Assurance of reliability of high-rise building structures at design stage as exemplified by residential building complex in Yekaterinburg

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Abstract. The intensive expansion of high-rise construction is observed in Russia during the last several decades. Today it is hard to imagine a Russian metropolitan city without a skyscraper, whether it is a multipurpose business-center or a residential building. High-rise buildings in Ekaterinburg (which is a center of Urals) include not only office buildings, but also residential buildings higher than 100 meters. It is worth mentioning that most of these high-rise buildings were designed by local design companies without the participation of foreign specialists. The reliability and strength of the building structures received the particular attention during the high-rise building design process irrespectively of the function of a building. It is well known that the reliability of building structures shall be assured as early as the design stage, and therefore it is necessary to pay a special attention to the analysis of bearing structures under worst-case combinations of design loads in order to prevent them from influencing the strength of the building structures in the course of its service. Also it is important to note that high-rise buildings are subject to factors extrinsic to low-rises, such as aerodynamic loads. In addition to the wind loads, aerodynamic conditions of the building location in general also have a significant effect. In this work the authors review the specifics of design of high-rise building in Urals region on the example of one of the high-rise residential complexes in Ekaterinburg. Basic design conditions are described and architectural, planning, and design features of the building are reviewed. Effects of harmful factors acting on the building frame, including the wind loads, are analyzed. Some distinctive features of the analysis of the bearing structures are given. The conclusion contains the summary on specifics of high-rise buildings design and construction in Urals.

Keywords: skyscraper, residential high-rise building, wind load, reliability.

1. Introduction

The intensive expansion of high-rise construction is observed in the whole world. Mostly, such expansion can be attributed to the reduction of areas allocated for the construction of new buildings. Not long ago, the high-rise buildings constructed in the majority of developing cities were dedicated for office use or were owned by the leading regional companies, but today the focus is shifted to design and construction of residential high-rises that have more usable area than the low-rise buildings. First modern high-rise residential buildings in Ekaterinburg were built in the beginning of the 21st century [1, 2]. It was the complex of residential buildings named Aquamarine, the maximum height of the buildings of this complex was 93 meters. As of today, there are more than 20 high-rise buildings with height varying from 75 meters and above in Ekaterinburg. One of the distinctive features of these projects is that most of the design works were carried-out by the companies located in Ekaterinburg, without engaging foreign experts and even Moscow design contractors. Local specialists were able to solve all complex problems that have arisen in the course of designing these high-rise buildings and after their commissioning.

2. Wind load considerations for high-rise buildings

Irrespectively of the building purpose, the design process is individual for every high-rise building. Many traditional design practices used for designing low-rise buildings are not effective for designing high-rises. Also, the incompleteness of Russian regulatory basis for designing high-rise buildings makes the job of designers even harder, and high level of reliability makes it necessary to carry-out a large amount of additional design and construction works. Therefore, despite the experience of previous projects designers have to create individual design solutions for every new high-rise building.

In order to ensure the reliability and load-bearing capacity of a high-rise building it is necessary to solve many complex problems, the most critical of which are aerodynamic issues [3-6]. Different shapes of the high-rise buildings and buildings surrounding them make it impossible to calculate the behavior of the building structures under the effect of wind loads theoretically, thus necessitating experimental investigations and numerical simulation of wind loads [7, 8]. Experimental studies include a physical simulation method, i.e. testing a building model in special aerodynamic tunnels [9, 10]. This method allows designers to assess deficiencies of the building design and possible causes of vibration and noise. The numerical simulation is performed with the help of different software complexes allowing the user to evaluate the wind speed, wind direction, and the wind load acting on the high-rise building in the urban environment. One of the most significant benefits of this method is the possibility to model not just a high-rise building or a complex of buildings, but a whole block of buildings. The aerodynamic testing of the models of new buildings provides for the assessment of strength and reliability factors as well as a comfort of areas surrounding the new building. Both of the abovementioned methods shall be used in conjunction in order to assess the full spectrum of the wind load distribution [11].

In some cases, to save time and expenses, contractors use only numerical method despite it not providing for the comprehensive evaluation of all conditions. Sometimes the numerical model includes only the new building or a complex of buildings without adjacent structures and buildings, and sometimes the block of buildings under construction is divided between different contractors who design and build "their" high-rises without considering the locations of other building being built nearby or those which will be built in the future. Such approach may lead to significant aerodynamic problems in the future, and solving such problems at the design stage is much easier than trying to rectify the deficiencies when the building is already built. Even if the built structure has no problems as regards its aerodynamic properties at the date of completion, new high-rise buildings being built nearby can significantly impair the aerodynamic situation in the future. Besides that, unaccounted for wind loads arising due to the abovementioned factors may significantly affect the reliability and load-bearing capacity of the structures of existing buildings and even put them out of service.

