DOI: 10.23968/2500-0055-2025-10-3-76-85

ASSESSMENT OF THE INFLUENCE OF BUILDING FACADE FACETING ON THE ACCURACY OF WIND LOAD SIMULATION

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Abstract
Introduction: The influence of the level of building facade detail (protruding and recessed balconies, fins, and other facade elements) — referred to as facade faceting — on the results of wind load simulations has been examined in various studies. It has been established that a higher level of facade faceting in models improves the consistency of computational fluid dynamics (CFD) results with results of wind tunnel experiments. However, in order to simplify calculations, under certain conditions, some details may be neglected. Nevertheless, clear recommendations regarding the degree to which such simplifications affect the final accuracy of simulation are rarely found. **Purpose of the study**: In this study, the influence of facade faceting detail on the distribution of wind flows around the investigated object was assessed using computational and experimental modeling. **Methods**: Physical testing of scale models of unique buildings and structures in a wind tunnel, as well as numerical simulation of wind effects, were carried out. **Results**: The study demonstrated a significant impact of facade faceting detail on the distribution of wind loads around the investigated building model. It is recommended to design facade structures with consideration of the turbulence effects of wind flow associated with their actual geometry. At the same time, the design of load-bearing structures should account for the maximum possible wind loads without incorporating facade faceting detailing.

Keywords: high-rise buildings, wind simulation, CFD, wind tunnel, facade detailing, faceting.

Introduction

Predicting wind loads on high-rise buildings is a critical stage in their design. Architectural facades, including balconies, mullions, shading boards, and ribs, are widely used in high-rise building design for both aesthetic and functional purposes. In this paper, facade faceting refers to various facade elements such as balconies, ribs, mullions, fins, etc. The influence of facade faceting on the aerodynamics of airflow is substantial, particularly at high wind speeds. Facade faceting significantly affects the distribution of velocities and stresses in the boundary layer. However, the requirements regarding the level of facade faceting detail in physical and numerical modeling of wind effects remain insufficiently studied.

In the study by Lalin et al. (2021), the necessity of accounting for facade details in wind load simulations was examined using numerical modeling. The paper presented the influence of recessed balconies on a building facade on pressure distribution using computational fluid dynamics (CFD). The results show that in all cases the pressure on a building facade without recessed balconies is higher, therefore, a building can be modeled without recessed balconies, for example, in structural strength calculations. However, there are certain areas where pressure values differ significantly.

Dagnew and Bitsuamlak (2013) summarized the main aspects of numerical wind load modeling for buildings and structures and concluded that more research is needed on transient inlet boundaries and near-wall modeling-related issues.

Li et al. (2023) presented a detailed comparison of CFD simulations with multiple Level of Detail (multi-LoD) geometric models in predicting wind pressure on a complex high-rise wooden tower. It was shown that the higher LoD model makes CFD results more consistent with those following the wind tunnel tests, especially on the leeward of the tower. Components affecting the shape of the structure (e.g., railings, ridges, and columns) have a significant impact on the wind flow. Fu et al. (2024) demonstrated that the level of detail in tree models significantly affects the accuracy of simulating wind flows in urban areas. Zheng et al. (2020) showed that the geometrical details of a facade can substantially influence the near-facade airflow patterns and pressures. This is especially relevant for building balconies as their presence can lead to multiple separation and recirculation areas near facades. Tieleman et al. (1981) compared wind-tunnel and full-scale wind pressure measurements. Based on the full-scale/model comparisons, it was shown that the non-stationary character of the natural wind has a significant effect on the mean, RMS and peak

For citations: Poddaeva, O., Kudinov, O., Mustafin, K. (2025). Assessment of the influence of building facade faceting on the accuracy of wind load simulation. Architecture and Engineering, No 3 (10), pp. 76–85. DOI: 10.23968/2500-0055-2025-10-3-76-85.

