European tall building with a height of 200 m and an irregular form – aerodynamic analysis methods

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Abstract

A tall building with an irregular form requires optimisation due to the impact of wind loads. The aerodynamic analyses should be carried out at an early concept stage. The decision which wind analysis method to choose is a key issue. This issue will be discussed on the example of an irregularly shaped skyscraper in Warsaw. The aim of this research was to determine and compare the results of three methods. The three methods were: the analytical analysis according to the European building codes (Eurocode 1), wind tunnel tests (a simulation in an aerodynamic tunnel at the Institute of Aeronautics and Applied Mechanics of the Warsaw University of Technology) and Computational Fluid Dynamics (numerical wind tunnel flow simulation in FLUENT). The possibility of examining the air flow around the building, wind pressure distribution on facades and net force values were analysed.

The methods differ in their accuracy and types of the obtained results. The Eurocode noticeably lacks methods for tackling irregular forms. Because the influence of the form of the building is treated very generally and the aerodynamic interference with the surrounding buildings is not taken into account, the results from the Eurocode calculations are characterized by a large safety factor. The results of a wind tunnel test are much more accurate. Values of pressures, forces and moments can be measured, but the presentation of the results requires statistical and/or graphic processing. Currently, it is the only method combining the accuracy and reliability of the obtained results. However, the precise, time-consuming tunnel tests should be conducted on the final form as the final verification of the adopted architectural and structural solutions. At the concept stage the architects need tools to quickly estimate the air flow and wind effects on the building. Computer simulations are easier and cheaper to conduct than tunnel tests. Moreover, the results of computational simulations can become the basis for understanding the air flow around the building. This method would be used more frequently if it did not require verification of its results.

Keywords: skyscraper, tall building, wind influence, Eurocode, wind tunnel testing, computational fluid dynamics

Introduction

In the context of obtaining an original architectural form and reducing construction costs the possibility of eliminating the adverse impact of wind raises investors' and designers' interest in wind engineering. This field which is particularly important in the case of tall buildings. It should be noted, however, that the influence of wind is strongly conditioned not only by the height of the building but also its shape, and the surrounding buildings. The unique shape and the vicinity of each skyscraper, especially the proximity of dense urban fabric, is associated with the need to conduct precise aerodynamic analyses [9].

The forms of contemporary European high-rise buildings become more varied. It happens so, among others, due to the resignation from simple forms, characterized by regular, repetitive floors. An effective form of a skyscraper requires the cohesion of a functional and spatial solution. As a basis for the design of a skyscraper, one should strive to limit stresses in structural elements [10], and in skyscrapers the magnitude and distribution of forces are affected to a large extent by its form [2]. The interaction between the wind and form determines the air flow and distribution of the wind pressure on facades. Optimizing the shape of a skyscraper may lead among others to i.e. an optimization of the load-bearing structure or the technical solution of the facade. Aerodynamic optimization analyses at the stage of developing the architectural concept are of particular importance in achieving more effective and economical spatial solutions. Aerodynamic optimization helps to reduce adverse impact of wind in the context of obtaining more rational design of load-bearing structures and the reduction of construction costs. A balanced approach to design, and often above all economic conditions, raise interest in reducing the adverse impact of wind.

In order to optimize the form and structure of a skyscraper, it is necessary to look for tools that allow for an accurate understanding of the wind effects. With the buildings forms becoming more complex and irregular the ability to accurately calculate and predict aerodynamic phenomena relies on the chosen method of aerodynamic analysis. In Europe, for buildings taller than 200 m, wind tunnel tests should be recommended. Designer can also chose to use computational methods, that are developing dynamically. When designing buildings of less than 200 meters (which account for over 96% of European tall buildings), wind loads can be calculated according to design standards described in Eurocode 1. There is a lack of scientific studies which would analyse both the effects of calculating the wind loads in accordance with Eurocode 1 and on the basis of the results obtained in the tunnel test and numerical simulations.

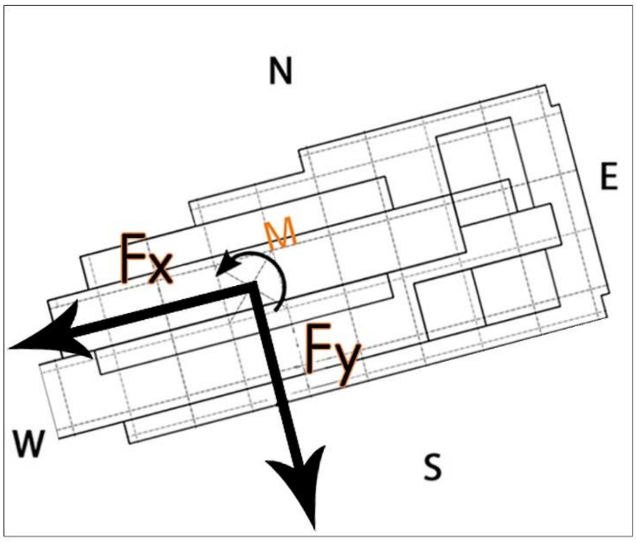


Figure 1. Analysed building - relation to the directions of the world and the coordinates system

