Full-Scale Measurements of Local Wind Loads on a High-Rise Building Using Wind Tunnel Based Predictions

To cite this article: Sergey Kuznetsov and Stanislav Pospisil 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **471** 052053

Full-Scale Measurements of Local Wind Loads on a High-Rise Building Using Wind Tunnel Based Predictions

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Abstract. Significance of full-scale experiments, analysing wind conditions and local wind pressures on tall buildings are evident from the attention that has been dedicated by researchers to these programs in the recent past. This paper presents some recent results measured from a tall building located on the left banks of the Dnieper River of Kiev, Ukraine. In the first part of this study, attention is devoted to the full-scale measurements of the wind flow atop a high-rise building as a comprehensive investigation on wind velocity and local wind pressures on surfaces using wind tunnel simulation. In the second part was concentrated on the comparison results of mean wind pressures, mean pressure coefficients obtained from full-scale measurements, and scale modelling in the wind tunnel.

1. Introduction

Land use and development is an important issue in densely populated cities where the available land resources are limited. As societal and cultural requirements evolve, urban renewal is an important mechanism in the overall strategy of making the best use of available land and infrastructure, especially in already formed built-up area. Urban renewal projects typically involve changing building forms from predominantly low-rise or medium-rise single buildings to high-rise building groups that are often located above a common podium with integrated infrastructure and community facilities. Due to the significant changes of building forms, community awareness has been raised and concerns have grown over how the newly built structures alter the surrounding wind environment and wind loads [1, 2]. To address these concerns, the basis for evaluation and the corresponding solutions suggested by designers and engineers are mostly based on personal and professional experience, which are often subjective. Therefore, there is a genuine need for solid scientific data to guide decision-making. Significance of full-scale experiments, analysing wind conditions and local wind pressures on tall buildings are evident from the attention that has been dedicated by researchers to these programs in the recent past [3, 4].

With the advances in the use of innovative structural systems and high-strength lightweight materials, it has become possible of taller and more flexible building structure. Therefore, the sensitivity of modern tall buildings to dynamic excitation by wind has increased [5, 6]. This has resulted in a greater emphasis on understanding the structural behaviour of modern tall buildings under strong wind actions [7]. Although there have been many advances in wind tunnel testing and numerical simulation techniques for investigating wind effects on buildings and structures [8], there are still many critical phenomena, which can only be investigated by full-scale experiments. It has been widely recognized that the most reliable evaluations of dynamic characteristics and wind effects are obtained from experimental measurements of a prototype structure [9]. With the development of data acquisition techniques during the last three decades, a number of full-scale measurements of wind effects on tall buildings have been made throughout the world [10-12]. However, the chance to conduct full-scale measurements is quite rare, and obtained data are very important and valuable. Thus, such a database needs to be collected and expanded.

In modern conditions, evaluation of wind loads on buildings and constructions is carried out mainly according Building Codes and Regulations, which were developed based on the wind tunnel tests for an isolated building in an open terrain [13]. However, it is not necessary to prove that wind loads on buildings in real environment could be rather different from wind loads, measured for isolated buildings. Surrounding built-up area and neighbouring buildings and constructions can decrease or increase wind-induced effects on a building, depending mainly on geometric shape and mutual location of these buildings, their orientation due to wind flow direction and type of terrain [14].

This paper presents some recent results measured from a tall building located on the left banks of the Dnieper River of Kiev, Ukraine. In the first part of this study, attention is devoted to the full-scale measurements of the wind flow atop a high-rise building as a comprehensive investigation on wind velocity and local wind pressures on surfaces using wind tunnel simulation. In the second part was concentrated on the comparison results of mean pressure coefficients obtained from full-scale measurements and scale modelling in the wind tunnel.

In this paper, local pressure coefficients (C_p) at high-rise building is investigated and discussed. C_p values are determined in the Wind Tunnel of the National Aviation University (NAU), Ukraine, and the Climatic Wind Tunnel Laboratory at the Centre of Excellence Telč (CET), Czech Republic, and full-scale experiments. The study uses the building models tested in a set of parametric wind tunnel experiments, comprising form the local pressure measurements and Particle Image Velocimetry (PIV). This research represents full-scale method of wind loads investigation and the wind tunnel experiments. Full-scale research of wind effects in natural environment could become verification of model experiments. Until now due to a range of objective reasons, there were few research works, concerning wind loads on full-scale objects. Complex study and comparison of the results of scale model and full-scale experiments could allow obtaining engineering information about the formation of wind flows in urban environment; wind loads measurements on a tall building and influence neighbouring low-rise buildings and constructions.