pressure coefficients. Under non-stationary wind conditions, the full-scale extreme peak coefficients may be as much as five times the wind-tunnel values. The authors concluded that the complex terrain is responsible for increased turbulence intensities of the horizontal velocity components as a result of increased low-frequency spectral energy. Xu et al. (2020) demonstrated that detailed BIM-based geometric models of buildings allow for significantly different predictions of wind load compared to simplified CAD models. Chen et al. (2022) showed that facade appurtenances significantly influence the fluctuating wind pressure on tall buildings but have a smaller effect on the mean wind pressure. Quan et al. (2016) investigated the effects of grid curtains on the local and overall wind loads of a high-rise building. The results showed that grid curtains increase the mean and fluctuating windward aerodynamic forces and reduce the fluctuating aerodynamic torsions. Agakhanov et al. (2017) examined the influence of building geometry on wind load modeling and found that buildings with complex spatial shapes require finite element analysis for accurate prediction of comfort parameters and wind pressures. Moravej (2018) emphasized that large-scale testing of low-rise buildings or components of tall buildings is essential as it provides more representative information about the realistic wind effects than the typical small scale studies, but as the model size increases, relatively less large-scale turbulence in the upcoming flow can be generated. This results in a turbulence power spectrum lacking low-frequency turbulence content. This deficiency is known to have significant effects on the estimated peak wind loads. Quan et al. (2017) investigated the influence of vertical ribs protruding from facades on the wind loads of super high-rise buildings and concluded that vertical ribs significantly decrease the most unfavorable suction coefficients in the corner recession and edge regions of facades and increase the mean and fluctuating along-wind overall aerodynamic forces. Liu et al. (2023) reached similar conclusions, showing that facade ribs can significantly affect the wind field and reduce the wind force on high-rise buildings.

The work of Rao (2018) is of particular value since it is essentially the only study to specify the exact degree of facade faceting that can be neglected without compromising accuracy. The author compared the flow around a smooth cylindrical profile with that around profiles having increasingly large facet sizes. The air flow patterns and dynamic pressure profiles at the surface were used as a means of comparison of the different geometric types. The experiments explored the effects of faceting for a circular geometry, with a radius of 20 m. The results showed that at 128 divisions (i.e., a facet size of 0.98 m), the effects of faceting are not consequential. This size can be rounded up to 1.0 m for similar results. At 256 divisions (i.e., a facet size of 0.49 m), the surface behaves almost exactly like its circular counterpart. In conclusion, it was shown that a completely smooth geometry can be faceted without noticeable impacts on air flows near the surface. Converting these lengths into a percentage value of the circumference, it showed that the facet size needs to be at least equal to or lesser than approximately 0.79 % of the length of the circumference. It must be noted that the length of the facet needs to be considered in conjunction with the angle between two adjacent facets, especially when the geometry is completely circular. Zdanchuk et al. (2022) modeled wind effects on a building with and without ledge to compare peak wind loads. They discussed the possibility of simplifying the geometry of a building in numerical modeling, namely, ignoring the protrusions on the facades of buildings when calculating the wind pressure. The investigation showed that when studying peak wind loads, facades with small protrusions could be considered as smooth facades.

Thus, existing studies demonstrate that building facade faceting, especially protruding and recessed balconies, has a significant impact on the distribution of wind loads. However, for the purpose of simplifying calculations, certain details may be neglected under specific conditions. Nevertheless, clear recommendations regarding the degree to which such simplifications affect the overall accuracy of modeling are lacking.

In this study, computational and experimental modeling was employed to assess the influence of facade faceting on the distribution of wind flows around the investigated object, as well as on the deformability of the structural system, taking into account its actual stiffness.

Materials and Methods

As the object of study, a high-rise multi-functional complex (Fig. 1) located in a dense urban environment was selected. The complex consists of two high-rise residential buildings located on a shared substructure.

These high-rise buildings have 50 above-ground and 3 underground floors each. The total building height is 181 m. The structural system is a frame-wall system made of cast-in-place reinforced concrete.

Two facade design options were considered (Fig. 2):

1) with open balconies and vertical partitions between them;

2) with smooth facades.

Experimental studies were conducted using a unique research setup — the Large Gradient Wind Tunnel, courtesy of the National Research Moscow State University of Civil Engineering. Considering the dimensions of the working section of the wind tunnel, the maximum possible model scale of 1:270 was

Fig. 1. Object under study

selected to minimize flow blockage effects (Fig. 3). Each model had pressure measurement points on its surface. Pressure from each opening was transmitted through copper — and then silicone — tubes to differential pressure sensors.

In addition, numerical simulations were performed using the ANSYS CFD software to complement the experimental research. The experimental data on mean pressure distribution at drainage points were used for verification and validation of the applied numerical modeling approach (Fig. 4).