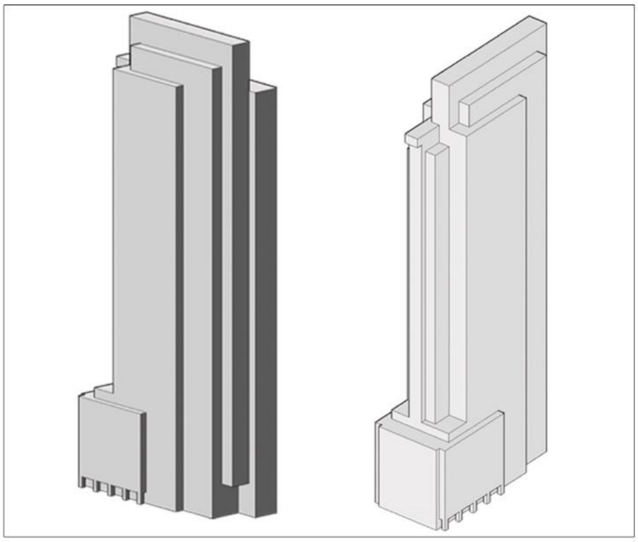


Figure 2. Model of the analysed building

Subject of the study

In particular, the forms which cause unfavourable aerodynamic phenomena, such as the non-aerodynamic, asymmetric, irregular buildings, should be carefully analysed[11]. Detailed analyses are also required for objects located in an urban space, in a context causing difficult to predict, variable and asymmetrical wind effects. This is evident in the example of the analysed building - a skyscraper constructed in the centre of Warsaw with a height of almost 200 m and an irregular, asymmetrical shape and geometry based on a right angles. The skyscraper was shaped from slender solids with different heights and widths (Fig. 2). The planned ground floor area is over 2,500 m^2. Functionally and spatially the building has been divided into: a base part with a height of 10 floors

(41 m) and a dominant with a height of 36 floors. The shape of the floor plan is similar to an elongated rectangle with the proportions of sides 1:3.5 (ca. 85 x 35 m in the base part, 65 x 30 m in the tower part).

The analysed skyscraper is located in the centre of Warsaw, in the intensive building zone. In the surroundings of the building there are tall office buildings, residential buildings and low shopping centres. From the north-east side (Fig. 1), a complex of multi-storey buildings is located, from the east there are mainly low and medium-rise buildings. On the south side there are low-rise buildings. On the north side there is a high-rise building complex, and another one is built from the west.

The research compared the results obtained for 10 selected floors and all facades [12][14]. The results presented in the article were limited to 4 selected floors (some of them were given only for the 25th floor) and the southern façade (Fig. 3).

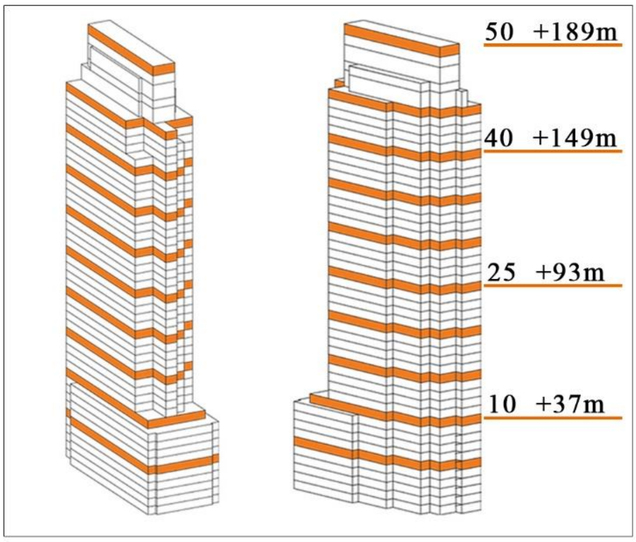


Figure 3. Floors selected for the analyses and presented in the article

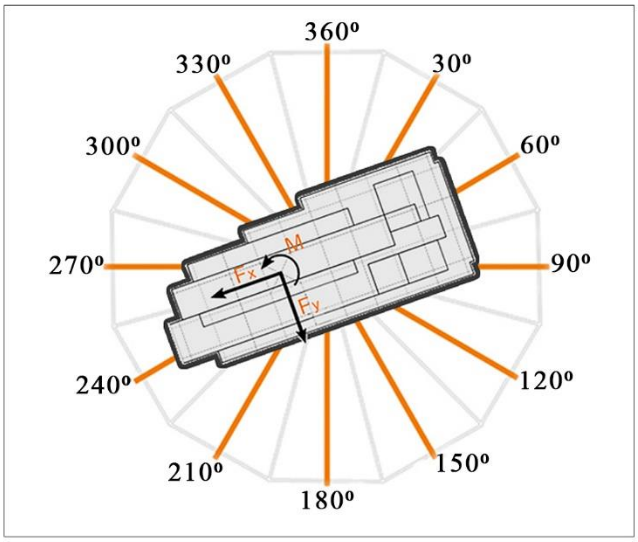


Figure 4. Analysed wind directions

Study Description

The task of wind engineering is to provide methods and tools for testing the wind-form-structure relationships and to find the criteria for deciding which procedure to choose [9]. Currently, engineers use three methods, and the purpose of this research was to compare them. The first method – based on design codes and standards, uses analytical methods in accordance with applicable regulations, recommendations or other similar documents. The second - empirical (experimental) method includes simulations conducted in a wind tunnel. The third method - a fully computational analysis, uses known mathematical models to define the impact of wind [7]. This group comprises primarily digital computational analyses.

According to European design standards analyses have been carried out for 12 wind directions (Fig. 4). The presented results of wind impact on the given object are: qualitative comparison of pressure distributions on facades (for 3 methods), peak pressures (calculated using code procedure and measured in a tunnel), comparison net forces transferred to the structure on the selected floor's levels. The possibility of analysing the air flow around the building was also examined.

Methods

PN-EN 1991-1-4: 2008 Eurocode 1

The first analysis included the analysis of the wind loads according to PN-EN 1991-1-4:2008 Eurocode 1 [13][17][18]. The code procedure did not take into account the detailed configuration of the surrounding buildings, only a very generally defined class of terrain. In accordance with the national annex to the Eurocode, 1st wind zone and terrain category IV were assumed. In all methods the characteristics of the atmospheric boundary layer were reproduced by adopting the standard mean velocity and turbulence intensity profiles . In order to accurately represent the actual structure of the wind at the ground-level, the results of climate analysis developed at the Faculty of Power and Aeronautical Engineering, WUT were used.

