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Numerical analysis of wind loads on complex shape structures

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This article evaluates the efficacy of numerical wind simulation as a superior alternative to standard code-based methods for assessing wind loads on complex structures. Conventional approaches, such as those outlined in SP 20.13330.2016, often struggle to accurately model the intricate flow fields and turbulence generated by non-standard geometries and the presence of adjacent buildings. This research employs high-fidelity transient CFD analysis to simulate these effects and provides a direct comparative assessment with code-derived results.

Keywords: computational fluid dynamics (CFD), numerical analysis, wind loads, steady state analysis, transient analysis.

Абдуллах Х., Алехин В.Н., Плетнев М.В., Погорелов С.Н.
Численный анализ ветровых нагрузок на конструкции сложной формы

В статье оценивается эффективность численного моделирования ветровых воздействий в качестве более совершенной альтернативы стандартным нормативным методам для оценки ветровых нагрузок на объекты со сложной формой. Традиционные подходы, такие как изложенные в СП 20.13330.2016, зачастую не позволяют точно смоделировать сложные поля течений и турбулентность, вызываемые нестандартными геометрическими формами и влиянием окружающей застройки. В данном исследовании применяется переходный CFD-анализ высокой точности для имитации этих эффектов и проводится прямое сравнительное сопоставление с результатами, полученными по нормам.

Ключевые слова: вычислительная механика жидкости и газа (CFD), численный анализ, ветровые нагрузки, стационарный расчет, нестационарный расчет.

Introduction

The progress of the construction industry, which began rapidly in the 20th century, led to the construction of high-rise and large-span buildings and structures, the appearance of light and at the same time durable materials. Along with this, problems arose in ensuring the required reliability, rigidity, and stability of the structures. The wind has become one of the most dangerous external factors affecting buildings and structures.

Wind loads on structures are determined using three primary methods:

- Experimental modelling uses wind tunnel tests to study complex or unique designs, replicating real-world turbulence and dynamic wind effects [3];
- The analytical method calculates wind loads by applying formulas and guidelines from established building codes and standards (e.g., Eurocode, ASCE, SP);
- Numerical modelling employs computational fluid dynamics (CFD) to solve complex equations, simulating physical wind flow to determine pressures and forces on a structure.

The accurate assessment of wind loads on non-standard structures remains a key challenge in wind engineering. Traditional building codes are inadequate for this task, as they provide data only for simple, standard shapes. This limitation was demonstrated in a study on an octagonal tall building, which showed that codes offer pressure coefficients for just a few wind incidence angles, creating a significant knowledge

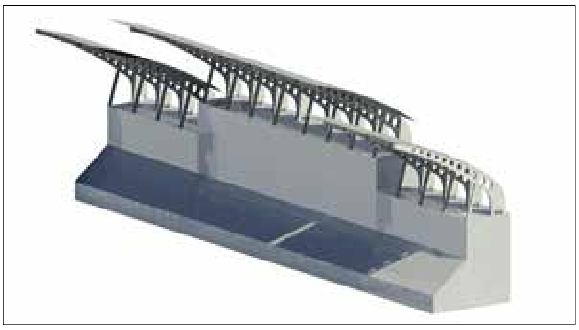

Figure 1. 3D stadium grandstand model. Author H. Abdullah

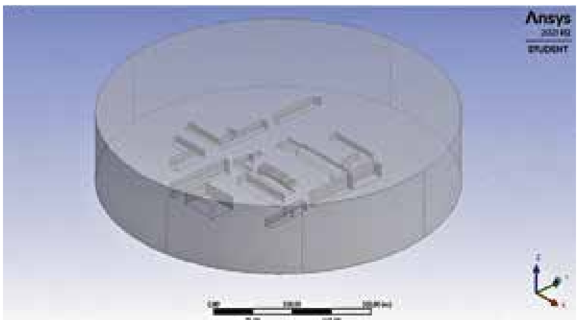

Figure 2. Computational domain for the studied structure with the surrounding buildings in ANSYS. Author H. Abdullah

gap for complex geometries [6]. For unique structures wind tunnel testing is the established benchmark. However, as highlighted in previous research, this method is expensive and time-consuming [9]. This has propelled Computational Fluid Dynamics (CFD) as a vital tool, offering a more flexible and cost-effective alternative for detailed aerodynamic analysis. A key strength of CFD is its ability to analyze wind effects at numerous incidence angles and visualize complex flow phenomena like vortex shedding, which are critical for understanding the behavior of unconventional forms, as demonstrated in prior research [6].