2. Full-scale measurements

New 34-storey high-rise buildings are one of the tallest buildings in Kiev (Ukraine); their height is 110 m. The program and technique of full-scale investigation was developed to study the complex of residential buildings, situated on the left bank of the Dnieper River in Kiev in Dneprovskiy district to the right of Paton Bridge. The complex of buildings “Silver Breeze” is surround by residential buildings, built in 1970-90, the height of which is 9 and 12 storeys (see figure 1). The system of construction is made of monolithic concrete. The upper part of a building (penthouse) has non-standard configuration, its roof rising under the angle 10° from the centre to the edges and the middle part has duopitch roof rising under the angle 38° to the centre.

In order to make meaningful comparisons between the field measurements and the wind tunnel test results, an additional wind tunnel testing was carried out. The locations of the anemometers installed at the mast atop the high-rise building and potential interferences were calibrated so that the correction factors for the reference wind velocities atop the building for various wind directions were determined. A wind vane and anemometer. The Gill MicroVane and 3-Cup Anemometer measure horizontal wind direction and wind speed. Sensitive enough for detailed wind studies, these sensors are rugged enough for permanent installation with only periodic maintenance.

Figure 1. Urban Complex “Silver Breeze Kiev” Ukraine: a) the outer view of the complex of buildings which is being built on the crossing of P. Tychina Avenue and Dneprovskaya Embankment in Kiev, Ukraine; b) location of the 3-cup anemometer and the vane mounted on a radio transmitting antenna mast at a height of 120 m above ground level.

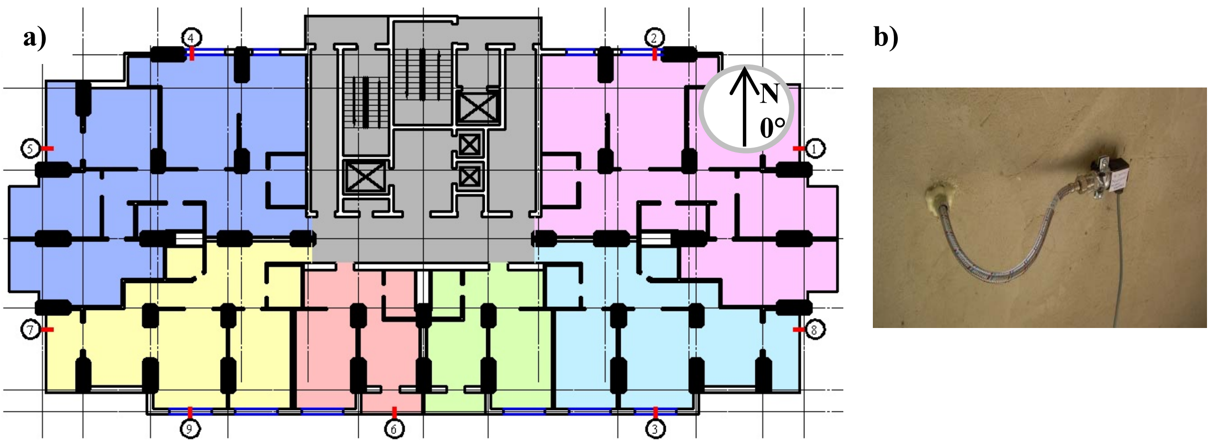

Figure 2. Arrangement of pressure sensors at level 25 of the floor (at a height of 72 m above ground level): a) the floor plan with the location of pressure taps; b) the fixation of pressure transducers.

As mentioned previously, a wind and movement monitoring system was installed on the high-rise building. Time series of wind speed and wind direction were recorded by a 3-cup anemometer and a wind vane mounted on a small crossarm installed on the mast a top the building. The height of the anemometer location was about 10 m above ridge of the roof, where is regarded to be little influenced by rooftop interferences. Moreover, the wind records chosen in this study satisfied a condition that the wind speed and direction from the three anemometers were consistent. Wind speed and direction were continuously and simultaneously acquired and digitized at 20 Hz by a high-resolution digital data logger. Differential pressure transducers were located along one horizontal line at one level 25th of the floor to measure local pressures against (see figure 2) the pressure in a pneumatic line connecting the reference ports of all 12 transducers to the ambient pressure in a central recording location on the 9th floor. Ambient absolute pressure in the recording room was also recorded.