Figure 5. Model of the analysed building and the surrounding in the wind tunnel

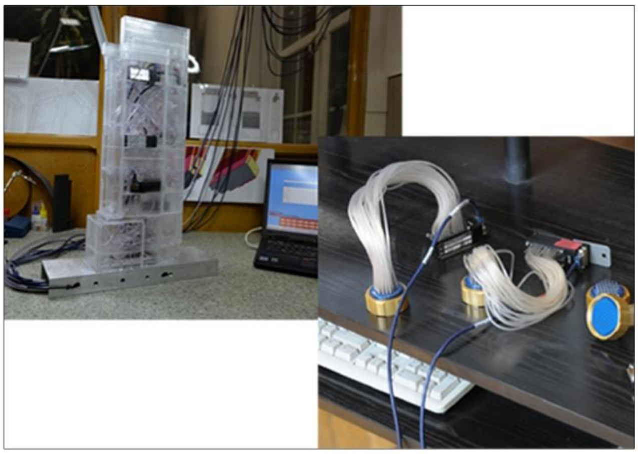


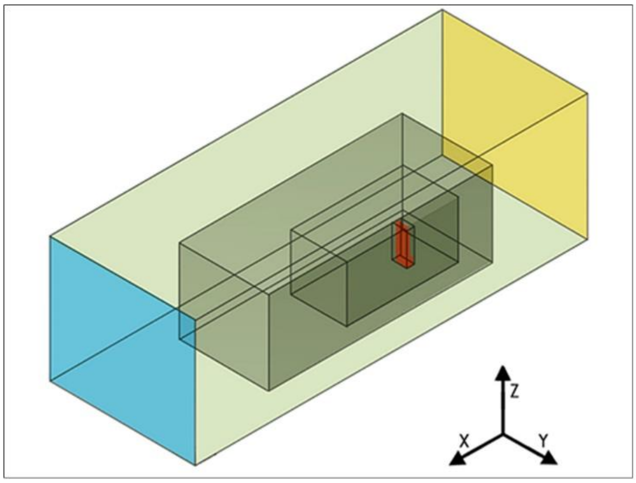
Figure 6. Pressure sensors – installed inside the model and connected to quick-release couplings

Wind tunnel testing

The empirical method consisted of experimental research in the wind tunnel at the Institute of Aeronautics and Applied Mechanics of the Warsaw University of Technology. The wind tunnel is a closed-loop tunnel measuring 2.60 x 2.25 x 11.00 m. Passive methods were used to map the atmospheric boundary layer characteristic in the tunnel. The analysed building together with the neighbouring buildings (within a radius of 500 m) was mapped in a 1:350 scale (Fig. 5). The model contained all the designed tall buildings, concepts of which were known at the time of the experiment. The tests were carried out using rigid models of buildings which allow the measurement of wind pressure on walls by means of pressure sensors (Fig. 6) and measurements of resultant forces and aerodynamic moments using aerodynamic balance [7]. The signals from the measurements were subjected to numerical processing, the aim of which was to obtain pressure and force values on the entire surface of the model.

Computational Fluid Dynamics

The computational method included simulation performed in the Ansys Fluent program, which is used by engineers at the Institute of Aeronautics and Applied Mechanics of the Warsaw University of Technology and is widely described in the scientific literature as a tool to analyse the impact of wind on cuboid high-rise buildings with proportions enabling precise determination of wall boundary layer separation points (e.g. [5][6]). The simulation was carried out according to the recommendations of [1][3][4][8][13][15][16].



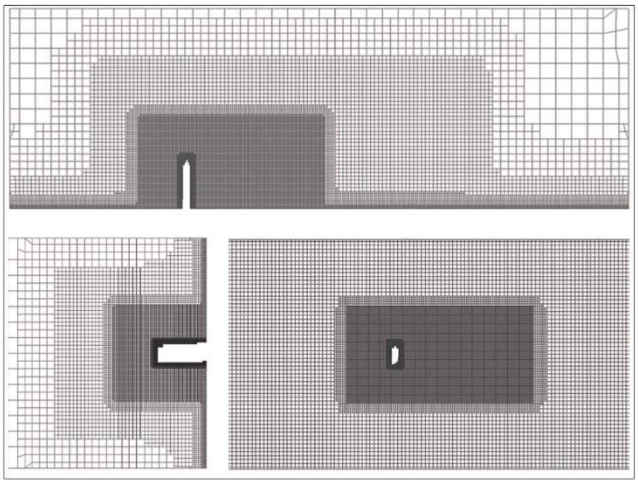


Figure 7. The computational domain - boundary conditions (description in the article)

Figure 8. The structural grid generated to discretize the computational domain

The goal of the computational analysis was to recreate the conditions of the wind tunnel experiment. The computing domain simulated the dimensions of the actual tunnel. The boundary conditions had been assigned to the appropriate surfaces limiting the computational domain (Fig. 7): inflow (the plane marked in yellow) and outflow (blue). The remaining boundaries of the domain (green) have been given the boundary condition of the wall *without slipping*. The grid compaction areas (grey) were modelled as surfaces fully permeable to the fluid (*internal* condition) (Fig. 7 and 8). The vertical profiles of mean wind velocity and turbulence intensity were set at the inflow. To obtain the results more similar to the results of the experiment, it was decided to choose the improved $k – \varepsilon$ *realizable* model from the RANS group [1][16]. A standard wall function was used to model the boundary layer. The flow was modelled as laminar. A *pressure based solver* was used. The *SIMPLE* algorithm, based on the *segregated* method, was used to solve the equations describing the flow. The finite volume method was used to discretize the model. *Standard* method recommended by Fluent producers was used for interpolation of pressure. The *upwind* method was used to discretize equations: moments, kinetic energy of turbulence and turbulence kinetic energy dissipation. The course of residual values was monitored until their convergence reached the value of $1e^{-5}$.

