NUMERICAL SIMULATION OF WIND FLOW USING THE DLUBAL RWIND TOOL

Marek KAWULOK[1], *Martin KREJSA*[2], *Stanislav POSPISIL*[3]

[1,2,3]Department of Structural Mechanics, Faculty of Civil Engineering, VSB – Technical University of Ostrava, Ludvika Podeste 1875/17, 708 33 Ostrava – Poruba, Czech Republic

marek.kawulok.st@vsb.cz, martin.krejsa@vsb.cz, stanislav.pospisil@vsb.cz

DOI: 10.35181/tces-2021-0002

Abstract. *This article is aimed at current methods of calculating wind loads in structural engineering for construction, where these values cannot be clearly established by standard procedures. A suitable tool for these cases can be, for example, computational software for numerical simulation of wind flow around the structure, which allows the results of the simulation to be directly implemented to the numerical model as a load. The article introduces software for numerical simulation of wind flow and determination of induced force effects on the object of the high-rise building. The resultant force determined by the software was compared with a simplified calculation carried out according to the currently valid standards for determination the actions of wind on the structure.*

Keywords

Wind, Dlubal RWIND, Dlubal RFEM, numerical wind flow simulation, CFD simulation, numerical modeling, high-rise building.

1. Introduction

Wind loading is a climatic load that no freestanding structure can avoid. It is therefore necessary and desirable to know its actions, which can be a decisive factor in the dimensioning of structures. However, determining them is a very difficult task.

Standards are the basic tool for calculating wind loads. These give the wind characteristics and procedures for determining the magnitude of the load. European standard EN 1991-1-4 specifies the calculation procedure only for structures with a standard-defined shape and roof. Although they cover the most common structures, in the case of horizontally and vertically diverse designs, engineers are forced to approximate or divide the shape of the building in such a way that a standard procedure can be used.

One of the possible solutions is to test these buildings in a wind tunnel, which is, however, costly and time-consuming. From an economic point of view, they are only applicable to large-scale projects, such as high-rise buildings, long-span bridges, or to verify academic work [1] and evaluate the accuracy of flow numerical models.

Numerical flow models and their utilization in numerical simulations is another possibility to analyze the actions of wind on the structure. The creation of these models is complicated mainly by the nonlinear character of the flow caused by its turbulent behavior. Methods used to simulate turbulent flow in computational fluid dynamics (CFD) are Reynolds average Navier-Stokes simulations (RANS) [2], Scale Resolving Simulation (SRS) [3], and Direct Numerical Simulation (DNS) [4], [5]. Development of numerical simulation was made possible mainly thanks to advances in computer technology. Nowadays, there are several programs available for performing CFD simulations.

The topic of this article is the application of numerical simulation of wind flow to a high-rise building using the commercial software Dlubal RWIND [6]. The resultant of wind force action on the structure obtained by simulation is compared with the resultant obtained by a simplified calculation according to the currently valid standard [7]. The calculation is performed on an approximate model that estimates the real shape of a high-rise building. In this case of simplified calculation, it is not determined the exact value of the structural factor c_sc_d, which takes into account the effect of wind action from the nonsimultaneous occurrence of peak wind pressure on the surface together with the effect of the vibrations of the structure due to turbulence. Furthermore, the calculation is not taking into account the changes of wind flow properties caused by the spatial arrangement of high-rise building.

2. Description of the analyzed building

The basis for the creation of the numerical model was a bachelor's thesis written by Ing. arch. David Juracka [8], a student at VSB – Technical University of Ostrava. The high-rise building designed by the architect is called Skyscraper 3Towers.

Fig. 1: Visualization of skyscraper 3Towers [8].

The article is aimed at the numerical simulation of wind load on the construction. Attention is therefore focused on the part of the structure above the first floor. The default zero height lies at the level of the main entrance to the building. All numerical models as well as a simplified model for standard calculation are created from this zero coordinate.

As can be seen in Fig. 1, this is a building consisting of several connected parts. The first four aboveground floors are formed by a common space intended for commercial and restaurant zones. Starting with the fifth floor, the skyscraper is divided into three towers of different heights. The lowest tower A reaches 94.2 m, tower B 142.2 m and the highest tower C rises to a height of 172.2 meters. The skyscraper consists of 57 floors. The storeys are 3 meters high except for the first one, which is 4.2 meters high. The passage between the towers is ensured by footbridges and two shared floors 27 and 28 at heights of 73.2 and 76.2 meters. This "disc" also provides the interaction between towers and increases the spatial rigidity of construction.

