Wind Loads of an Irregularly Shaped Tall Building in Warsaw – Eurocode 1 Standard Analysis and Wind Tunnel Testing

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Abstract. This paper analyses wind loads of an irregularly shaped skyscraper in Warsaw. The aim of this study was to compare the results of two methods: analysis conducted according to the Eurocode 1 Standard and wind tunnel testing. The wind pressure distribution on façades and net force values were analysed. In the Eurocode-based analysis, the role played by the form of the building is treated in general terms and the aerodynamic interference with surrounding buildings is not taken into account. The results are characterized by a high design factor of safety. The results of wind tunnel experiments are much more accurate, more reliable, and could be the basis for assuming lower wind loads.

1. Introduction

The construction of modern tall buildings requires solving increasingly complicated architectural and construction problems, structural, installation, and communication issues, as well as technical and fire safety problems. It should be noted that the scale of difficulty in the design process and implementation technologies is primarily related to the height of the buildings. With regard to the load-bearing structure, a building is considered as a tall building when the process of designing its load-bearing structure is decisively affected by wind load [1]. However, the impact of wind on a given structure is strongly influenced not only by the latter’s height but also its shape and other buildings in its immediate surroundings. Determining the location of a skyscraper, especially within dense urban tissue, requires relatively precise aerodynamic analyses [2].

When designing a high-rise building, one should strive to limit excessive tension in structural elements [3], bearing in mind that the spatial form greatly affects the size and distribution of forces [4]. The interaction between the form and wind determines the air mass flows around the building and wind pressure distributions on the façades [2]. To obtain more effective solutions, it is important to perform aerodynamic optimization analyses at the initial stage of the development of architectural concept. The possibility to eliminate the adverse impact of wind in the context of obtaining an innovative spatial form, as well as the possible reduction of construction costs, results in a greater interest in wind engineering research on the part of investors and designers [5].

In order to optimize the form and construction of a skyscraper, increasingly precise tools are needed to better understand the size and nature of aerodynamic interactions. This applies, in particular, to the erection of irregularly shaped buildings whose complexity means that the ability to accurately recognize aerodynamic phenomena is related to the chosen method of aerodynamic analysis. In Europe, wind tunnel testing is recommended for buildings higher than 200 metres. When designing buildings lower than 200
meters (which constitute over 96 per cent of European high-rise buildings), loads arising from the effects of wind can also be assumed according to Eurocode 1 European Standard [6, 7]. This essay presents the results of a comparative analysis carried out to verify the loads assumed in accordance with Eurocode 1 in relation to the results of wind tunnel experiments.

2. Subject of the study
Despite the fact that simple, geometric shapes characterize most of the high-rise buildings currently being erected in Europe, there is a visible, emerging tendency to design irregular forms. It is particularly necessary to conduct more precise analyses of spatial forms that cause the formation of adverse aerodynamic phenomena, for example: non-aerodynamic, asymmetrical, irregular forms, or those positioned transversely to the wind direction [8]. Objects located in urban space, in an environment that causes difficult to predict wind effects also require detailed analysis. This can be seen on the example of the analysed building, currently under construction in Warsaw city centre – an almost 200 m tall building, irregular and asymmetrical shape with numerous facade recesses and geometry based on right angles. The tower is formed of slender blocks of various heights and widths (Figure. 1). Functionally and spatially separated there are: a 10-level plinth part and a 36-level high dominant. The shape of the ground floor projection is similar to an elongated rectangle measuring 85 x 35 m in the plinth part and 65 x 30 m in the tower part.

The tower is located in an intensive development zone. On the northeast side (Figure. 2) there is a complex of multi-level buildings. On the east side, low and medium-high buildings prevail. On the south side there are some low-rise buildings. On the north side, a tall building complex is being developed, with another being built from the west.

![Figure 1](image1.png) **Figure 1.** Model of the analysed building. Highlighted: floors selected for the analyses and presented in the article.

![Figure 2](image2.png) **Figure 2.** Analysed building – the coordinates system, geographical and wind directions.

3. Description of the study
The aim of the undertaken aerodynamic studies was to compare the results obtained while using two different methods: the ‘European standard method’, which consisted in carrying out calculations in accordance with applicable regulations and standards, and the empirical (experimental) method included wind tunnel experiments.