In order to check the numerical calculations the global net forces acting on the analysed model were compared with the forces measured in tunnel test. The comparison of the results showed their certain convergence. The results obtained in the computational analysis reflected the nature of the occurring aerodynamic phenomena and were then used for qualitative analyses. However, they were not included in more detailed quantitative analyses.

Results

Wind pressure distributions on facades

The first analysis was aimed at comparing the results obtained with the 3 methods (Fig. 9). Due to the limitation of the impact of the surroundings, the analysis was limited to the comparison of pressure distributions on the south facade with wind from the same direction. The results obtained in the Eurocode analysis are characterized by significant inaccuracy. However, after adopting appropriate assumptions, in a tunnel test and in a computational analysis one can get similar precision of the results, which can then be the basis for a detailed optimization of a complex building. The numerical calculations have been quite accurate as to the reproduction of the qualitative nature of the phenomenon. The zones of pressure and suction on facades and their changes have a similar distribution. One can also notice how the results obtained from the norms are simplified when compared to the exact simulation of real conditions. The differences in pressure distribution resulting from irregularities of the form are not visible in the design code results. Moreover, the changes in pressure values are a very big simplification in relation to reality.

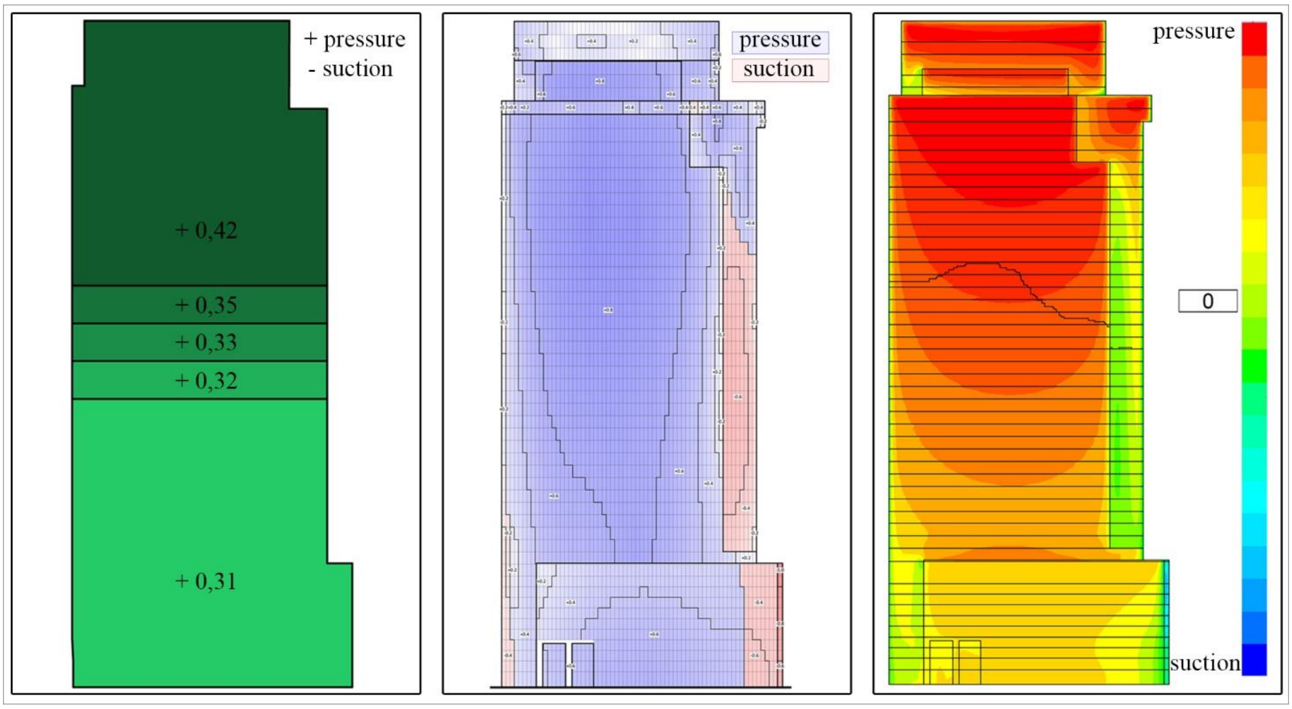


Figure 9. Maps of the wind pressure distributions on the southern façade, obtained according to: Eurocode procedure, wind tunnel testing and computational simulations. 160° wind direction

Peak pressure envelopes

Since similar results are obtained both in the analytical method and tunnel tests, further analyses have been limited to the comparison of the methods giving extreme results, i.e. the Eurocode and the wind tunnel testing.

First, the peak pressures envelopes for selected floors were analysed (Fig. 10). It can be observed that the effect of suction is particularly important. Practically all the corners achieve much higher values than the flat sections. For short sections of the façades, the analytical method does not reflect differences in the suction volume. The distribution of suction force for long facades is also different. In terms of pressure, according to analytical method its values remain the same along the length of the facade, while in the tunnel results there is significant differentiation.

Peak pressure

For long facades – the northern and southern (Fig. 11) one the peak pressure values obtained from the calculations are even twice as large as those measured in the wind tunnel (Table 1 and 3). In the case of the shorter (eastern and western) facades and corners (Fig. 12) the results are similar (Table 2 and 4). Strict norms regarding the edges and corners of the building have been confirmed experimentally.