Results and Discussion

A comparison of the obtained results demonstrates a significant influence of faceting on the facade of the studied object on the distribution of wind loads across the facades. The difference is most clearly visible in the isofields of the distribution of aerodynamic external pressure coefficients on the facades of the studied object (Fig. 5).

Analysis of the isofields shows that, in addition to quantitative changes in the values of aerodynamic coefficients, the overall pattern of wind load distribution across the facades also changes. This results from the altered behavior of the flow around the buildings. The presence of facade elements introduces additional turbulence into the wind flow in the immediate vicinity of the facades and even shifts the position of the “separation point” As a consequence, substantial differences in wind load values are observed in corresponding zones, including changes in the sign from (+) to (−).

As an example, Table 1 presents the percentage ratio of wind load values for specific zones on the building facades with a wind direction of 45°.

From the perspective of the practical applicability of the obtained results, the greatest interest lies in comparing the integral (total) wind load on the supporting structures of the object under study. This comparison is presented in Table 2.

As can be seen from Table 2, without accounting for faceting due to the presence of balconies, the total wind load on building C1 at a wind direction of 45° increases by 28 %, or 1.39 times, compared to the design scheme in which such faceting was considered. For building C2, the total wind load

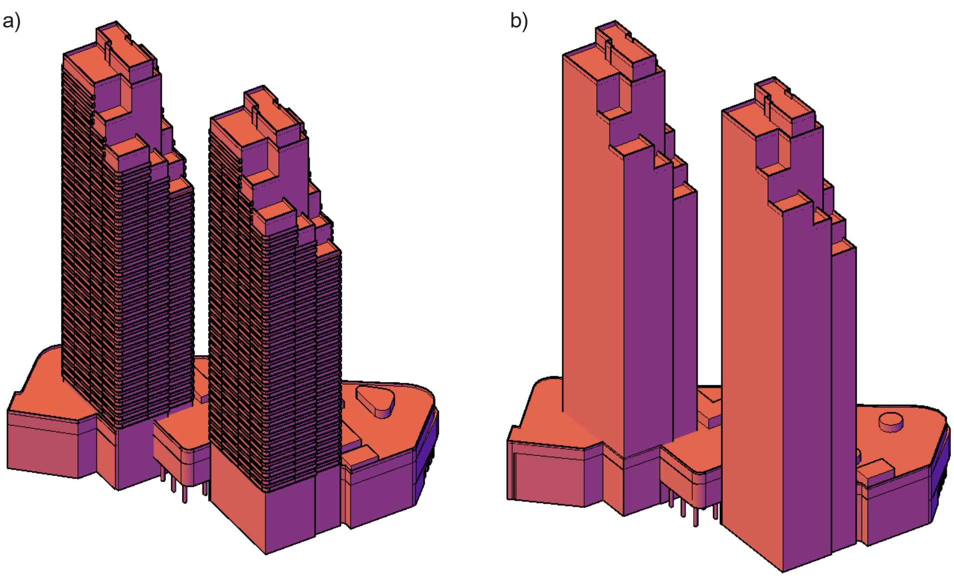

Fig. 2. Facade configurations: a — facades with balconies; b — smooth facades

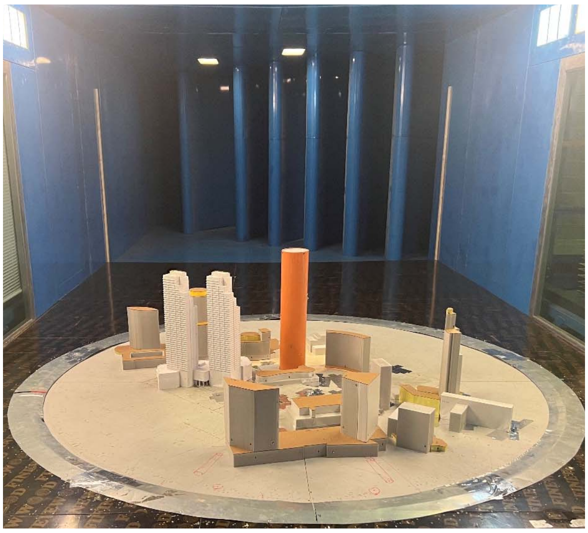

Fig. 3. Model of the studied object in the working section of the wind tunnel

increase at a wind direction of 15° reached 40 %. The ratio of change in integral wind loads for cases with and without balconies is 1.39 for C1 and 1.67 for C2.