A crucial factor in urban wind analysis is the effect of surrounding buildings. One study emphasizes that CFD's «greater flexibility in design parametrization» allows for the accurate incorporation of the urban context, moving beyond the simplified isolated-building model to capture channeling effects and turbulence from adjacent structures [9].

The integrated use of experimental and numerical methods is widely recognized as a best practice. As shown in a recent study that combined wind tunnel tests with Finite Element Analysis (FEA), such a methodology provides a comprehensive assessment of a building's structural response and occupant comfort under complex wind conditions [11]. This approach ensures high-fidelity simulations that are grounded in empirical data.

Furthermore, the credibility of CFD depends on rigorous verification and validation (V&V). As shown in a dedicated verification study, validating numerical results with experimental data is mandatory to ensure accuracy in structural aerodynamics [9]. This process is crucial for transitioning CFD from a research tool to a reliable asset in the design process.

While previous research has extensively focused on tall buildings, this study addresses a notable gap by applying a validated CFD methodology to a complex-shaped canopy. Such structures, with their horizontal orientation and proximity to the ground, present a fundamentally different aerodynamic challenge than vertical towers. This research aims to provide a reliable numerical framework for the design of these unconventional structures within complex urban settings.

Wind engineering usually describes the mean velocity as a random function of time and a deterministic function of space; in contrast, it describes turbulence as a random function of space and time [8].

To describe the velocity profile by height:

$$v(z) = v_{anem}\left(\frac{z}{z_{anem}}\right)^{\alpha}, \qquad (1)$$

where:

v_{anem} — flow velocity at standard anemometer placement level (10 m), m/s;
z — height above ground, m;
z_{anem} — anemometer location level, m;
— an exponent that depends on temperature stratification and the roughness of the ground surface.

Wind movement in the lower layers of the atmosphere is turbulent and, therefore, it is characterized by an irregular change not only by height but also by time. Then the wind speed profile can be described by the equation:

$$V(z,t) = \bar{V}(z) + \Delta V(z,t), \qquad (2)$$

where:

$\bar{V}(z)$ — mean wind velocity component, m/s;
$\Delta V(z,t)$ — fluctuating velocity component (pulsating component) described by random functions, m/s.

According to Van der Hoven wind spectrum curve, the dynamic velocity component can be represented using the harmonic law [4]. Then, considering the coefficients of wind gustiness, the dependence of wind speed on height above ground level and on time is given by the formula [5]:

$$V(z,t) = \bar{V}(z)\cdot\left[1 + \sum_{i=1}^{n}(K_{ni} - 1)\cdot\sin(\omega_i \cdot t)\right], \qquad (3)$$

where:

K_{ni} — random statistically dependent value;
ω_i — Angular frequencies of wind gusts, s-1.

Computational domain

The research object for this study is the designed roof canopy structure over the grandstand of the stadium at Ural Federal University.

The modelling of the canopy (Figure 1) was performed in the Revit 2019 software.

Next, the computational domain was created to determine the wind pressure closest to reality, where the surrounding buildings of studied structure were included (Figure 2).

Initially, steady state analysis was conducted, assuming the invariability of the flow characteristics over time, and the average wind pressure was determined for each of eight directions: North, South, West, East, North-West, North-East, South-West, South-East (Figure 3). According to steady state analysis results, for the most unfavourable directions, a transient analysis was carried out, considering the change in the flow characteristics over time, then the mean and pulsating components of the wind pressure on the canopy were determined.

This approach efficiently identifies pressure values for the most critical wind directions, minimizing both computational time and resource expenditure since wind loads determined using the results of the transient analysis considered more reliable than those determined using the steady state analysis[1].

In this research it was decided to use SST (Shear Stress Transport Turbulence Model) as a turbulence model for

1 СТО 02066523-089-1-2024. Численное моделирование ветровых и снеговых воздействий: дата введения 22.04.2024. URL: https://files.noccm.ru/files/documents/STO-02066523-089-1-2024/СТО_Численное_моделирование_ветровых_и_снеговых_воздействий.pdf.

