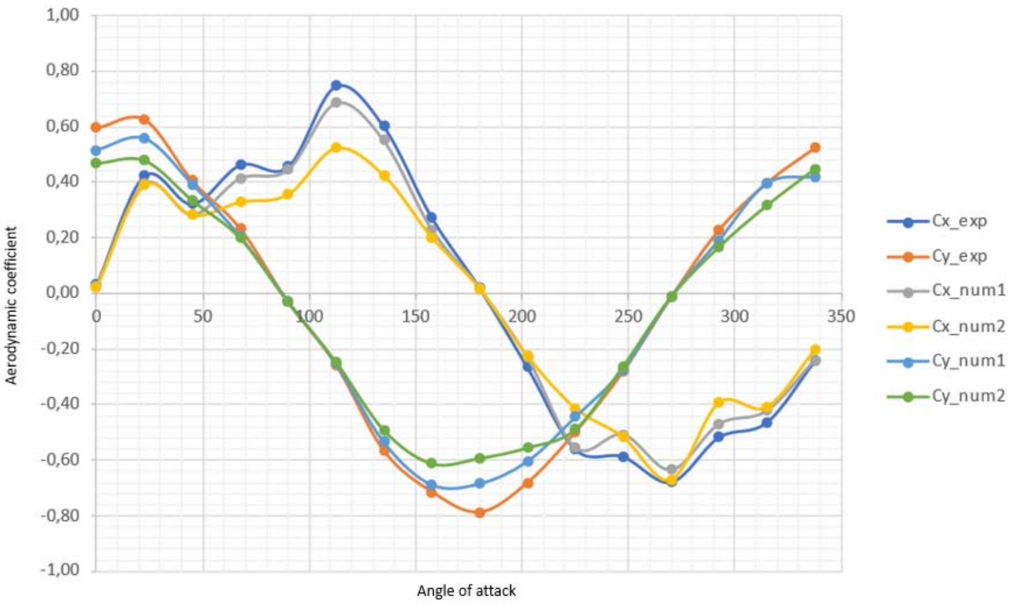

Fig. 10. Results of the verification studies for the chimney as part of the coke oven complex

Acknowledgments

All tests were carried out with the use of equipment of the Head Regional Shared Research Facilities and the Large Gradient Wind Tunnel, courtesy of the National Research University "Moscow State University of Civil Engineering".

Funding

The research was funded by the National Research University "Moscow State University of Civil Engineering" (grant for fundamental and applied scientific research, project No. 01-392/130).

References

Aboshosha, H., Elshaer, A., Bitsuamlak, G. T., and El Damatty, A. (2015). Consistent inflow turbulence generator for LES evaluation of wind-induced responses for tall buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 142, pp. 198–216. DOI: 10.1016/j.jweia.2015.04.004.

Blocken, B. (2014). 50 years of computational wind engineering: past, present and future. *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 129, pp. 69–102. DOI: 10.1016/j.jweia.2014.03.008.

Galerkin, Y. B., Solovyeva, O. A., and Ucehovscy, A. A. (2020). Methodology of calculation and verification of vaneless diffusers test results in a virtual wind tunnel. *AIP Conference Proceedings*, Vol. 2285, Issue 1, 030059. DOI: 10.1063/5.0026537.

Kareem, A., Spence, S., Bernardini, E., Bobby, S., and Wei, D. (2013). Using computational fluid dynamics to optimize tall building design. *CTBUH Journal*, Issue III, pp. 38–43.

Murakami, S. (1998). Overview of turbulence models applied in CWE–1997. *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 74–76, pp. 1–24. DOI: 10.1016/s0167-6105(98)00004-x.

Poddaeva, O. (2022). *Fundamentals of ensuring technosphere safety of critical transportation infrastructure facilities within their life cycle*. DSc Thesis in Engineering. Russian University of Transport.

Ricci, M., Patruno, L., Kalkman, I., de Miranda, S., and Blocken, B. (2018). Towards LES as a design tool: wind loads assessment on a high-rise building. *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 180, pp. 1–18. DOI: 10.1016/j.jweia.2018.07.009.

Zhang, Y., Habashi, W. G., and Khurram, R. A. (2015). Predicting wind-induced vibrations of high-rise buildings using unsteady CFD and modal analysis. *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 136, pp. 165–179. DOI: 10.1016/j.jweia.2014.11.008.

ВЕРИФИКАЦИЯ РЕЗУЛЬТАТОВ ЧИСЛЕННОГО МОДЕЛИРОВАНИЯ ВЕТРОВЫХ ВОЗДЕЙСТВИЙ НА УНИКАЛЬНЫЕ ЗДАНИЯ И СООРУЖЕНИЯ

Поддаева Ольга Игоревна

УНПЛ АИИСК НИУ МГСУ, Москва, Россия

E-mail: poddaevaoi@gmail.ru

Аннотация

Введение: Основным методом определения ветрового воздействия на уникальные здания и сооружения остается физическое моделирование в аэродинамических трубах, однако испытания в аэродинамических трубах дорогостоящие и трудоемкие. CFD обеспечивает более высокую вариативность, расчеты выполняются быстрее и бюджетнее. Однако остается открытым вопрос корректности полученных в результате численного моделирования интегральных характеристик и, соответственно, проведения процедуры верификации. На сегодняшний день в области строительной аэродинамики обязательным требованием к использованию результатов численного моделирования является их верификация с данными эксперимента. В исследованиях последних лет изучаются возможности CFD для точных прогнозов ветровой нагрузки, но не найдено ни одного исследования, которое представляло бы всестороннее описание и реализацию системы верификации и валидации для анализа ветровых воздействий на уникальные здания и сооружения. **Целью исследования** являлось сравнение результатов CFD с данными wind-tunnel test для трех различных объектов, анализ результатов и предложения по самой методики верификации и валидации CFD анализа ветровых воздействий на уникальные здания и сооружения. Были использованы следующие **методы**: физические испытания макетов уникальных зданий и сооружений в аэродинамической трубе, включая подробную методику экспериментальных исследований по определению интегральных аэродинамических характеристик, численное моделирование ветровых воздействий с использованием ПК ANSYS. Численное моделирование выполнялось в двух поставках: как с моделированием виртуальное аэродинамической трубы, так без моделирования. **В результате,** показано, что моделирование виртуальной аэродинамической трубы позволяет добиться лучшей согласованности данных при верификации результатов численного моделирования с данными физического моделирования, а корректное использование технологии численного моделирования может существенно сократить сроки и стоимость проведения экспериментальных исследований в аэродинамической трубе и/или сократить сроки проектирования уменьшив количество рассматриваемых сценариев нагружения.

Keywords: верификация; CFD; аэродинамическая труба; интегральные аэродинамические характеристики.