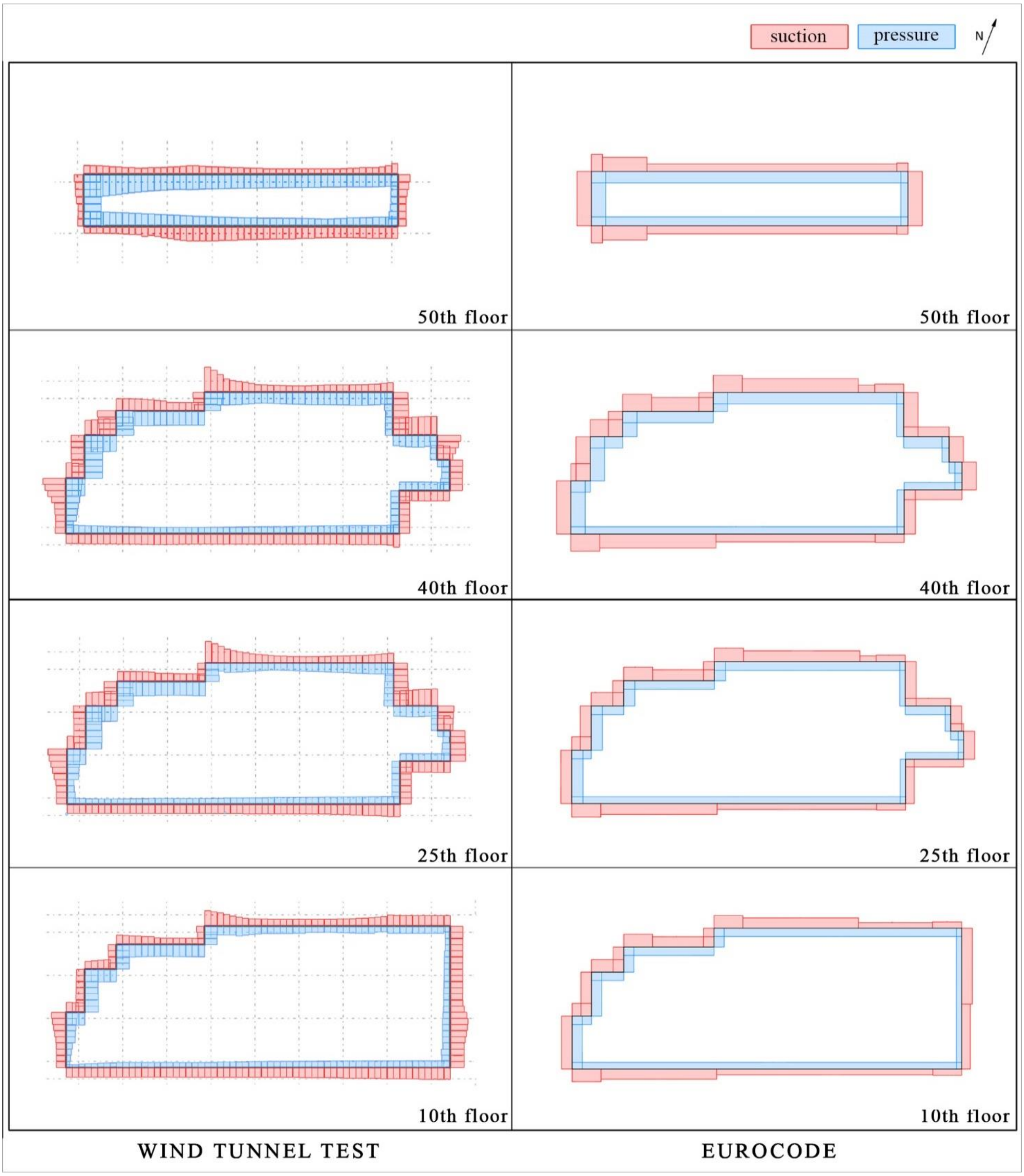


Figure 10. Peak pressure envelopes according to wind tunnel tests results and Eurocode procedure obtained for floors: 10th, 25th, 40th and 50th

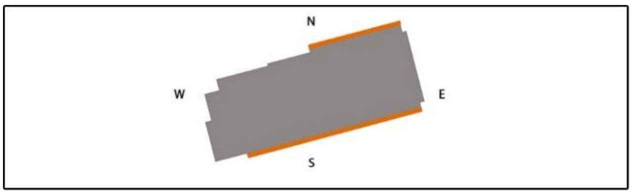


Figure 11. Facades for which the results are presented in Tables 1 and 3.

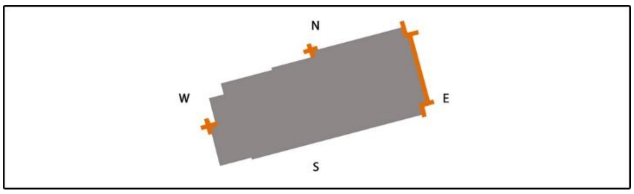


Figure 12. Facades and corners for which the results are presented in Tables 2 and 4

Table 1. Peak pressure values for the northern facade

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

Table 2. Peak pressure values for the western facade

	Pressure [kPa]		Suction [kPa]	
	Euro code	Tunnel Test	Euro code	Tunnel Test
10th floor	0,50	0,27 - 0,50	0,83 – 1,02	0,73 – 1,03
25th floor	0,52	0,35 – 0,55	0,83 – 1,05	0,80 – 1,00
40th floor	0,68	0,39 – 0,54	1,09 – 1,38	0,39 – 0,54
50th floor	0,68	0,40 – 0,50	1,38	0,35 – 0,66

Table 3. Peak pressure values for the southern facade

	Pressure [kPa]		Suction [kPa]	
	Euro code	Tunnel Test	Euro code	Tunnel Test
10th floor	0,65	0,20 – 0,39	0,57 - 1,02	0,55 – 0,69
25th floor	0,67	0,29 – 0,44	0,59 – 1,05	0,54 – 0,70
40th floor	0,88	0,36 – 0,48	0,78 - 1,38	0,60 - 0,65
50th floor	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

	Pressure [kPa]	
	Eurocode	Tunnel Test
W corner	1,05	1,09
N corner	1,29	1,27
N-E corner	0,63	0,58
S-E corner	0,63	0,73

Net force values

The impact of the selected test method on the design of an irregular structure of the building is better reflected by the analysis of the forces acting on the load-bearing structure. They can be considered, among others in the form of net forces e.g. separately for each floor. The Tables 5 and 6 present the components F_x and F_y of the net forces for the selected floors. The observed differences in the results are significant. Usually the results obtained from the standard calculations are 2-3 times larger than those measured in the tunnel (e.g. F_y component force for the 340° direction), and in extreme cases the differences are 7-10 fold (70° direction - F_x component force for the 50th floor and F_y component force for 10th floor) and even the forces have an opposite vector direction (component force F_x for the 340° direction). The analyses confirm the hypothesis that the results obtained with different methods are divergent and the choice of method has a significant impact on the adopted technical solutions.