In the full-scale measurement, mean pressure coefficient can be defined as:

$$C_{p-ful} = \frac{2P_i}{\rho U_r^2}, \quad (1)$$

$$U_r = \frac{U(h)}{k(h)}, \quad (2)$$

where P_i is the 10-min mean wind pressure, ρ is the air density, U_r is reference wind velocity, $U(h)$ is the 10-min mean wind velocity with the height h above the roof, $k(h)$ is ratio of reference wind velocity to wind flow above the roof of the high-rise building with the height h.

3. Wind tunnel tests

Wind tunnel testing is an important tool to evaluate the wind effects on buildings and structures. However, it is sometimes difficult to reproduce the exact field conditions such as incident turbulence and terrain characteristics in wind tunnel tests. Therefore, validations of wind tunnel predictions against full-scale measurements are always desirable to evaluate the accuracy of model test results and the adequacy of the techniques used in wind tunnel tests as well as to provide better understanding of the physics. Moreover, the model test results are compared with the field measurements for verification of the wind tunnel test techniques.

The wind tunnel experiments have been carried out in the boundary layer wind tunnels at the National Aviation University and the Centre of Excellence Telč. In this study, wind tunnel experiments using NAU for the ratio of reference wind velocity to wind flow above the roof and CET for local pressure measurements on the model of the high-rise building were conducted. The scaled models were 1:100 of the NAU wind tunnel (see figure 3) and 1:200 of the CET wind tunnel (see figure 5) reproduction of the high-rise building. The dimensions of the working sections of the wind tunnels are 4 m wide × 2 m high of the NAU, and 1.9 m wide × 1.8 m high of the CET. Typical boundary layer wind flow fields representing urban flow environment were simulated for the model tests by means of placing a barrier at the entrance of the wind tunnel, triangular shaped spires and arrayed cubic roughness elements with different sizes on the tunnel floor upstream of the building models [15]. The mean wind speed profile of the typical boundary layer flow was found to follow a power law with exponents of $\alpha = 0.28$. The turbulence intensities at the top of the building (excluding the mast erected atop the building) corresponding to 100 m height in full-scale (1 m and 0.5 m over the test section in the wind tunnels respectively) was 9.42%.

Five-hole probe was used to obtain the scalar and vector properties of complicated flow fields such as those encountered around the roof of the high-rise building in terms of static and total pressure and three-dimensional (3D) velocity components respectively. The results of the five-hole probe investigation were used to determination of the acceptable height of the 3-cup anemometer and the ratio of reference wind velocity to wind flow above the roof of the high-rise building.

The combination of pressures used to form a parameter, must be independent of any reference pressure or Reynolds number. This will make the relationship between the denominator and the measured pressures valid in all unknown flows, and will allow the probe to be used regardless of the particular flow conditions. Consequently, pressure parameters will be non-dimensional. The relationship must be true for any combination of pitch angle, and yaw angle. That is to say that the relationship between parameters are not a function of α or β, although the parameters themselves may be a function of pitch and yaw angles (see figure 4).