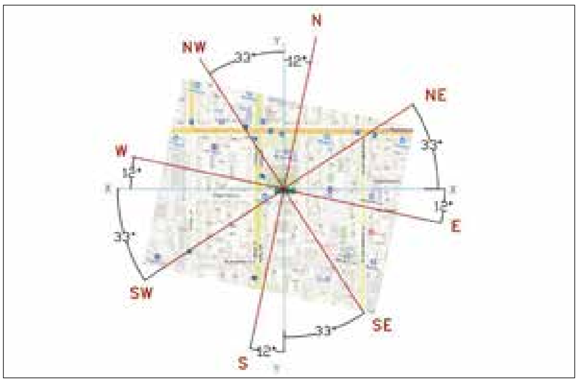

Figure 3. Structure location according to the cardinal points. Author H. Abdullah

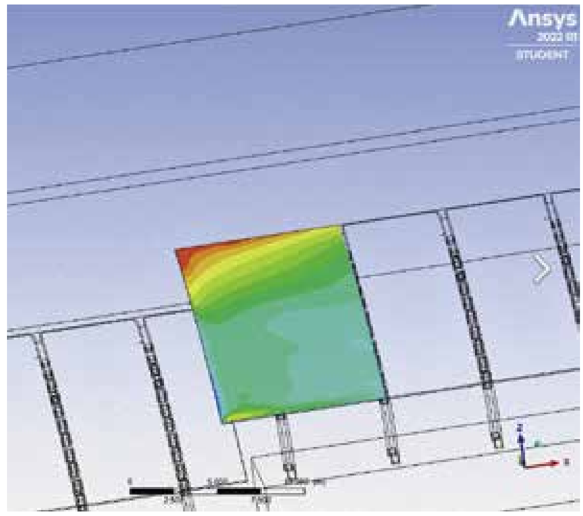

Figure 4. The canopy part for which the calculation was conducted. Author H. Abdullah

the wind flow since it is the most universal (suitable for both steady and transient analyses), which quite accurately describes the behavior of the flow in the near-wall zone and in areas far from the walls with a smooth transition between them, as well as suitable for the calculation of buildings and structures of complex shape [1; 2; 6; 7].

Boundary conditions

Wind speed distribution by height is calculated by the formula[2]:

$$U(z) = U_0 \left(\frac{z}{z_0} \right)^{\alpha}, \tag{4}$$

where:
U_0 — characteristic wind speed, m/s;

$$U_0 = \left(\frac{2 \cdot w_0}{\rho} \right)^{0,5}, \tag{5}$$

z — vertical distance from the ground surface, m;
z_0 — standard wind parameter, m;
α — parameter that determines the change in the velocity head of the normative wind by height z;
w_0 — nominal value of wind pressure, depends on the wind zone, Pa;
ρ — air density, kg/m³.

Turbulence intensity value was applied (Medium, Intensity = 5%), according to the recommendations [8; 5].

Steady state analysis

After analysing the results of steady state analysis, it was revealed that the most unfavourable directions of wind load on the canopy are the North-West (NW) and the South-East (SE), (direction with maximum pressure on the canopy and it's opposite) (Table 1).

Table 1. The maximum and minimum pressures values on the canopy surface (steady analysis)

Flow direction	Leeward (–)		Windward (+)	
	Pa	kg/m²	Pa	kg/m²
N	–602	–61,3	282	28,7
NE	–166	–16,9	94	9,6
E	–348	–35,4	69	7,0
SE	–328	–33,4	167	17,0
S	–141	–14,4	51	5,2
SW	–110	–11,2	—	—
W	–260	–26,5	255	26,0
NW	–1161	–118,3	421	42,9

According to steady analysis results, the total pressure is determined as the sum of average pressure obtained in the ANSYS program and the pulsating pressure calculated by formula[3]:

$$w = w_m + w_g. \tag{6}$$

Mean pressures were determined for the most dangerous sections: the cantilever and span sections of the canopy (Figure 4).

Transient analysis

As mentioned before, the results of steady state analysis confirmed that the most tow unfavourable wind directions on our structure are North-West and South-East. Therefor transient analysis was carried out for these directions, considering the wind characteristics change over time. In this case, the time step Δt was given by the equation [2]:

$$C_0 = \frac{V_{\max} \cdot \Delta t}{\Delta x_{\min}} < 3, \tag{7}$$

where:
$\Delta x_{\min}$ — is the minimum linear size of the mesh volume element;
$V_{\max}$ — is the maximum flow velocity at the level of the calculated surface, m/s.

As a result of the transient analysis, wind pressures on the canopy were obtained for each time step.

After analysing the results, for canopy surface, it is possible to determine the maximum $P_{\max}$, minimum $P_{\min}$, and mean P values of wind pressure, as well as its pulsating components P_{puls+}, P_{puls-} according to the formulas:

$$P_{\max} = \max_{i \in [m,n]} (p_i),$$
$$P_{\min} = \min_{i \in [m,n]} (p_i),$$
$$P = \frac{1}{n - m + 1} \sum_{i=m}^{n} p_i, \tag{8}$$
$$P_{puls+} = P_{\max} - P,$$
$$P_{puls-} = P_{\min} - P,$$

where:
p_i — pressure at the i-th time step, Pa;
n — total number of time steps;
m — step from which results processing starts.