The study compared the results obtained for 10 selected floor levels (Figure. 1) and all façades. The results presented in this article were limited to 4 selected floor levels (some are given only for floor 25) and the southern façade.
The analyses were conducted for 12 wind directions (Figure 2) (because in the Eurocode, the variation of the directional coefficient $c_{dir}$ is included for 12 directions). This paper presents the comparisons in terms of: pressure distribution on façades, envelopes and magnitude of peak pressures, and the magnitude of the net forces $F_x$ and $F_y$ transferred to the structure at the selected floor levels.

4. Methods

4.1 PN-EN 1991-1-4:2008 1 Eurocode 1.
The ‘European standard method’ included the analysis of building load conditions according to PN-EN 1991-1-4:2008 Eurocode 1 (described in [9]) and in accordance with Eurocode guidelines did not take into account the detailed configuration of the surrounding buildings, only a very generally described terrain class. According to the Polish annex to Eurocode, 1 wind load zone and IV category of terrain were assumed. The atmospheric boundary layer characteristic was mapped in all methods by adopting a standard mean wind velocity and turbulence intensity profiles.

4.2 Wind tunnel testing.
The empirical method consist in experimental research in a closed-loop wind tunnel carried out at the Institute of Aeronautics and Applied Mechanics at the Warsaw University of Technology (described in [9]). Passive methods were used to map the atmospheric boundary layer characteristic in the tunnel. The examined building, together with neighbouring buildings within a 500 m radius, was modelled on a scale of 1:350 (Figure 3). The experiments were carried out with the use of rigid building models that allow measuring wind pressure on the walls using pressure sensors, as well as measuring net forces and aerodynamic moments using an aerodynamic balance. The signals from the measurements have been processed numerically.

5. Findings

5.1 Peak pressure values.
The first analysis concerned the distribution of pressure on the façades (Figure 4). To limit the impact of the environment, the analysis has been restricted to comparing pressure distributions on the windward southern façade (160° wind direction). The results obtained in the Eurocode-based analysis are significantly inaccurate. The differences in pressure distribution resulting from the irregular shape of the

[Figure 3. Model of the analysed building and its surroundings in the wind tunnel.

Figure 4. Maps of the wind pressure distributions on the southern façade, obtained according to: Eurocode-based procedure and wind tunnel testing. 160° wind direction.]
structure are not visible. Moreover, the occurring changes in pressure values are largely simplified in relation to reality. On the other hand, in wind tunnel experiments it is possible to obtain highly precise results that could form the basis of a detailed optimization of a building with a complicated form.

Afterwards, peak pressure values were analysed. Comparing peak pressure values for long façades (north and south) (Figure 5, Table 1 and 3), one can see that the values obtained from the Eurocode-based calculations can be twice as high as those measured in the wind tunnel. For the shorter eastern and western façades and around corners and bends the results are similar (Figure 6, Table 2 and 4). Strict Eurocode-based guidelines regarding the edges and bends of the building, with respect to short or broken-up façades, have been experimentally confirmed.

One can see that the effect of suction is particularly important here. Much higher values are observed on virtually all corners, rather than on flat sections. For the western façade, the Eurocode-based method does not reflect the differences in the amount of wind suction. The differences between the Eurocode-based values and values obtained from the wind tunnel tests are the largest for the southern façade and flat surfaces of the northern façade. When it comes to wind pressure according to Eurocode, the values remain

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**Figure 5.** Façades for which the results are presented in Tables 1 and 3.

**Figure 6.** Façades and corners for which the results are presented in Tables 2 and 4.

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### Table 1. Peak pressure values for the northern façade (EC – Eurocode, TT – Tunnel Test)

| Floor | Pressure [kPa] | Suction [kPa] |
|-------|---------------|---------------|
|       | EC  | TT | EC  | TT | EC  | TT |
| 10th  | 0,83 | 0,37 – 0,53 | 0,55 – 1,02 | 0,41 – 0,60 |
| 25th  | 0,85 | 0,40 – 0,62 | 0,57 – 1,05 | 0,37 – 0,73 |
| 40th  | 1,12 | 0,64 – 0,75 | 0,74 – 1,38 | 0,38 – 0,70 |
| 50th  | 1,12 | 0,61 – 1,00 | 0,74 – 1,38 | 0,27 – 0,44 |