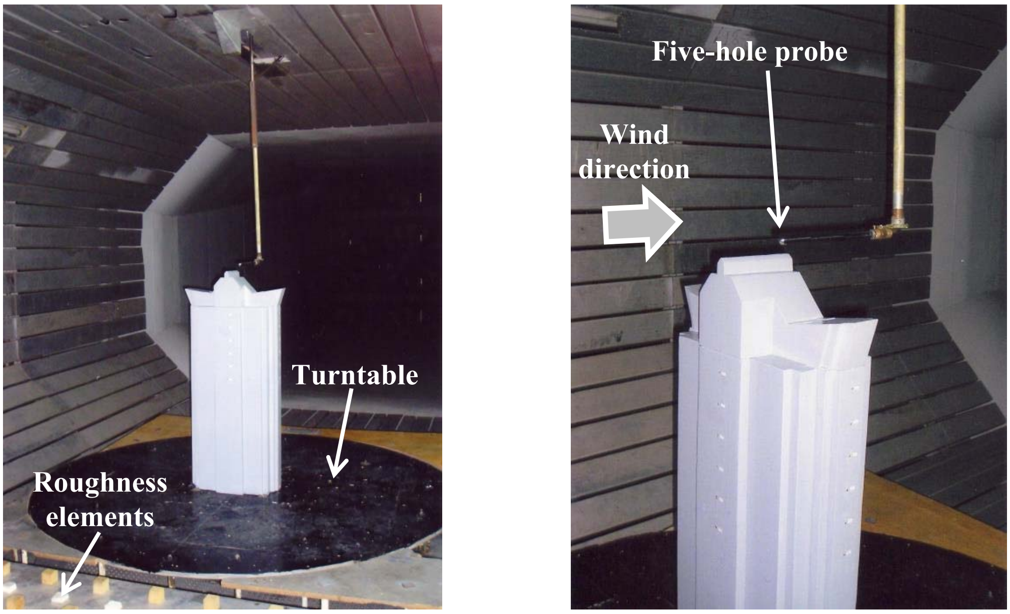

Figure 3. Model of the Urban Complex "Silver Breeze Kiev" in the wind tunnel test of the NAU (the scale of 1 to 100).

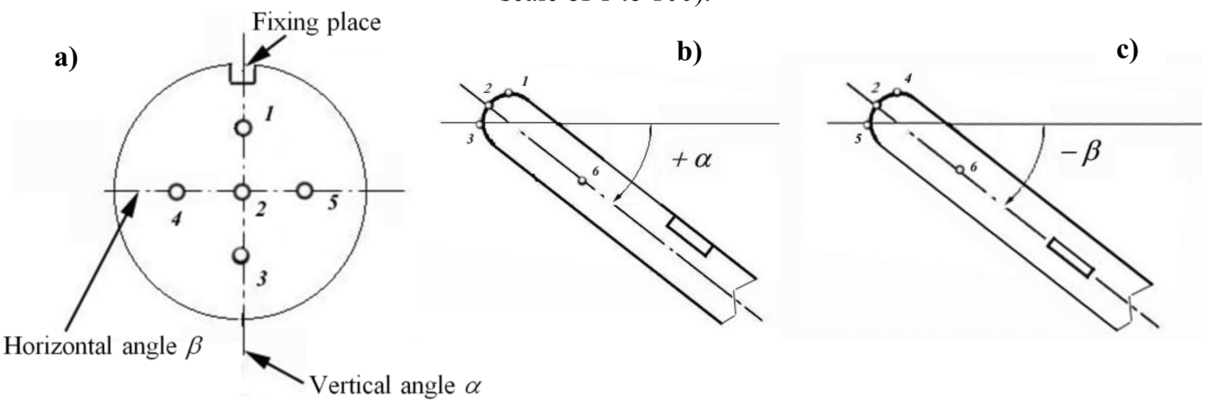

Figure 4. Five-hole probe for determination flow direction: a) schematic of probe hole numbering; b) the pitch angle α (points 1, 2, 3); c) the yaw angle β (points 4, 2, 5 and point 6 is static pressure).

This is necessary as neither the pitch, or yaw angles are known before the calibration coefficients are calculated. It was found that the following two parameters met most of the requirements:

$$\Delta\alpha = 0.237 + 7.065 \cdot K_\alpha + 0.16 \cdot K_\alpha^2 + 0.089 \cdot K_\alpha^3, \tag{3}$$

$$\Delta\beta = -0.39 - 8.568 \cdot K_\beta + 0.158 \cdot K_\beta^2 + 0.033 \cdot K_\beta^3, \tag{4}$$

$$k(h) = \sqrt{\frac{p_2 - p_6}{p_s - p_a}}, \tag{5}$$

$$K_\alpha = \frac{(p_3 - p_a) - (p_1 - p_a)}{2(p_2 - p_6) - [(p_3 - p_a) + (p_1 - p_a)]}, \tag{6}$$

$$K_\beta = \frac{(p_5 - p_a) - (p_4 - p_a)}{2(p_2 - p_6) - [(p_5 - p_a) + (p_4 - p_a)]}, \tag{7}$$

where p_1, p_2, p_3, p_4, p_5, p_6 are pressure measured at holes 1,2,…,6 in accordance with the scheme (see figure 5); p_s is the static pressure of the pitot-static tube (the reference pressure); p_a is the atmospheric pressure.