2 ГОСТ Р 56728–2015. Здания и сооружения. Методика определения ветровых нагрузок на ограждающие конструкции. URL: https://docs.cntd.ru/document/1200127225.

3 СП 20.13330.2016. Нагрузки и воздействия. Актуализированная редакция СНиП 2.01.07–85*. URL: https://docs.cntd.ru/document/456044318.

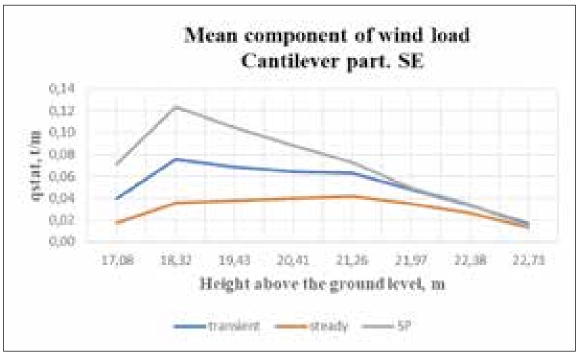

Figure 5. Mean component of wind load (cantilever part) — SE.
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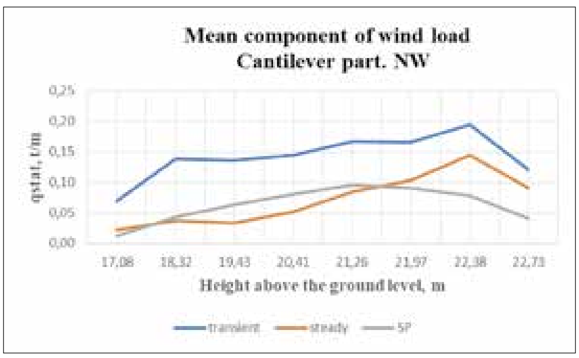