The load-bearing system of the building was designed as a steel-concrete composite consisting of composite columns and composite slimfloor floors. Each tower also has its own reinforced concrete core. The outer shell is made up of glass panes, which cover the vertical facade of the building and footbridges. The antennas that can be seen on the roof in Fig. 1 are not included in any of the models presented in this article.

3. Calculation according to standard

The aim of this chapter is to determine the resultant of wind load actions on the structure described in Chapter 2, which is then used for comparison with CFD simulation results. The procedure is further divided into three subchapters.

3.1. Wind velocity and velocity pressure

The author Ing. arch. David Juracka in his bachelor's thesis assumes the location of a skyscraper in the Nova Ves in Ostrava. This locality falls according to national annex NA.4 to wind zone II. It sets the fundamental value of the basic wind velocity $v_{b,0} = 25.0$ m/s. From the architect's description of the surroundings, the building was assigned to the terrain category III. Based on these data, the basic wind velocity was determined $v_b = 25$ m/s considering the directional factor $C_{dir} = 1$ and the season factor $C_{season} = 1$.

Before the calculation, it should be mentioned that the values that depend on the height are determined for the whole range of the standard, because some of these values are then also used as input values to the numerical simulation. Standard is according to chapter 1.1, paragraph (2), applicable for buildings with heights up to 200 meters. Thus, the value of maximum height is set as $z_{max} = 200$ m. Other important height data z_{min} and z_0 are given by table 4.1 of the standard. Their values depend on the terrain category (category III.) and in this case they are equal to $z_{min} = 5$ m and $z_0 = 0.3$ m. Based on this information, it is possible to calculate the terrain roughness $C_r(z)$:

- for $z_{min} \leq z \leq z_{max}$

$$C_r(z) = k_r \cdot \ln\left(\frac{z}{z_0}\right) \ [-], \tag{1}$$

- for $z \leq z_{min}$

$$C_r(z) = C_r(z_{min}) \ [-], \tag{2}$$

where the terrain factor $k_r = 0.19 \left({z_0}/{z_{0,II}}\right)^{0.07} = 0.215$.

Knowledge of $C_r(z)$ is necessary to determine the mean wind velocity $v_m(z)$. This velocity is given by equation (3), in which $C_0(z) = 1$. The dependence of the mean wind velocity on the height z is shown in Fig. 2.

$$v_m(z) = C_r(z) \cdot C_0(z) \cdot v_b \ \left[\frac{\mathrm{m}}{\mathrm{s}}\right] \tag{3}$$

The same z_{max}, z_{min} and z_0 are taken for calculating the turbulence intensity $I_v(z)$:

- for $z_{min} \leq z \leq z_{max}$

$$I_v(z) = \frac{k_I}{c_0(z) \cdot \ln(z/z_0)} \ [-], \quad (4)$$

- for $z \leq z_{min}$

$$I_v(z) = I_v(z_{min}) \ [-], \quad (5)$$

where the recommended value of the turbulence factor k_I is given by the national annex $k_I = 1$. The turbulence intensity as a function of height can be seen in Fig. 3. The last wind characteristic that is needed for the following calculations is the peak velocity pressure $q_p(z)$, which includes mean and short-term velocity fluctuations. Its determination is given by the equation:

$$q_p(z) = [1 + 7 \cdot I_v(z)] \cdot \frac{1}{2} \cdot \rho \cdot v_m^2(z) \ [\text{ Pa }], \quad (6)$$

in which ρ is the air density, which depends on the altitude, temperature, and barometric pressure to be expected in the region during windstorms. The standard gives this value as $\rho = 1.25$ kg/m^3.

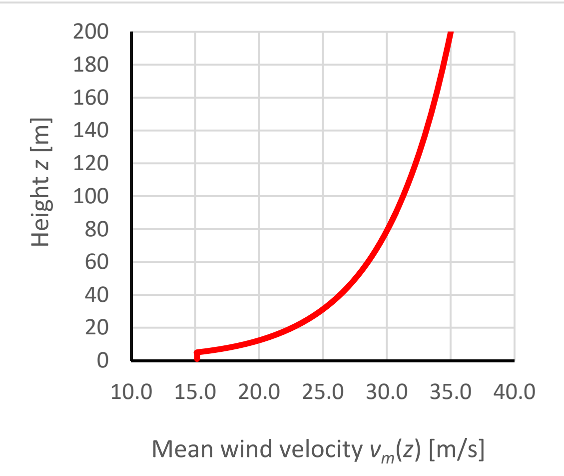

Fig. 2: Graph of the mean wind velocity $v_m(z)$.