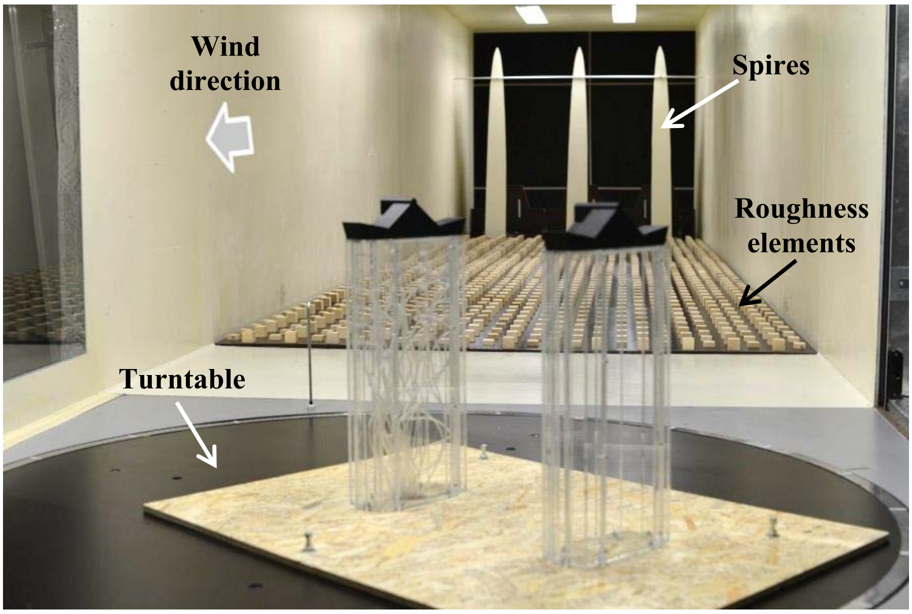

Figure 5. Turntable with the model of the Urban Complex "Silver Breeze Kiev" in the test section of the CET (the scale of 1 to 200).

Local mean pressure coefficient distributions on the high-rise building model were acquired at 24 pressure taps for all wind direction. The holes of the model were connected to a 16-port pressure scanner (Scanivalve, DSA 3217) by tubes. The digitized signal was then transferred to a computer and Dewetron software was used to analyse the data. The reference flow speed at the height of roof level was measured using a pitot-static tube connected to the same pressure scanner. The static pressure of the tube was used as the reference pressure. The sampling frequency and sampling time at each measurement point were 200 Hz and 30 s, respectively. The pressure measurement was repeated three times for each configuration. The average values have been used in the following analysis. The non-dimensional pressure coefficient C_p is defined as:

$$C_p = \frac{p_x - p_s}{q} = \frac{p_x - p_s}{p_T - p_s}, \tag{8}$$

where p_x is the pressure at a pressure tap on the building model; p_T is the total pressure.

As the input of the building responses, the wind characteristics simulated in the wind tunnel tests should be similar to those encountered in the field measurements. The power spectral densities of the approaching wind velocity measured at the top of the building model in the wind tunnel test CET and the prototype building, respectively. It can be seen from the figure that the measured spectra from the wind tunnel test and the field measurements all agree fairly well with the von Karman spectrum. The turbulence integral length scale measured at the top of the building model (380 mm), and the averaged value of turbulence integral length scale from the field measurements during the monitoring was h=120 m [15]. The turbulence integral length scale was adequately modelled in the wind tunnel test.

4. Results and discussions

One of the questions by the study is the level of location above the building of the 3-cup anemometer, which will record wind flow parameters with the appropriate calibration factor $k(h)$. The effect of the roof on dynamic pressures as measured by the five-hole probe, with the constant dynamic pressure was investigated (see figure 6).