Based on the results of the conducted studies, it can be concluded that detailing of facade structures in wind load modeling has a significant impact on both the qualitative distribution of wind loads across the facades and their quantitative values.

Moreover, increasing the level of detail in modeling of facade elements (increasing faceting detail) reduces the integral wind load acting on the facades of the entire building across different wind directions by approximately 30–40 %.

For individual floors (10th, 20th, 30th) within different height zones of the buildings, differences in wind loads between models with and without facade faceting can vary from 1.3 to 2.0 times or more. Figs. 6 and 7 show the ratio of change in the total wind load per floor, comparing cases with and without faceting, for buildings C1 and C2, respectively.

Thus, accounting for facade faceting in experimental studies of wind effects reduces the calculated horizontal loads on the building and may negatively affect the reliability of the structural system as a whole.

When performing wind load modeling, it is important to pay attention to the installation sequence of facade structures. If elements that generate faceting (e.g., fins and other decorative components) are installed after the primary facade systems (such as curtain wall glazing or suspended facades), it may be advisable to conduct studies using models with smooth facades and determine the maximum possible wind loads on the studied object (with a safety margin).

Calculations

To assess the influence of facade faceting, when determining wind loads based on the results of aerodynamic tests, on the deformability of the structural system of high-rise buildings, taking into account its actual stiffness, a calculation model for the complex with balconies on high-rise buildings as well as a separate calculation model for the complex without balconies on high-rise buildings were developed.

The structural analysis of the designed complex was performed using the finite element method in a three-dimensional setting, taking into account the mutual interaction between the structural system, foundations, and base under vertical and horizontal loads, using the STARK ES 2025 software.

The average component of the wind load on the buildings was determined based on aerodynamic coefficients obtained from the wind tunnel tests. The pulsation component of the wind load was calculated using dynamic analysis of the buildings' natural vibrations, considering the first vibration modes of the system. The formation of these loads was carried out in accordance with the main provisions of Code of Practice SP 20.13330.2016. For high-rise building C1, the critical directions of 45°, 150°, 195°, 345° were adopted as the design wind loads.