### Table 2. Peak pressure values for the western façade (EC – Eurocode, TT – Tunnel Test)

| Floor | Pressure [kPa] | Suction [kPa] |
|-------|---------------|---------------|
|       | EC  | TT | EC  | TT | EC  | TT |
| 10th  | 0,50 | 0,27 – 0,50 | 0,83 – 1,02 | 0,73 – 1,03 |
| 25th  | 0,52 | 0,35 – 0,55 | 0,83 – 1,05 | 0,80 – 1,00 |
| 40th  | 0,68 | 0,39 – 0,54 | 1,09 – 1,38 | 0,39 – 0,54 |
| 50th  | 0,68 | 0,40 – 0,50 | 1,38 | 0,35 – 0,66 |

### Table 3. Peak pressure values for the southern façade (EC – Eurocode, TT – Tunnel Test)

| Floor | Pressure [kPa] | Suction [kPa] |
|-------|---------------|---------------|
|       | EC  | TT | EC  | TT | EC  | TT |
| 10th  | 0,65 | 0,20 – 0,39 | 0,57 – 1,02 | 0,55 – 0,69 |
| 25th  | 0,67 | 0,29 – 0,44 | 0,59 – 1,05 | 0,54 – 0,70 |
| 40th  | 0,88 | 0,36 – 0,48 | 0,78 – 1,38 | 0,60 – 0,65 |
| 50th  | 0,88 | 0,35 – 0,66 | 0,78 – 1,38 | 0,36 – 0,70 |

### Table 4. Peak pressure values for the chosen corners on the 25th floor (EC – Eurocode, TT – Tunnel Test)

| Corner | Pressure [kPa] |
|--------|---------------|
|        | EC  | TT |
| W      | 1,05 | 1,09 |
| N      | 1,29 | 1,27 |
| N-E    | 0,63 | 0,58 |
| S-E    | 0,63 | 0,73 |
identical over the entire length of the façade, while the wind tunnel analysis results show some clear differences.

5.2 Net Forces.
The study analysed the $F_x$ and $F_y$ components of net forces for selected floors combined for a fixed point in the building's coordinate system (Figure 2). Significant differences in the results were observed: usually the results obtained from the Eurocode-based calculations were 2-3 times greater than those measured in the tunnel (e.g. $F_y$ component for 340° direction – Table 5), and in extreme cases the differences can be 7-10 times greater (70° direction – $F_x$ component for the 50th floor and $F_y$ component for the 10th floor – Table 6), and the component forces can even have an opposite direction ($F_x$ component, direction 340° – Table 5).

**Table 5.** The components $F_x$ and $F_y$ of net forces for selected floors – 340° wind direction (EC – Eurocode, TT – Tunnel Test)

| Floor | $F_x$ [kN] | $F_y$ [kN] | Floor | $F_x$ [kN] | $F_y$ [kN] |
|-------|------------|------------|-------|------------|------------|
| 10th  | -98,06     | 13,80      | 330,25| 175,80     |            |
| 25th  | -72,88     | 26,50      | 245,46| 75,90      |            |
| 40th  | -66,43     | 15,30      | 223,72| 74,80      |            |
| 50th  | -70,79     | -4,90      | 211,93| 66,10      |            |

**Table 6.** The components $F_x$ and $F_y$ of net forces for selected floors – 70° wind direction (EC – Eurocode, TT – Tunnel Test)

| Floor | $F_x$ [kN] | $F_y$ [kN] | Floor | $F_x$ [kN] | $F_y$ [kN] |
|-------|------------|------------|-------|------------|------------|
| 10th  | 75,25      | 26,30      | -106,58| -10,20     |            |
| 25th  | 55,93      | 16,00      | -79,21 | -11,30     |            |
| 40th  | 50,98      | 15,10      | -72,20 | -25,50     |            |
| 50th  | 43,62      | 6,80       | -68,17 | -28,50     |            |