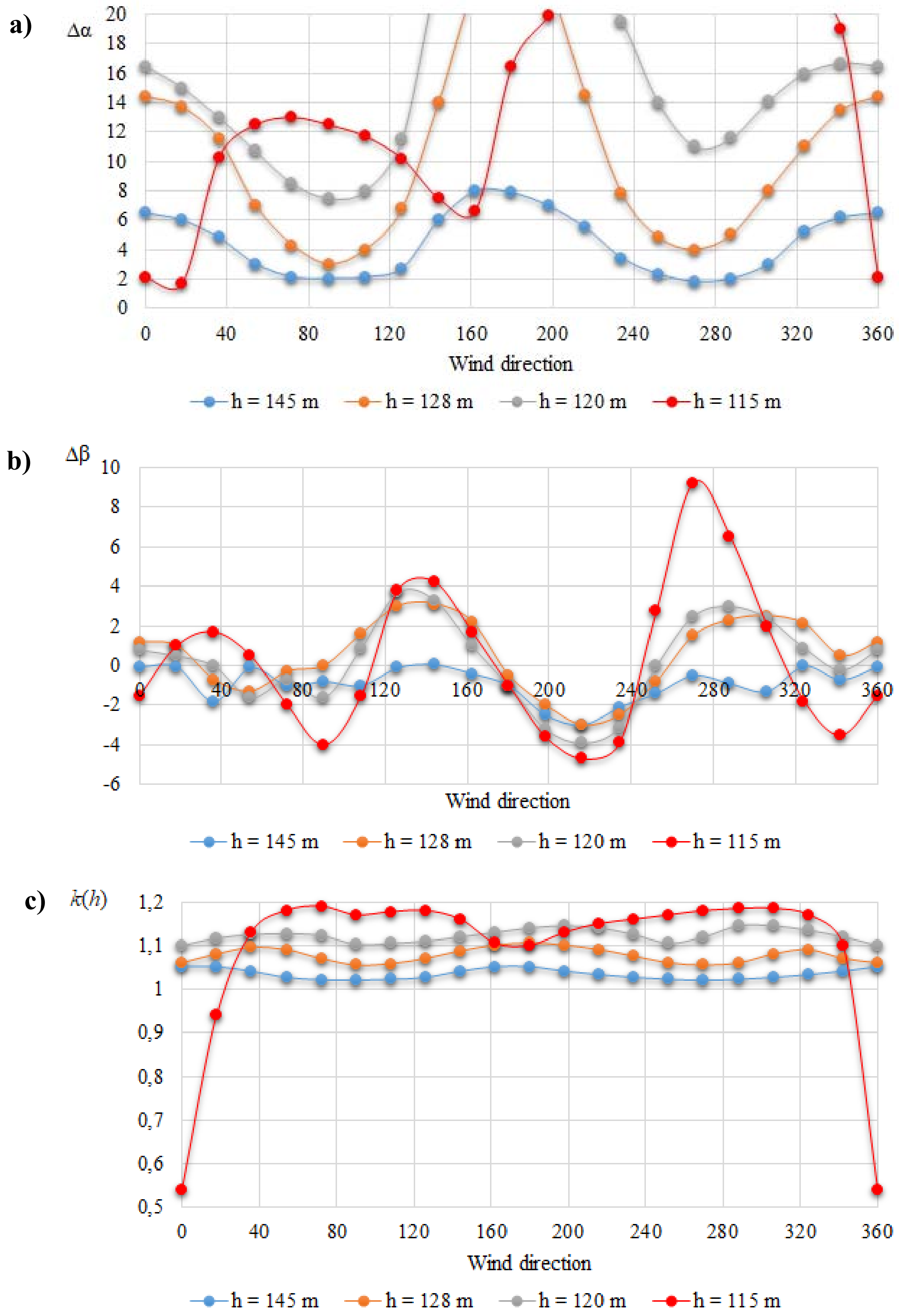

Figure 6. The five-hole probe experiments: a) the pitch angle α; b) the yaw angle β; c) the ratio of reference wind velocity to wind flow above the roof $k(h)$.

The wind tunnel tests were carried out for both cases of an isolated target building and the target building with the existing surrounding conditions. In this study, the wind direction is defined as an angle θ from the building north along a clockwise direction (see figure 2). In the wind tunnel tests, the measurements were performed with the wind direction varying from 0° to 360° with increments of 18°. C_p pressures were the result of the integration of the simultaneous acquisitions of the pressures measured by the 24 pressure taps located at a certain level of the model. As is well known, local wind pressures on a stationary bluff body are functions of the approach flow characteristics, its geometrical parameters and elevation. The mean coefficients of local wind pressures at each measurement under different wind directions are presented in figure 7a. Figure 7b shows a comparison between the full-scale measurements and wind tunnel tests. Here we see the wind tunnel experiments matches almost identically with the full-scale investigations.