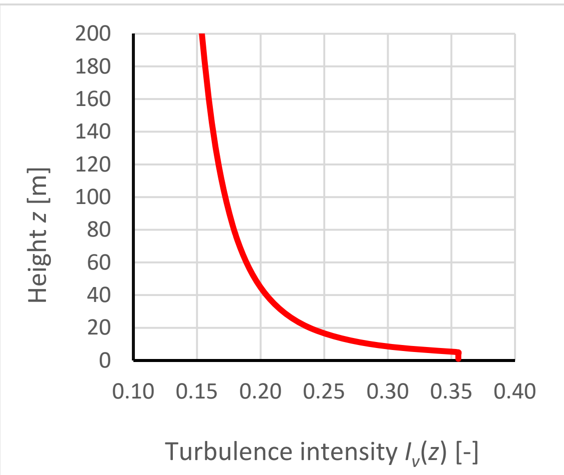

Fig. 3: Graph of the turbulence intensity $I_v(z)$.

3.2. Simplified model of construction

As already mentioned in the introduction, the standard specifies the procedure for calculating wind loads only for selected building shapes. Atypical shapes must therefore be divided or replaced by an approximate shape which corresponds to that described in the standard. Due to the horizontal and vertical diversity of the analyzed object, it was necessary to use this procedure for this high-rise building.

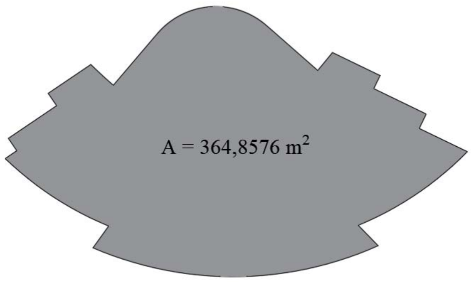

Fig. 4: Example of determining the area of the 37th floor.

In the case of the 3TOWERS skyscraper, a cylinder was chosen as a representative shape. Each floor was replaced by this cylinder with corresponding geometric dimensions. The diameter of the base was determined using the floor area measured by the software (see Fig. 4) and the height of the cylinder was chosen in accordance with the height of the storey. The equation for calculating the diameter of the cylinder b (7) was derived from the formula for calculating the area of a circle.

$$b = \sqrt{4 \cdot A_{storey}/\pi} \ [\text{ m }] \quad (7)$$

In this way, all floors were replaced. A simplified model is shown in Fig. 5.

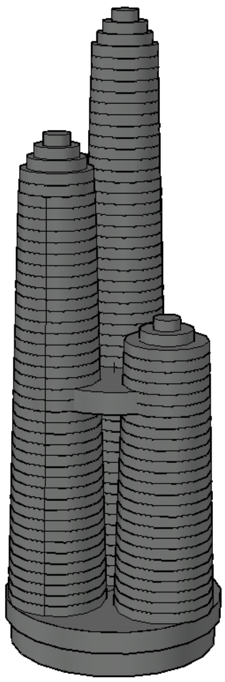

Fig. 5 Simplified model of construction.

3.3. Determination of the wind forces

The required result of the calculation described in this chapter is the resultant of the force caused by the action of the wind. This is determined as the sum of the partial forces determined for the individual floors. Before determining its value, it is necessary to mention the procedure for calculating the partial forces for individual floors.

To maintain the consistency of the input data between the norm calculation and the numerical simulation, the profiles of wind velocity, turbulence intensity and peak velocity pressure $q_p(z)$ described in subchapter 3.1 were considered. Based on them, the peak wind velocity $v(z_e)$ depending on the height z_e was determined according to formula (8).

$$v(z_e) = \sqrt{2 \cdot q_p(z)/\rho} \;\; [\mathrm{m/s}] \tag{8}$$

The values of the Reynolds numbers Re are defined by expression (9) for circular cylinders. The kinematic viscosity of the air is equal to $\nu = 15 \cdot 10^{-6}$ m²/s and the diameter of the cylinder b is always considered for the currently analyzed storey.

$$Re = \frac{b \cdot v(z_e)}{\nu} \;\; [-] \tag{9}$$

Tab. 1: Resultant force of wind action set by the norm procedure.