Table 5. The components Fx and Fy of the net forces for the selected floors - 340° wind direction

340° DIRECTION (N)	Fx [kN]		Fy [kN]	
	Euro-code	Tunnel Test	Euro-code	Tunnel Test
10th floor	-98,06	13,80	330,25	175,80
25th floor	-72,88	26,50	245,46	75,90
40th floor	-66,43	15,30	223,72	74,80
50th floor	-70,79	-4,90	211,93	66,10

Table 6. The components Fx and Fy of the net forces for the selected floors - 70° wind direction

70° DIRECTION (E)	Fx [kN]		Fy [kN]	
	Euro-code	Tunnel Test	Euro-code	Tunnel Test
10th floor	75,25	26,30	-106,58	-10,20
25th floor	55,93	16,00	-79,21	-11,30
40th floor	50,98	15,10	-72,20	-25,50
50th floor	43,62	6,80	-68,17	-28,50

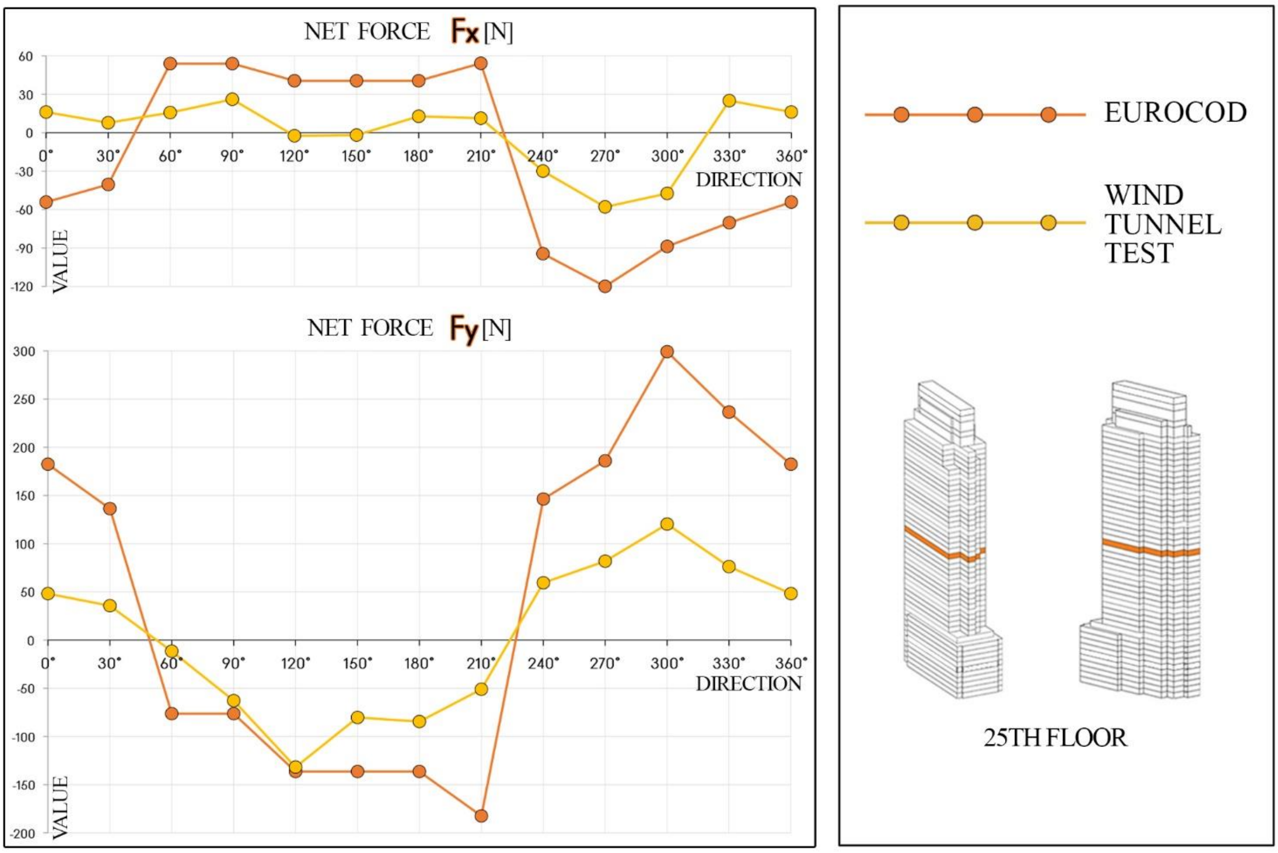


Figure 13. The components Fx and Fy of the net forces for the 25th floor, depending on wind direction

The impact of the surrounding

Analysing the chart of the component net forces values, e.g. for 25th floor, the influence of the surroundings on the obtained results can be noticed (Fig. 13). The most varied are the results for the northern (300°, 330° and 0°/360°) and western (210°, 240° and 270°) directions, which results, among others, from close proximity to high-rise buildings. On the other hand, the smaller differences of resultant forces for the south-eastern wind directions (120°, 150° and 180°) result from the lack of significantly tall objects in the immediate vicinity, however, setting the building perpendicular to the wind direction results in some variation of the obtained results. For the winds from the east (60° and 90° directions), the results are even more convergent. There are no tall objects from this side, and the wind flow is parallel to the longer side of the analysed building.

There are also some similarities between results from both methods. One can notice a difference in the stiffness of a building with a plan similar to an elongated rectangle - the components F_y (parallel to the shorter side) reach much higher values than the components F_x (parallel to the long side).