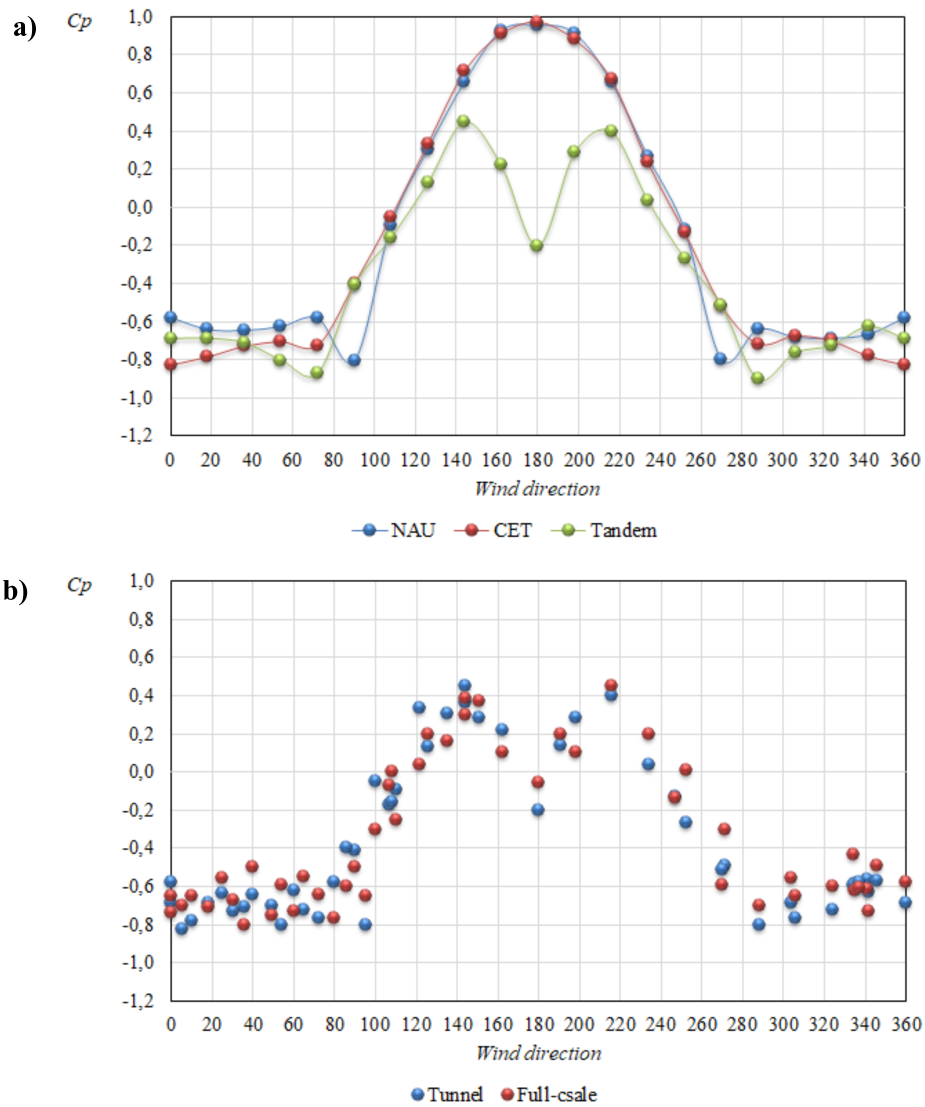

Figure 7. The comparison of local wind load measurements C_p in pressure tap No. 6: a) wind tunnel tests with two high-rise buildings in tandem arrangement; b) wind tunnel and full-scale tests.

Figure 8 illustrates the results obtained by typical PIV methods. Results of each method are represented with the corresponding bars of error. The PIV measurements provide instantaneous 2D velocity data, here υ_x and υ_z, which is averaged in time for further analysis. Results of the PIV experiments the mean vector field above roof of the single high-rise building (see figure 8a is present the wind direction of 270°), the mean streamlines above roof of the single high-rise building (see figure 8b), the mean vector field between the high-rise buildings (see figure 8c is present the wind direction of 180°), the mean streamlines between the high-rise buildings (see figure 8d).