Table of forces F_w [kN] acting on storeys									
Storey	Force F_w [kN]				Storey	Force F_w [kN]			
	Bottom part	Tower A	Tower B	Tower C		Bottom part	Tower A	Tower B	Tower C
1	60.961	-	-	-	30	-	32.349	51.810	52.572
2	51.497	-	-	-	31	-	14.838	51.830	52.592
3	61.402	-	-	-	32	-	-	51.830	52.592
4	67.552	-	-	-	33	-	-	51.813	52.575
5	-	33.777	37.317	37.866	34	-	-	51.778	52.540
6	-	35.526	39.267	39.845	35	-	-	51.728	52.488
7	-	36.995	40.912	41.513	36	-	-	51.662	52.422
8	-	38.249	42.320	42.943	37	-	-	51.581	52.340
9	-	39.332	43.540	44.181	38	-	-	51.487	52.244
10	-	40.274	44.607	45.263	39	-	-	51.378	52.134
11	-	41.099	45.544	46.214	40	-	-	51.257	52.011
12	-	41.824	46.373	47.055	41	-	-	51.124	51.876
13	-	42.463	47.107	47.800	42	-	-	50.979	51.728
14	-	43.027	47.759	48.462	43	-	-	50.822	51.569
15	-	43.525	48.339	49.050	44	-	-	48.392	51.411
16	-	43.964	48.854	49.573	45	-	-	41.165	51.242
17	-	44.350	49.312	50.037	46	-	-	31.448	51.063
18	-	44.688	49.717	50.448	47	-	-	17.205	50.873
19	-	44.983	50.076	50.812	48	-	-	-	50.675
20	-	45.239	50.391	51.132	49	-	-	-	50.467
21	-	45.459	50.667	51.412	50	-	-	-	50.249
22	-	45.645	50.906	51.655	51	-	-	-	50.024
23	-	45.800	51.112	51.863	52	-	-	-	49.790
24	-	45.926	51.286	52.040	53	-	-	-	49.547
25	-	46.026	51.431	52.188	54	-	-	-	49.297
26	-	46.101	51.550	52.308	55	-	-	-	41.434
27	-	46.152	51.642	52.402	56	-	-	-	33.442
28	-	46.182	51.711	52.472	57	-	-	-	18.278
29	-	44.336	51.771	52.533	-	-	-	-	-
TOTAL FORCE		6002.88 kN							

To determine the partial wind force F_w, the expression was used:

$$F_w = c_s c_d \cdot c_f \cdot q_p(\mathrm{z}) \cdot A_{ref} \, [\mathrm{N}], \quad (10)$$

where $c_s c_d$ is the structural factor. It takes into account the effect on wind action from the non-simultaneous occurrence of peak wind pressure on the surface together with the effect of the vibrations of the structure due to turbulence. The value of the factor $c_s c_d$ is not precisely determined in this case. This value is taken as $c_s c_d = 1$. The force coefficient C_f for a finite circular cylinder is calculated according to equation (11).

$$C_f = C_{f,0} \cdot \psi_\lambda \, [-] \quad (11)$$

The force coefficient of cylinders without free-end flow $C_{f,0}$ depends on the value of the Reynolds number and an equivalent roughness k/b as can be seen in formula (12). The roughness of the glass facade is given by the value $k = 0.0015$ mm and b is the diameter of the storey. In some cases, the roughness may be determined by numeric calculation [9].

$$C_{f,0} = 1.2 + \frac{0.18 \cdot \log(10 \cdot k/b)}{1 + 0.4 \cdot \log(Re/10^6)} \, [-] \quad (12)$$

Free-end flow is taken into account in expression (11) by the end-effect factor ψ_λ, determined as a function of the slenderness ratio λ:

- for $l \geq 50$ m:

$$\min\begin{pmatrix} \lambda = 0.7 \cdot l/b \\ \lambda = 70 \end{pmatrix} [-], \quad (13)$$

- for $l < 15$ m:

$$\min\begin{pmatrix} \lambda = l/b \\ \lambda = 70 \end{pmatrix} [-]. \quad (14)$$

Calculation of ψ_λ was performed separately for all four parts. However, for all, the solidity ratio $\varphi = 1$ and the corresponding curve in Table 7.36 of the standard are assumed. The resulting values of ψ_λ are listed in Tab. 2. The slenderness ratio was determined by formula (14) for the common lower floors and by formula (13) for the towers. In these equations, l is the height of the part and b is the diameter of the cylinder determined as the average value of b for the entire analyzed part.