Figure 6. Mean component of wind load (cantilever part) — NW.
Author H. Abdullah

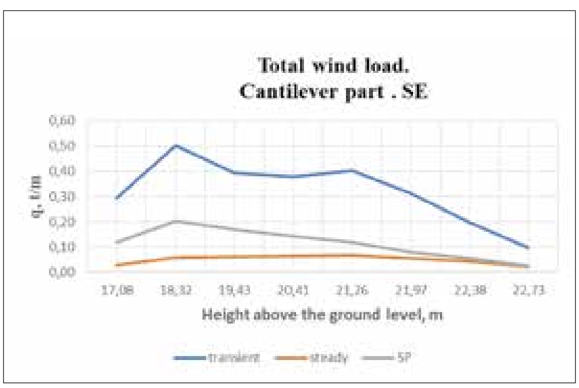

Figure 7. Total wind load (cantilever part) — SE.
Author H. Abdullah

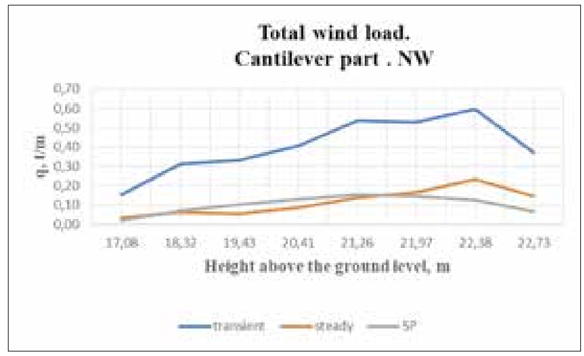

Figure 8. Total wind load (cantilever part) — NW. /
Author H. Abdullah

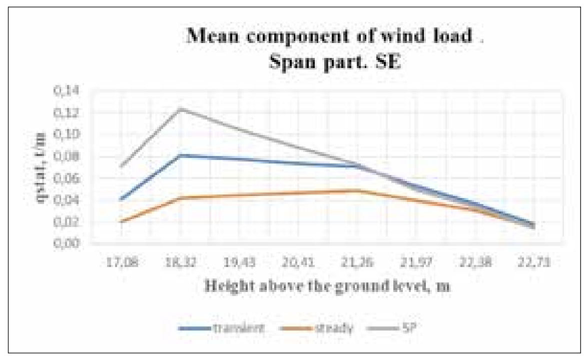

Figure 9. Mean component of wind load (span part) — SE.
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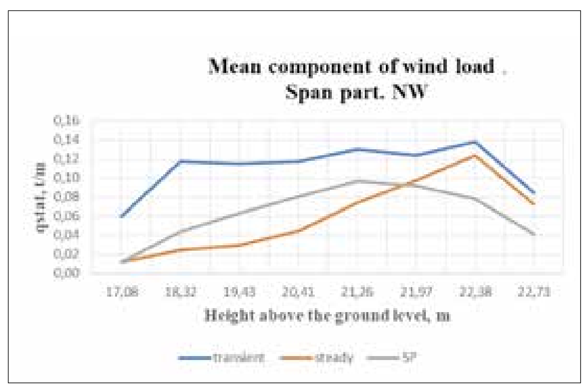

Figure 10. Mean component of wind load (span part) — NW.
Author H. Abdullah

Wind load according to Russian construction code SP.20.13330.2016

As shown in formula 6, the nominal value of the wind load is the sum of average (mean) w_m and pulsating (fluctuating) components w_g.

The average component of the wind load w_m depending on the equivalent height z_e above the ground level is determined by the formula:

$$w_m = w_0 \cdot k(z_e) \cdot c, \tag{9}$$

where:
w_0 — nominal value of wind pressure for the I wind zone;
$k(z_e)$ — coefficient depending on the type of terrain and considering the change in wind pressure for altitude $z_e = h$;
c — is the aerodynamic coefficient determined for the canopy depending on the direction of the wind and canopy slope.

Since the first mode frequency of the structure ($f_1 = 2,69$ Hz) exceeds the limiting value ($f_{\lim} = 2,36$ Hz), then the nominal value of the pulsating component of the wind load at the equivalent height z_e should be determined by the formula1:

$$w_g = w_m \cdot \zeta(z_e) \cdot \nu, \tag{10}$$

where:
$\zeta(z_e)$ — pulsating coefficient depending on the type of terrain and considering the change in wind pressure for altitude $z_e = h$;
ν — is the coefficient of spatial correlation of pressure fluctuations.

Wind load values comparison

According to the results obtained, graphs were created to compare wind loads obtained in the calculation by three different methods (Figure 5–8 for the cantilever part, Figure 9–12 for the span part).

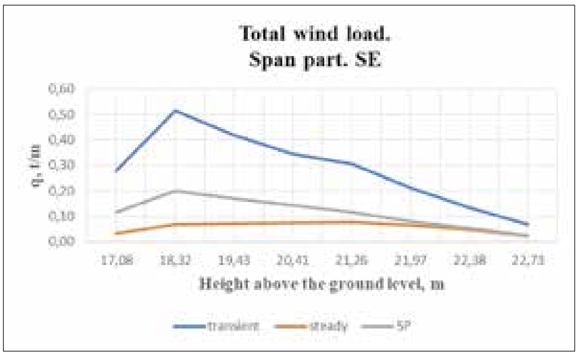

Figure 11. Total wind load (span part) — SE. Author H. Abdullah

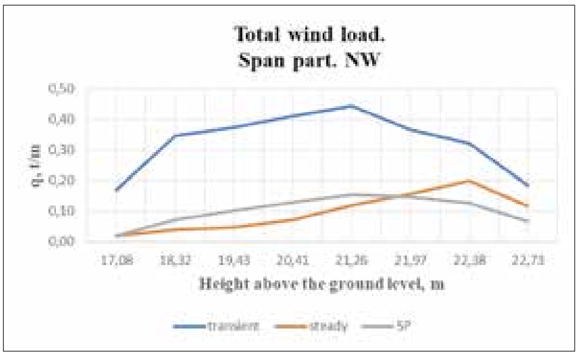

Figure 12. Total wind load (span part) — NW. Author H. Abdullah

Conclusion

Analysis of the wind load graphs reveals:

- The mean pressure from the South-East is highest at lower canopy elevations per the SP standard, equalizing higher up.
- Transient analysis shows the highest mean pressure values from the North-West.
- Steady and transient pressure graphs have similar patterns, but transient values are higher.
- Total loads from transient analysis exceed those calculated by the SP standard.
- Comparing the graphs shows the pulsating (dynamic) component contributes significantly to the total load in transient analysis but is less pronounced in the standard calculation. This discrepancy may be due to the standard's inaccurate terrain consideration or errors in its spatial correlation coefficient for this structure.
- Obtained results indicate the need for numerical or experimental modelling of wind effects for the most accurate understanding of the distribution of wind pressure over the surface of buildings and structures of atypical shape.

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