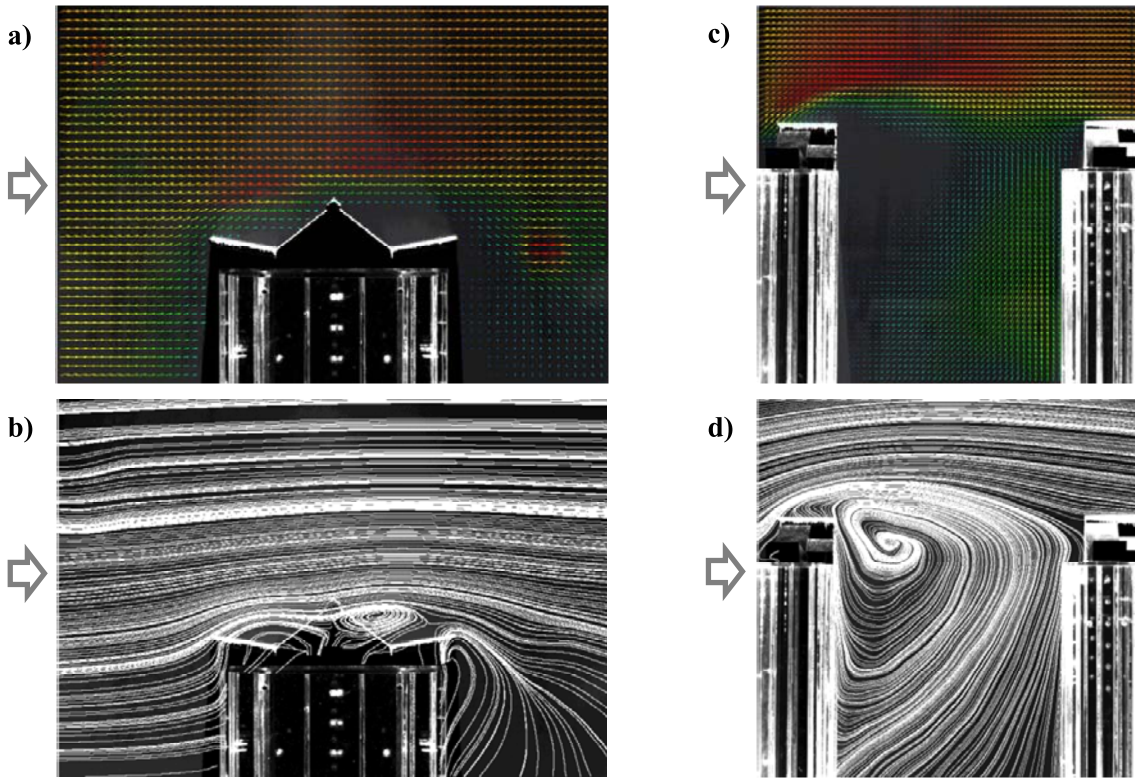

Figure 8. The mean vector fields and the mean streamlines of the PIV experiments.

Updrafts, downdrafts, and swirling eddies, zones of accelerated wind speeds and zones of reduced air circulation (wind shadows) were observed during the PIV visualisation. The height of a building and its placement relative to each other influence the pattern of the airflow around it. At the windward corner of the building roof, there are unexpected increases in wind speeds. This is due to air being forced around the windward corners from high pressures on the windward face to low pressures in sheltered areas at the sides and rear. Wind velocity increases with height, when the high-rise building is exposed to wind flow; the pressure is higher than that at the base. This different in pressure forces the high pressure at the top down the windward face that dramatically increases bottom wind speeds.

5. Conclusions

The results of the boundary layer wind tunnels and full-scale study are presented and discussed to investigate the local wind loads on a high-rise building with a height of 110 m in Kiev, Ukraine. Cross-validation between the model testing results and the field measurements was made for verification of the wind tunnel experimental techniques. At the design stage of a high-rise building, wind tunnel tests are widely adopted for the predictions of structural responses. However, wind tunnel tests have limitations in reproducing the exact wind field characteristics and mismatching of Reynolds number etc. Therefore, it is essential to validate wind tunnel predictions by field measurements, to assess the accuracy of model test results and the adequacy of the wind tunnel testing techniques. The comparison between the present wind tunnel test results with the full-scale tests for the Urban

Complex "Silver Breeze Kiev" showed that the agreement between the three sets of data was satisfactory, thus verifying the reliability of the present wind tunnel tests.

The interference effects from the surrounding buildings were significantly dependent on the incident wind direction, which mainly led to a reduction in the mean wind loads when the target building was sheltered by upwind buildings. The neighbouring high-rise building has the biggest interference effects on principal building at the south wind directions. There is a big relevance among local mean pressure coefficients on every surfaces of the test building, and many windward side pressure coefficients are relatively large (larger than +1 or –2).

Acknowledgments
This research was financially supported by the project LO1219 (SaDeCET) sustainability project of the Centre of Excellence Telč CET and the Wind Engineering Laboratory of the Donbass National Academy of Civil Engineering and Architecture (Ukraine).

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