Experimental studies of wind impact on religious buildings

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Abstract. This article is devoted to the description of experimental studies of wind impact on a religious temple in compliance with religious purposes. Studies of aerodynamic characteristics should be carried out using experimental methods for each Orthodox church individually. In the first chapter, the authors describe the specifics of the design of religious buildings, in the type of design of Orthodox churches. In the second chapter, brief information on the conduct of experimental studies of wind impact on the basis of NRU MGSU is launched. In the third chapter, a description of the experimental study of the wind effect on the Orthodox church, created in the Moscow region. Conclusions regarding this study.

1. Introduction
Design and construction of religious buildings and structures is one of the most complex and specific engineering tasks. The construction of objects of various religious denominations has a number of features in comparison with city-wide buildings.

First, it is necessary to determine the belonging of objects to a particular religion. For example, the specificity of designing Orthodox churches differs significantly from mosques or Catholic churches (figure 1).

![Figure 1. Religious buildings: a - Cathedral of Christ the Savior, Moscow, b - White Mosque, Tatarstan, c - Catholic Church of the Immaculate Conception of the Virgin Mary, Moscow.](image)

At the same time, the purpose and functional component of religious buildings should be noted: religious buildings of a particular religious affiliation include various buildings and related buildings, erected for specific purposes [1, 2].

The most widespread and large-scale type of religious buildings in Orthodoxy is the church (temple), intended for public worship. For example, in an Orthodox church, three parts are distinguished: the porch, the middle part of the temple, which is the main volume of the temple, and the altar (figure 2). It must be emphasized that the middle part of the temple, due to its intended purpose, must meet regulatory requirements to ensure the safety of people.
Figure 2. The main parts of the Orthodox church.

The most important role in the design of religious buildings is played by symbolism, which is closely related to their style, canonized requirements for the design of objects of a certain denomination and, consequently, with the design features of the object [3]. Based on the traditions of temple construction, as well as based on the provisions of regulatory documents related to the construction of religious buildings from an engineering point of view (for example [4]), designers should also take into account the requirements for ensuring the safety and reliability of building structures.

It is important to note that temple construction is a typical, which boils down to the need for a comprehensive structural analysis of building structures, which includes determining the wind load on the facades of objects. In the study of external aerodynamics, aerodynamic coefficients play an important role, depending on the geometric parameters of religious buildings. In the course of determining the distribution of aerodynamic forces over the outer surfaces of temples under wind action, engineers encountered inaccuracies or contradictions when using reference literature [5]. In this regard, studies of aerodynamic characteristics should be carried out using experimental methods for each Orthodox church individually [3].

2. Aerodynamic research at the National Research Moscow State University of Civil Engineering
A distinctive feature of NRU MGSU is the presence of a unique experimental base, which includes a wind tunnel of architectural and construction type, as well as a modern high-precision complex of measuring equipment. Aerodynamic tests are carried out on the basis of a unique scientific installation - the Large Research Gradient Wind Tunnel (figure 3).
NRU MGSU has developed a methodology for experimental studies of wind impact on construction sites. This method has been presented earlier in the following articles [6, 7]. Based on ensuring the requirements of the similarity theory [8, 9], the technique is the following algorithm:

1. Development of a three-dimensional geometric model of the object;
2. Analysis of meteorological and topographic data in the development area and assignment of wind characteristics;
3. Design and creation of a scaled-down model;
4. Tests in a wind tunnel of a scale model of the object. Determination of average and peak values of aerodynamic pressure coefficients $C_p$ at control points on the surface of the object under study. The actual testing process is described in [6, 7];
5. Development of conclusions and recommendations based on the results of the study.

3. Aerodynamic research of a traditional Orthodox church

3.1. Description of the object under study and creation of a 3D model

In 2020, the Main Church of the Russian Armed Forces was opened in the Moscow region, the construction of which was timed to coincide with the 75th anniversary of Victory in the Great Patriotic War (figure 4a). This temple was designed in the monumental Russian-Byzantine style, which is a majestic cathedral with large golden domes. All dimensions of the temple are symbolic and refer to the most important figures associated with the history of the Great Patriotic War, the history of Russia and the Russian Armed Forces [10, 11]. A distinctive feature of this structure is its height (95 m), which makes the temple one of the highest Orthodox churches in Russia. The capacity of the inner church, taking into account its dimensions ($65.4 \text{ m} \times 97.9 \text{ m}$), is up to 6 thousand people, which indicates that the building belongs to the category of a higher level of responsibility.
Based on the initial data obtained, a 3D geometric model was developed, which was necessary for the study (figure 4b).

### 3.2. Analysis of meteo- and topographic data of the area

The projected construction site is located in the Moscow region, Odintsovo district, Kubinka. The climate of the region is moderately continental, with a clearly pronounced seasonality, but the degree of its continentality relative to other large European cities is much higher. The average annual temperature is +5.8 °C. The average annual wind speed is 2.3 m/s. The average annual air humidity is 77%. Figure 5 shows a wind rose.

![Wind rose in the construction area.](image)

**Figure 5.** Wind rose in the construction area.

### 3.3. Designing a scaled-down model

For experimental studies, a 3D model of the investigated object was developed. Taking into account the dimensions of the wind tunnel test section, the scale of models 1:100, which is the maximum possible from the conditions of blocking the flow, was chosen. The investigated model was installed on an automated rotary table located in the working area of the wind tunnel (figure 6). The model was made using 3D printing technology.
Figure 6. Model of the investigated object and installation of the pneumatic route.

Next, the model was prepared for experimental research; pressure collection points were placed on the surface of the model. From each point (hole), pressure is transmitted through copper and then through silicone tubes to differential pressure sensors (figure 6) [7].

3.4. Experimental results
During a series of physical tests on a scaled-down model of the temple, the average and peak values of the $C_p$ coefficient were obtained at control points on the surface of the model. The research results are presented in a table 1 of the form:

| № of point | 0°  | 15° | … | 75° | 90° | … | 345° |
|------------|-----|-----|---|-----|-----|---|------|
| 1          | -1.66 | -1.65 | … | -0.40 | -1.01 | … | -1.38 |
| …          | …   | …   | … | …   | …   | … | …   |
| 186        | -0.83 | -0.72 | … | 0.20 | 0.33 | … | -0.94 |

In the process of carrying out experimental studies, the average and peak values of the aerodynamic coefficient $C_p$ at control points on the surface of the model were experimentally determined. While the average values are in the range from -2.94 to 2.39, the peak values are in the range from -3.32 to 2.86. The maximum modulus values of aerodynamic coefficients are typical for the corner zones of facade structures, domes and facades of light drums.

4. Conclusions
In the course of the work, the most unfavorable wind directions were identified in terms of wind load -75 and 90 (figure 7).
These directions require strengthening of the structural part in order to increase the reliability and safety of structures. Providing the required parameters in the design of the temple will allow for a long time to preserve its external and internal decoration and unique architecture [2, 5, 6].

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