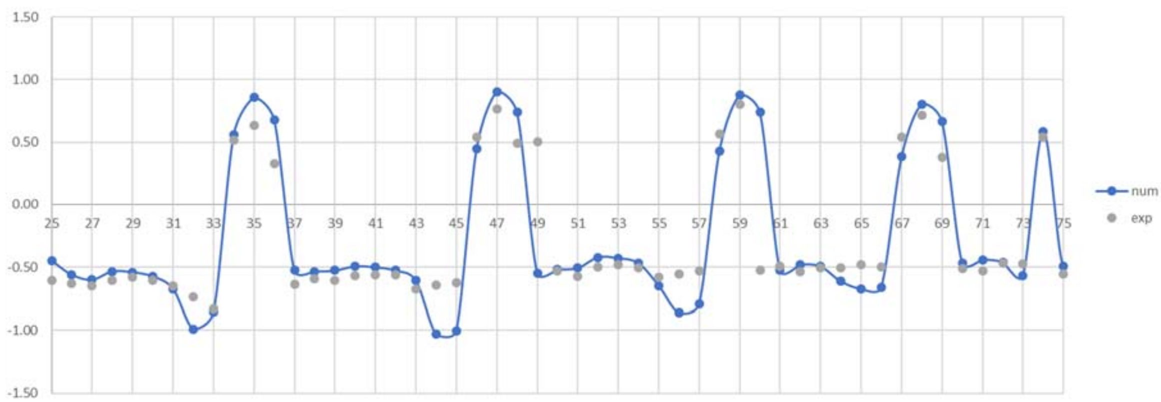

Fig. 4. Validation of numerical modeling results

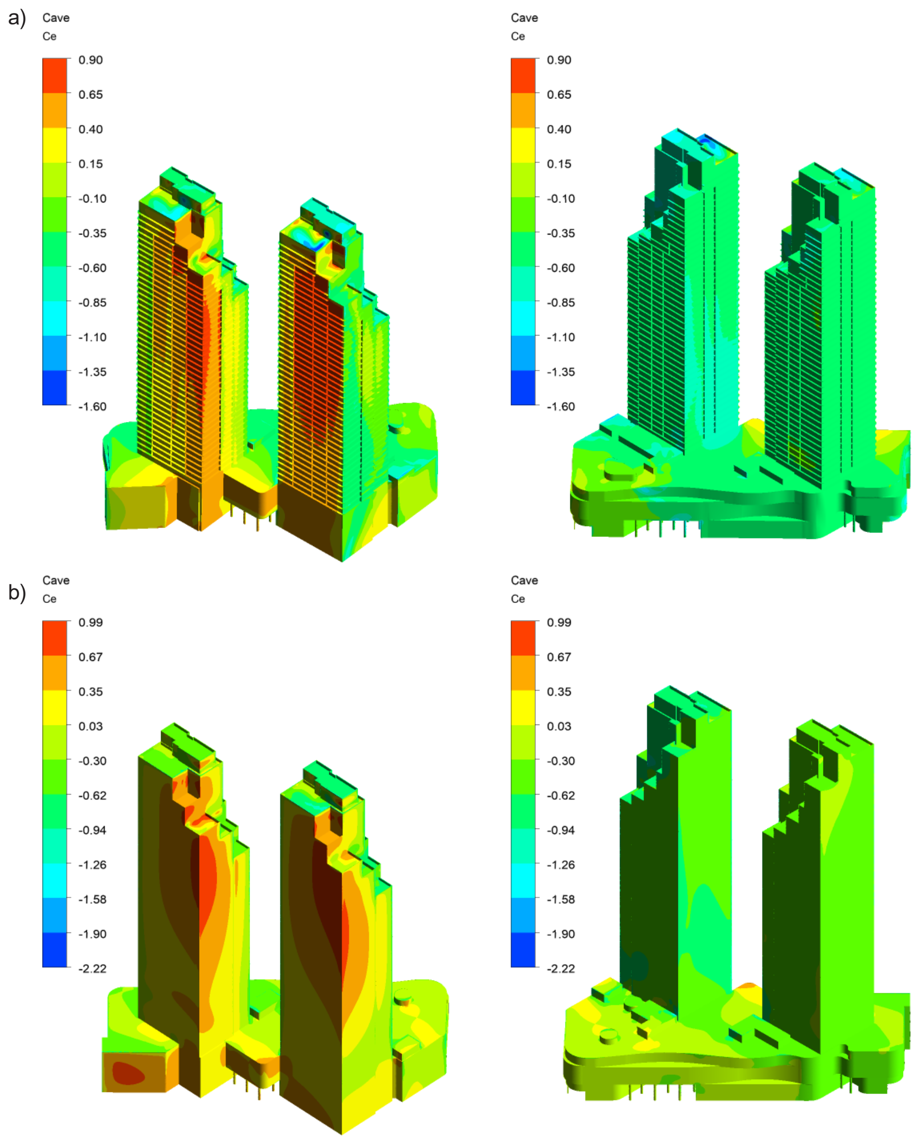

Fig. 5. Distribution of aerodynamic external pressure coefficients on the facades of the studied object: a — facades with balconies, b — smooth facades. Flow direction: 45°

Table 1. **Comparison of wind loads on specific facade zones of the studied object for different facade configurations**

Smooth facade (w_1)												
Belt/Zone	1	2	3	4	5	6	7	8	9	10	11	12
1	–157	–197	–82	–12	27	66	74	–6	–239	–173	–153	–173
2	–159	–164	–59	81	181	181	119	–33	–226	–228	–235	–176
3	–186	–210	–73	134	296	320	218	–8	–245	–237	–272	–183
Facade with balconies (w_2)												
Belt/Zone	1	2	3	4	5	6	7	8	9	10	11	12
1	–99	–108	–70	–78	–96	59	113	31	–152	–146	–124	–101
2	–115	–118	–76	–85	–132	90	152	33	–172	–170	–160	–122
3	–117	–117	–67	–41	–96	144	169	34	–170	–167	–169	–130
Ratio (w_2/w_1)												
Belt/Zone	1	2	3	4	5	6	7	8	9	10	11	12
1	0.63	0.55	0.85	6.53	3.56	0.90	1.53	5.16	0.64	0.84	0.81	0.59
2	0.72	0.72	1.29	1.05	0.73	0.50	1.28	0.99	0.76	0.74	0.68	0.69
3	0.63	0.56	0.93	0.31	0.32	0.45	0.78	4.22	0.69	0.70	0.62	0.71