3. Peculiarities of designing high-rise buildings in Urals region and ensuring their reliability and load-bearing capacity under wind loads.

One of the newest residential complexes being built in Ekaterinburg (the capital of the region) is the Champion Park complex (fig. 1). This complex is a part of a new prospective block located on the bank of Iset river. The Champion Park residential complex consists of three buildings. The architectural appearance of the complex was inspired by the design of the first complex of high-rise residential buildings in Ekaterinburg – Aquamarine, but the new complex will be significantly higher than its predecessors: the height of new buildings will reach 128 meters. The infrastructure of the new complex will meet all modern requirements, it will include an underground parking area, shops, restaurants, fitness and sports centers for kids and adults, etc.

Figure 1. Champion Park residential complex, visual appearance.

All buildings of the complex are similar frame-and-core-design buildings consisting of a central rigid core, solid reinforced concrete columns, and flat slab floors. In the cross-section, the buildings have the shape of a square with rounded angles. Such geometry allows reducing the effect of wind loads [12, 13]. However, the spacing of buildings is as important for the aerodynamic performance as their shape. For example, (basing on the common experience of the high-rise building design) it may be noted that the worst arrangement of buildings is when similar buildings are located on the same line or in a criss-cross pattern. Such arrangement of buildings may cause creation of wind corridors (wind acceleration areas) and vortices impairing the structural capacity and reliability of the buildings and comfort of the surrounding territory. As of today, most of the high-rise complexes being built in Ekaterinburg are arranged in the such suboptimal patterns. The buildings of the Champion Park complex are arranged in criss-cross (chequered) order. No abnormal wind loads have been observed during the construction of the first building of the complex. However, as the following buildings were built the aerodynamic situation in the area had begun worsening, e.g. significant wind acceleration had been detected in the new complex area. Also it was found that the buildings surrounding the new complex were not taken into account in the calculation of wind loads that was performed at the design stage. To solve this problem it was decided to create a comprehensive mathematical model of the residential complex and surrounding buildings.

The numerical model was created using the finite element method in ANSYS software. The calculations were performed by the specialists of Institute of Civil Engineering and Architecture of Urals Federal University (CEIA UrFU) and designers of TECHCON LLC. The model described the profile of the outer surface of the building superstructure with the accuracy of one centimeter in order to ensure the most accurate assessment of interaction between air flow and building structures. The analysis included the evaluation of wind load distribution over the outer surfaces of the building for ten possible wind directions [14]. The analysis was performed using the finite volume method, high order numerical scheme for convective and ductile elements, and the SST turbulence model (Shear-Stress-Transport) k-ω that allows simulating continuous flows and flows with developed turbulent separation [7, 15, 16]. In the calculation, the buildings of the residential complex were put in a domain. The following types boundary conditions were used on the computational domain boundaries: "Inlet" (wind flow can only enter the domain), "Opening" (flow at the boundary may be directed inside or outside the domain), and "Wall" (at the surface of the building and the ground). The building model was turned by an appropriate angle to simulate the wind direction change [17].

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In the result of the analysis it was found that with certain directions of the wind the air flow speed can exceed 6 m/s at the elevation of 1.5 meters from the ground surface around the buildings and in a pedestrian walkway area of the complex (fig. 2). It means that the territory of the complex was not convenient for pedestrians as well as for the residents of the complex [6, 18].

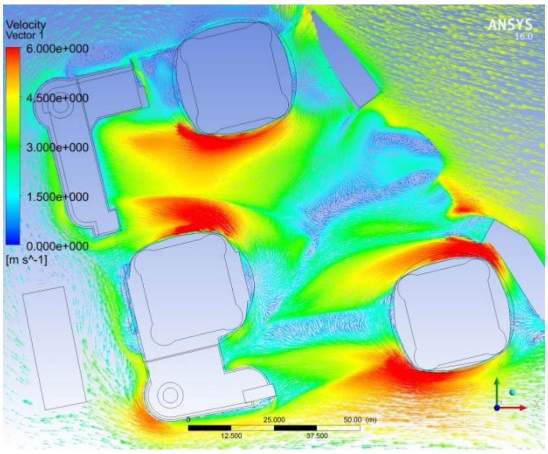

Figure 2. Distribution of wind flows at the elevation of 1.5 meters.

These aerodynamic conditions persist because of the wind flows hitting the high-rise building and flowing down guided by its surface [19, 20]. The speed of wind flows in these conditions may be doubled as compared with the initial speed of the wind before the contact with building. In order to solve this problem, the designers decided to carry-out another analysis, this time including a 3-meter-high barriers installed on the perimeter of the complex. The results of this analysis showed that the barriers are not effective and do not provide for the significant wind speed reduction (fig. 3).