**Figure 7.** The components $F_x$ and $F_y$ of net forces for the 25th floor, depending on the direction of wind

By analysing the chart of the components of net forces, e.g. for the 25th floor (Figure. 7), the impact of surrounding buildings on the magnitude of wind forces can be clearly observed. The most varied are the net forces calculated for winds blowing from the north (300°, 340°, 0°) and west (210°, 240°, 270°), which results, among others from close proximity to high-rise buildings. On the other hand, smaller differences in the net forces for the south-eastern wind directions (120°, 150°, 180°) result from the lack of objects of significant height in this area in the immediate vicinity. However, the position of the building –
perpendicular to the direction of wind – results in a greater variation in the results obtained. For east winds (60°, 90°), the results are even more convergent. There are no tall constructions on this side, the wind blows parallel to the longer side of the analysed building and its form can be treated as more streamlined.

6. Summary
The accuracy of the results obtained in wind tunnel analysis testing allows for a fairly precise determination of pressure distributions and net forces transmitted to the structure. During the analysis of pressures on building façades, the possibility to optimize based on the results of experimental research was determined. Particularly large differences were noticeable in the analysis of net forces acting on the building. The net forces values measured experimentally were much smaller than those calculated in accordance with Eurocode. Not only the impact of the complex geometry of the building, but also the influence of neighbouring high-rise buildings and the resulting aerodynamic shadows are noticeable.

7. Conclusions
Due to significant wind load effects on tall buildings, optimization of their form requires to identify those loads as accurately as possible. Determining methods for conducting wind analysis becomes a key issue, as the results obtained can differ significantly. The analyses confirmed the hypothesis that results obtained with different methods are divergent and the choice of method has a significant impact on the adopted technical solutions.

The analysed methods differ in the accuracy of the results obtained. Wind-tunnel testing allow more accurate analysis of the wind load effect on objects located in a complex environment, and especially those with unusual geometry. The European Standard procedures have been developed to analyse simple, basic geometries, not taking into account the impact of the surrounding environment, and the results obtained often lead to the adoption of excessive safety factors. A simplified representation of the wind load nature in relation to their value and distribution also results in under-clarification and overestimation of the values calculated.

Although the European Standard can be applied to buildings up to a height of 200 m, the procedures described are only sufficient for calculating wind loads of simple, regularly shaped buildings. For buildings with complex, irregular geometry, the Standard does not specify any more accurate procedures. Because the Eurocode-based methods do not adequately analyse many aspects of structural design, the safety factors assumed are too high. On the other hand, the results obtained from experimental tests, as more reliable, can provide a reference point for accepting lower wind load values. It should be noted, however, that structural design process based on the Eurocode Standard is a safe procedure and accepting lower load than those described in the Eurocode should be each time justified by detailed analytical analyses.

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8. References
[1] Boda, D. and Banda, L. (2011). *Wind effects on typical tall structures*. Saarbrücken: Lambert Academic Publishing.
[2] Irwin, P., Denoon, R. and Scott, D. (2013). *Wind Tunnel Testing of High-Rise Buildings: An output of the CTBUH Wind Engineering Working Group*. Chicago: Council on Tall Buildings and Urban Habitat, Routledge / Taylor and Francis Group.
[3] Kahn, F. R. (1982). *The rise and fall of structural logic in architecture*. *Chicago Architectural Journal*
[4] Billington, D. (1983). *The tower and the bridge: The new art of structural engineering*, Princeton University Press, Princeton.
[5] Flaga, A. (2008). *Inżynieria wiatrowa. Podstawy i zastosowania*. Warszawa: Arkady.
[6] PN-EN 1991-1-4:2008 Eurokod 1: oddziaływania na konstrukcje. Część 1-4, Oddziaływania ogólne: oddziaływania wiatru.

[7] Żurański, J. A. and Gaczek, M. (2011). Oddziaływania klimatyczne na konstrukcje budowlane według Eurokodu 1. Komentarz z przykładami obliczeń. Warszawa: Instytut Techniki Budowlanej.

[8] Lawson, T. (2001). Building aerodynamics. Londyn: Imperial College Press.

[9] Pietrzak, J., Rutkowski M. and Wrona M. (2017). Analizy normowe oraz badania modelowe oddziaływania wiatru na budynek wysoki o nieregularnej formie na przykładzie projektowanego wieżowca w Warszawie. Unpublished manuscript, Politechnika Warszawska, Wydział Architektury, Warszawa.