Air flow around the building

Detailed results of pressure and forces values do not always show what they result from. To explain the obtained results it is important to understand the aerodynamic phenomena occurring around the building. The precise data on this subject is provided only by digital computational methods. In addition, this methods allow for quick changes and analysis of many variants. Due to their graphical form (Fig. 14) of presentation they can be more understandable and useful for architects. The obtained results can be used for general optimization of the building form at the conceptual stage.

Figure 15 shows wind speed distributions obtained in the Fluent program. On the presented visualizations one can notice an increase in the value of the wind velocity vector as a function of height, differences resulting from: the lack of symmetry of the building (flow around the model, the shape of the wake), the irregularity of the form (the boundary layer separation point and turbulences), the changes of wind direction.

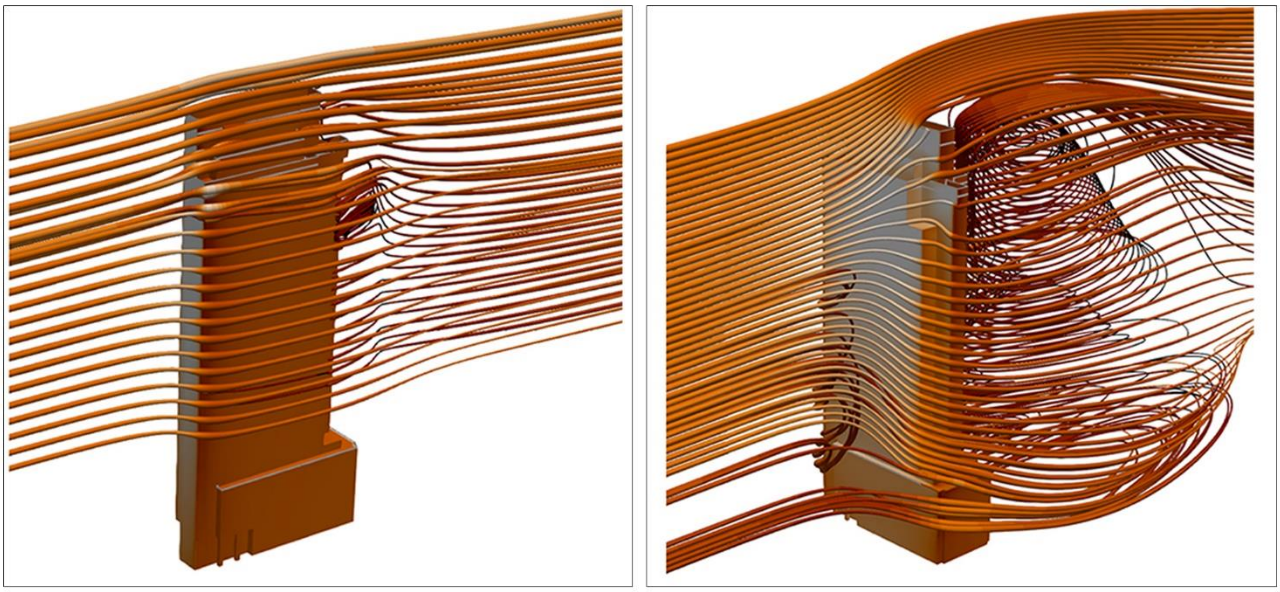


Figure 14. Air flow around the building depending on the wind direction

Summary

The analysed methods differ in accuracy and types of obtained results.

PN-EN 1991-1-4: 2008 Eurocode 1

The calculations according to design codes do not require access to a laboratory, special software or a lot of time, and financial expenses. However, analytical procedures have been developed to analyse simple, basic geometries, and the results obtained in them are not always reliable. In the standard calculations, the effects of the wind on the building are examined, not the character of the flow. The influence of the surrounding is not taken into account and the results obtained lead to a too large safety factors being incorporated. A simplified representation of the wind's influence as to the value and spatial distribution also results in imprecision and overestimation of the calculated quantities.