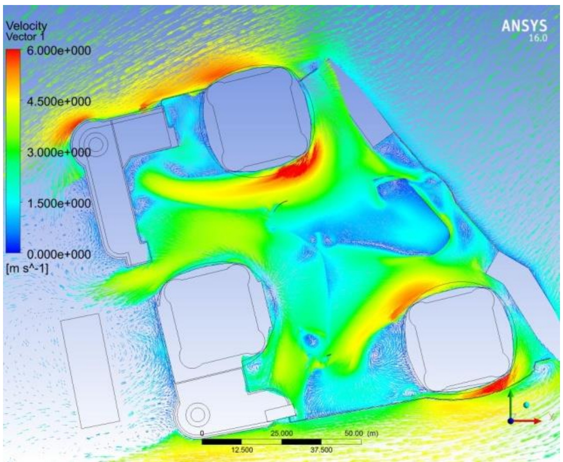

Figure 3. Distribution of wind flows at the elevation of 1.5 meters after the installation of 3-meter-high barriers around the perimeter of the complex.

Since the buildings have already been built, it was not possible to install additional elements on the building frames to break the wind flows. Therefore, it was suggested to install wind shields near pedestrian walkways and open areas of the residential complex (fig. 4) in addition to the barriers around the perimeter. It was decided to use 2-meter-high wind shields.

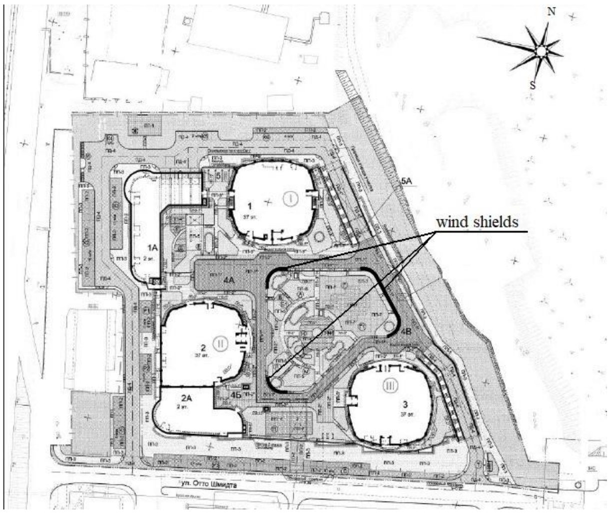

Figure 4. Layout of wind shields.

The analysis performed taking into consideration the wind shields showed that the speed of wind in adverse effect areas had been reduced significantly (fig. 5); thus, it was proved that the installation of the wind shields will help to increase comfort of people within the territory of the complex.

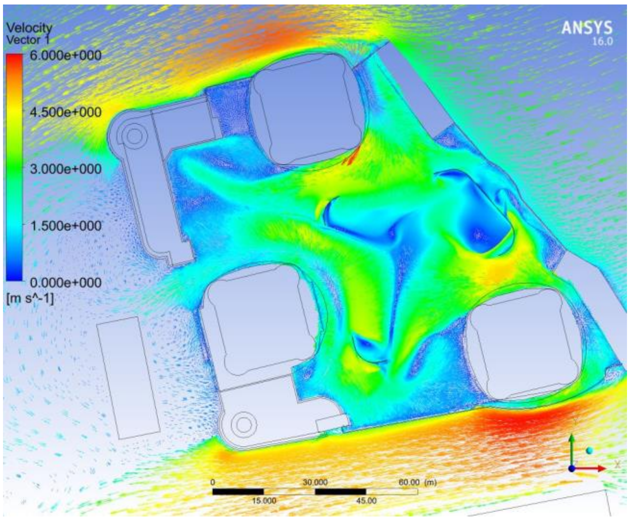

Figure 5. Distribution of wind flows at the elevation of 1.5 meters after the installation of 3-meter-high barriers around the perimeter of the complex and the wind screens inside it.

4. Conclusions

Construction of high-rise buildings becomes a high priority area. The reliability of such structures shall be taken care of as early as at the design concept stage. All design and engineering solutions shall be validated by calculations and, if necessary, by experimental investigations. Aerodynamic aspects shall be paid special attention during all such tests. Due to the limited experience of designing high-rise buildings and insufficient Russian regulatory base, it may be hard for local designers to evaluate wind effects correctly. However, the numerical modeling methods provide for the accurate assessment of the wind load distribution over the building surfaces and make it possible to calculate design load values. The numerical model shall be created as accurate as possible taking into account not only the building being built but also the buildings surrounding the construction site. In order to prevent creating adverse aerodynamic conditions during the construction of the building and its service life it is necessary to create the model of the building and the surrounding environment at the design stage.

To ensure the completeness of the design assessment it is necessary to use the numerical modeling method in conjunction with experimental analysis methods. Matching the results of numerical simulations done using different software complexes and data received by testing allows the designer to make more accurate assessment of load-bearing capacity and reliability of building structures and aerodynamic conditions.

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