Table 2. **Comparison of integral wind loads for critical wind flow directions**

Facade configuration	C1			C2		
	45°			15°		
	Fx	Fy	Rxy	Fx	Fy	Rxy
Facade with balconies	1,649	613	1,759	1,640	417	1,692
Facade without balconies	2,152	1,173	2,451	2,727	728	2,822
			28.23 %			40.04 %

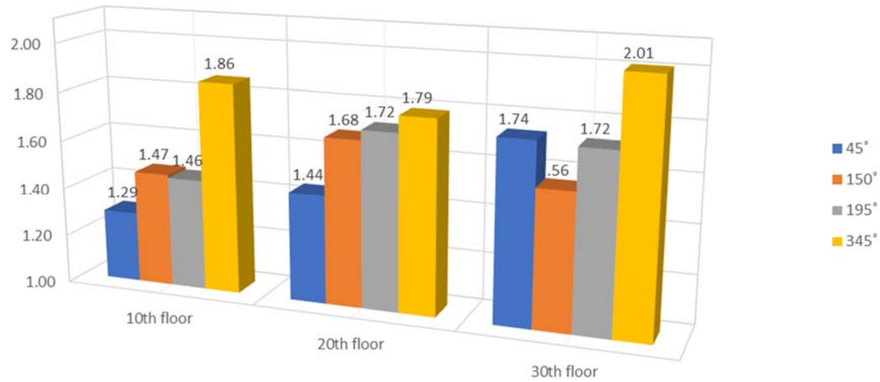

Fig. 6. Change in the total wind load with and without faceting due to the presence of balconies, depending on the height of the floor location and wind direction for building C1

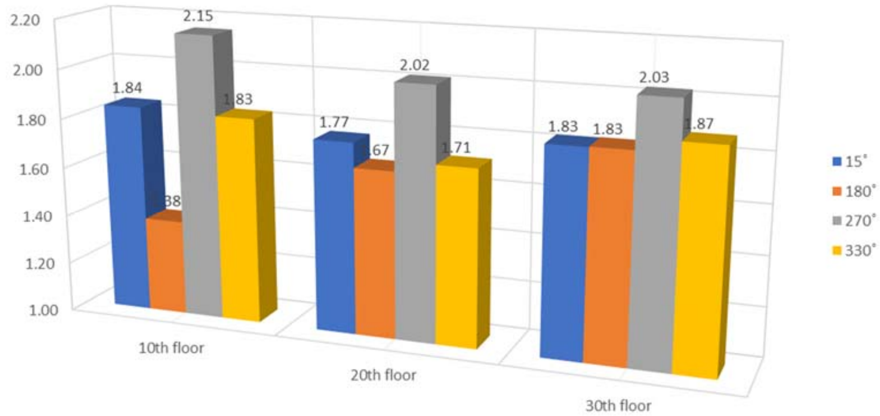

Fig. 7. Change in the total wind load with and without faceting due to the presence of balconies, depending on the height of the floor location and wind direction for building C2

For high-rise building C2, the critical directions were 15°, 180°, 270°, and 330°.

At the first stage, the structural system of the buildings was analyzed under standard wind loads only. The results showed that horizontal displacements for building C1 without balconies along the design directions exceed those for the building with balconies by a factor of 1.32–1.58.

The largest displacements under wind loads only occur in both cases at a wind direction of 45°. An increase in horizontal displacements at 45° wind direction was 1.32 times, corresponding to an increase in the integral wind load by 1.39 times. Table 3 presents the results of the calculation and comparison of the horizontal displacements of the C1 structure due to wind load.

For building C2, horizontal displacements increased by a factor of 1.47 to 1.65. The largest displacements under wind loads only occur in both cases at a wind direction of 15°. An increase in horizontal displacements at 15° wind direction was 1.57 times, corresponding to an increase in the integral wind load by 1.67 times. Table 4 presents the results of the calculation and comparison of the horizontal displacements of the C2 structure due to wind load.