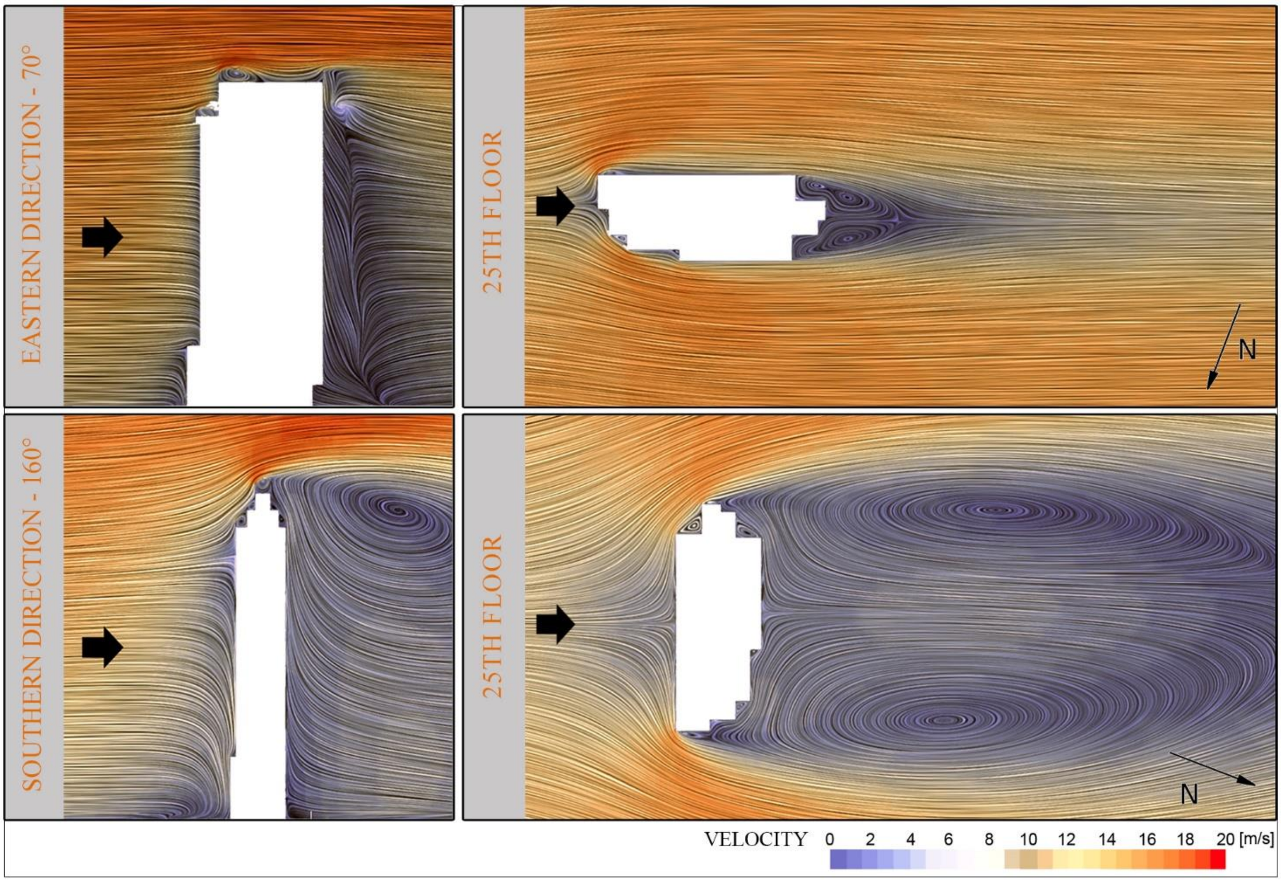


Figure 15. Wind velocity map obtained from computational analyses in Ansys Fluent program in the planes of cross-sections and 25th floor - wind direction parallel to the plane mapped

Wind tunnel testing

The wind tunnel testing allows to study objects with an unusual geometry located in a complex environment. Accuracy of the results obtained in the experiment allows for a relatively precise determination of pressure distribution and calculation of resultant forces transmitted to the structure. However, the measurements refer only to discrete points, usually located on the surface of the building model. Presentation of the results requires statistical and/or graphical processing, e.g. the obtained results can be interpolated to the distributions on whole facades. With a sufficiently large number of measurement points, the result can be very precise. Using the aerodynamic balance, one can measure the magnitudes of resultant forces and moments that accurately reflect reality. However, this method is time-consuming and requires large financial expenses.

Computational Fluid Dynamics

Less time-consuming and cheaper analysis can be carried out using computational methods. The CFD numeric programs used in these methods, such as Ansys Fluent, are used to reproduce real conditions or wind tunnel tests. The results of the computational simulation help the designers understand the nature of the flow in the entire domain, as well as to simulate the measurements performed using the aerodynamic balance. Thanks to the flow simulations, it is possible to collect detailed data impossible to measure in the tunnel and to visualize the occurring phenomena in a relatively simple way. This is especially important in enabling the designers to understand the qualitative aspect of the occurring phenomena. In order to perform quantitative analyses, it is necessary to generate data in a tabular form and then subject it to processing.

Computer simulations also enable relatively fast variant testing and would probably be used much more often if it was not necessary to verify the assumptions and the results. Appropriate definition of boundary conditions and adoption of preliminary assumptions are generally based on the experience of aerodynamic experts. Checking the correctness of the results is problematic if we do not compare them with measurements in reality or in a tunnel simulation. In addition, an appropriate tool for the analyzed geometry should be selected, because the turbulent flow models used in CFD programs have been calibrated to a certain type of task, e.g. Fluent is dedicated to simulating the air flow around cuboid bodies.

Conclusions

Optimization of the form of a tall building due to the impact of wind requires as accurate as possible recognition of the magnitude of the loads. The key issue here is the choice of the wind analysis method, because the results return different values.

Although the wind standards in Europe can be applied to buildings with a height of up to 200 m, the procedures described are sufficient only for the calculation of wind loads for a simple object with a regular shape. For buildings with a complex, irregular geometry, the standard procedures do not specify a more precise procedure. Because the Eurocode methods do not analyse numerous factors as accurately, the safety factors are far larger than necessary. It should be noted, however, that design in accordance with the Eurocode standards is a safe procedure, and accepting loads lower than standard provisions should always be justified by detailed analyses.

Precise determination of loads for irregularly shaped buildings located in the vicinity of tall buildings becomes possible after tunnel tests or numerical simulations using various CFD programs (after verifying the reliability of results).

Currently, tunnel tests are the only method that combines the accuracy and reliability of the results obtained. However, taking into account scientific and technical progress, we can expect further development of computational methods in the field of CFD. Thanks to the simulation of the wind flow the designers can collect detailed data on the flow of air masses around a building, impossible to measure in the tunnel test. Also when comparing different concepts CFD allows to effectively re-examine the modified model. Accurate understanding of the nature of the phenomena occurring around the designed skyscraper allows for effective optimization of its form and supporting structure. Then by interpreting the results graphically they can be more easily understood by designers.

Optimization of an irregular form due to wind loads requires a very accurate recognition of aerodynamic interactions. Aerodynamic analysis should be considered at the conceptual stage when changes in the geometry of the building are possible. The results of standard calculations are so imprecise that they do not constitute a good basis for spatial and structural optimization. At this stage, complicated, expensive and long-lasting tunnel tests will also be of limited use. Only the digital tools for computational analysis can be used to quickly estimate the basic flow characteristics. Simple analyses of the flow around a building do not require interdisciplinary cooperation if the architect has the right tools which can support the design process. The obtained results may even be slightly inaccurate. Precise model tests may be used to obtain the skyscraper's final form and constitute the final verification of the adopted architectural and structural solutions.

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