The actual deformability of the building complex structural system was assessed in accordance with Code of Practice SP 430.1325800.2018 under standard combinations of vertical and horizontal loads. For instance, for building C1 without balconies, the largest horizontal displacements were observed

Table 3. **Comparison of the horizontal displacements of the C1 structure under wind loads (excluding vertical loads) for wind directions 45°, 150°, 195°, and 345°, with and without consideration of facade faceting due to the presence of balconies**

Wind direction	Facade without balconies			Facade with balconies			Ratio U_{xy1}/ U_{xy2}
	Along X axis U_{x1}, mm	Along Y axis U_{y1}, mm	Total horizontal U_{xy1}, mm	Along X axis U_{x2}, mm	Along Y axis U_{y2}, mm	Total horizontal U_{xy2}, mm	
45°	95.5	35.9	102.0	75.8	14.8	77.2	1.32
150°	–77.5	13.8	78.7	–51	30.1	59.6	1.32
195°	–89.7	–26	93.4	–67	–16.1	69.1	1.35
345°	90.4	22	93.0	55.9	18.9	59.0	1.58

at the design wind direction of 195° and amounted to 162 mm in the X direction and 36 mm in the Y direction, with total horizontal displacements of 166 mm. Fig. 8 shows the horizontal displacements of the C1 structure under the standard load combination (considering both vertical and horizontal loads) for a wind direction of 195°, without accounting for facade faceting due to the presence of balconies.

For the structural system of building C1 with balconies, the largest horizontal displacements considering horizontal and vertical loads also occurred at a design wind direction of 195°. However, the maximum values were 138 mm in the X direction and 23 mm in the Y direction, totaling 140 mm.

Fig. 9 shows the horizontal displacements of the C1 structure under the standard load combination (considering both vertical and horizontal loads) for a wind direction of 195°, with accounting for facade faceting due to the presence of balconies.

Thus, accounting for balconies in wind load modeling reduces the horizontal displacements under the standard full load combination for building C1 in the critical direction by 16 %. For horizontal displacements under wind loads only, the reduction is 26 %.

The obtained horizontal displacements for buildings with and without balconies do not exceed the allowable limit specified in Code of Practice SP 20.13330.2016 (1/500 of the building height, or 362 mm), indicating sufficient stiffness of the structural system. However, the relatively large horizontal displacements indicate significant horizontal loads on the structural system, which necessitates their consideration when providing additional strength reserves for load-bearing vertical structures, and generally increases the material consumption during construction.

Conclusions

Based on the results of the computational and experimental studies, it is recommended, in order to ensure the required reliability of the building structural system, to carry out design under the maximum possible wind loads with no account for facade faceting detail. The design of facade structures should consider the turbulence effects of the wind flow when accounting for their actual geometry.

Table 4. **Comparison of the horizontal displacements of the C2 structure under wind loads (excluding vertical loads) for wind directions 15°, 180°, 270°, 330°, with and without consideration of facade faceting due to the presence of balconies**

Wind direction	**Facade without balconies**			**Facade with balconies**			**Ratio U_{xy1}/ U_{xy2}**
	Along X axis U_{x1}, mm	**Along Y axis U_{y1}, mm**	**Total horizontal U_{xy1}, mm**	**Along X axis U_{x2}, mm**	**Along Y axis U_{y2}, mm**	**Total horizontal U_{xy2}, mm**	
15°	119	24	121.7	77.2	8.9	77.7	1.57
180°	–95.2	7.7	95.5	–64.2	9.6	64.9	1.47
270°	33	–60	68.6	12.5	–43.4	45.2	1.52
330°	108	–41	115.3	58.9	–37.5	69.8	1.65

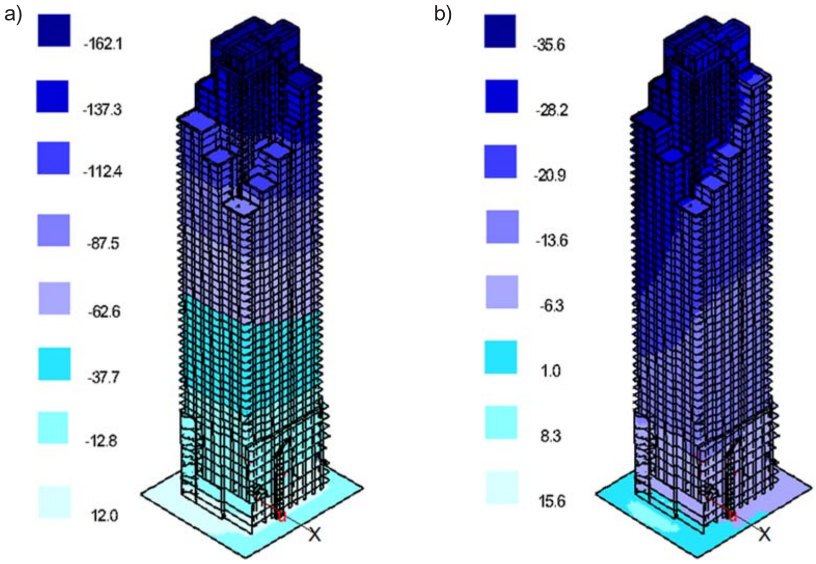

Fig. 8. Horizontal displacements of the C1 structure under the standard load combination (considering both vertical and horizontal loads) for a wind direction of 195°, without accounting for facade faceting due to the presence of balconies: a — displacements along x, b — displacements along y

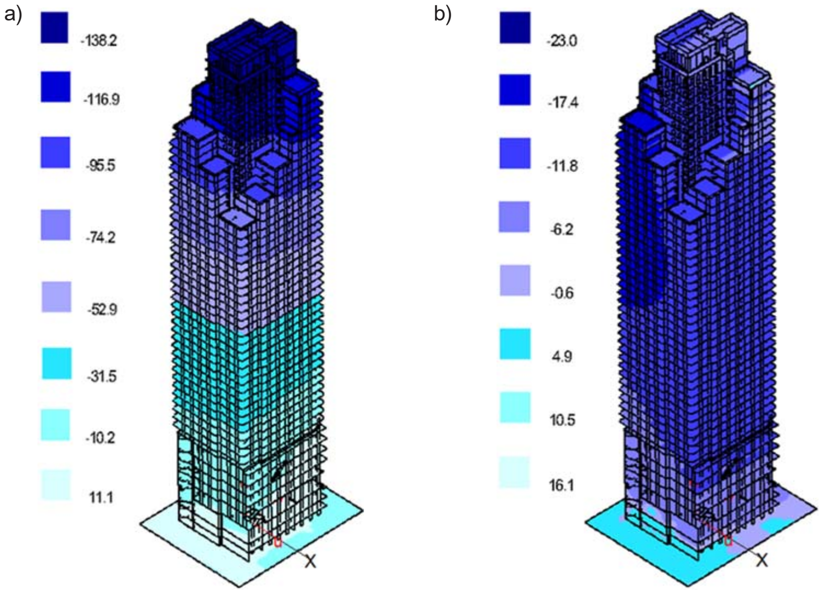

Fig. 9. Horizontal displacements of the C1 structure under the standard load combination (considering both vertical and horizontal loads) for a wind direction of 195°, with accounting for facade faceting due to the presence of balconies: a — displacements along x, b — displacements along y

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ОЦЕНКА ВЛИЯНИЯ «ШЕРОХОВАТОСТИ» ФАСАДА ЗДАНИЯ НА ТОЧНОСТЬ МОДЕЛИРОВАНИЯ ВЕТРОВЫХ ВОЗДЕЙСТВИЙ

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Аннотация
Введение: Влияние степени детализации фасада зданий (балконов, лоджий, ламелей и других элементов фасада) – «шероховатость» фасада – на результаты моделирования ветровой нагрузки было изучено в различных исследованиях. Было установлено, что более высокий уровень «шероховатости» моделей повышает согласованность результатов вычислительной гидродинамики с испытаниями в аэродинамической трубе, однако для упрощения расчетов, при определенных условиях, можно пренебречь некоторыми деталями, но четких рекомендаций по степени влияния введенных упрощений на конечную точность моделирования практически не встречается. **Цель исследования:** В настоящей работе с помощью расчетно-экспериментального моделирования выполнена оценка влияния детализации «шероховатости» фасада здания на распределение ветровых потоков на исследуемый объект. **Методы**: физические испытания макетов уникальных зданий и сооружений в аэродинамической трубе, численное моделирование ветровых воздействий. **В результате** показано существенное влияние степени детализации «шероховатости» фасадов исследуемой модели здания на распределение ветровой нагрузки. Проектирование фасадных конструкций рекомендуется выполнять с учетом эффекта турбулизации ветрового потока при учете их фактической геометрии, а проектирование несущих конструкций необходимо осуществлять с учетом максимально возможных ветровых нагрузок без учета детализации «шероховатости» фасадных элементов.

Ключевые слова: высотные здания, моделирование ветра, вычислительная гидродинамика, аэродинамическая труба, детализация фасадов, шероховатость.