Tab. 2: The end-effect factor ψ_λ.

	l_{part} [m]	b_{mean} [m]	λ [-]	ψ_λ [-]
Bottom part	13.2	58.38	0.23	0.6
Tower A	94.2	22.68	2.91	0.65
Tower B	142.2	22.31	4.46	0.67
Tower C	172.2	21.63	5.57	0.68

Magnitude of the force coefficient C_f for each individual floor depends on the tower in which it is located (see (11) and Table 2). Reference area A_{ref} is determined by the expression:

$$A_{ref} = l \cdot b \, [\mathrm{mm}^2] \quad (15)$$

in which l is the height and b is the diameter of the analyzed floor.

To create a global resultant of the wind force acting on the structure in the direction of flow, the individual forces were summed. The results of the calculation are given for individual floors and the whole building in Tab. 1.

4. Numerical simulation of wind flow

This chapter is focused on the numerical simulation of wind flow. The following text describes the software RWIND, including the simulation solver settings and results.

4.1. Software RWIND

Nowadays, there are several commercial and noncommercial software on the market that allow you to perform Computational Fluid Dynamics (CFD) simulations. In the case of 3TOWER analysis, the RWIND software was selected. This is one of the stand-alone programs distributed by Dlubal Software company. This software was developed in collaboration with PC Progress and CFD Support. RWIND is used to generate loads that are induced by wind flow around the structure and to analyze the wind flow itself.

The computational core of the CFD simulation consists of a modified version of the OpenFOAM® code provided by CFD Support called OpenFOAM® for Windows. Numerical solver is a steady-state solver for incompressible turbulent flow, using the Semi-Implicit Method for Pressure Linked Equations (SIMPLE) algorithm. The result of the CFD simulation is an area of pressure on the building envelope (which is also used to calculate the force loads) and a three-dimensional field of wind velocity [10].

Reynolds-averaged Navier-Stokes (RANS) equations are used in this software to solve a nonlinear problem of turbulent flow. Specifically, there are two equation models, which solve two separate transport equations for two independent turbulent quantities that are related to the time scale and turbulence length. It is possible to choose between two models K-ε and K-ω. In both cases, one of the transport equations is of the kinetic energy K. The second differs depending on the type of model, where ε is the turbulent dissipation rate and ω is the reciprocal turbulent time scale [11]. The developer [10] says that, in some cases the K-ω model may be more stable than K-ε.

4.2. Numerical model of construction

As mentioned in the previous section, software RWIND is focused on performing CFD simulations. Therefore, it does not include a tool that allows you to create a numerical model of the construction directly in this software, but it is required to import it. For example, the import of a file (model) with the extensions *.vtp, *.stl, and others is supported. The best synergies can be expected with other Dlubal products, such as RFEM or RSTAB, for numerical modeling and finite element method (FEM) structural analysis.

Already mentioned RFEM software [12] together with CAD software AutoCAD [13] was used to create a model of the 3TOWERS skyscraper. The creation of the numerical model is divided into two phases. In the first phase, the basic geometry of the object was created according to the architect's design (see Chapter 2) in the AutoCAD software. In the second phase, the geometry was imported as a line model into RFEM. This phase involved the creation of surface elements (slabs, walls and shells), as well as the assignment of cross-sections to the individual beam elements. The construction prepared in this way can already be exported directly from RFEM to RWIND.

4.3. CFD simulation settings

One of the main reasons for performing simulations with RWIND software is the possibility to determine the load induced by the actions of wind on the structure. These are exported directly from RWIND to RFEM as load cases. The number of load cases depends on the user's requirements for the number of wind flow directions on the structure. In the case of the 3TOWERS skyscraper, it was decided to perform a total of eight simulations, where the direction was always changed by 45 °. The flow directions are set to 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315° and the settings described in this chapter are the same for all of them.

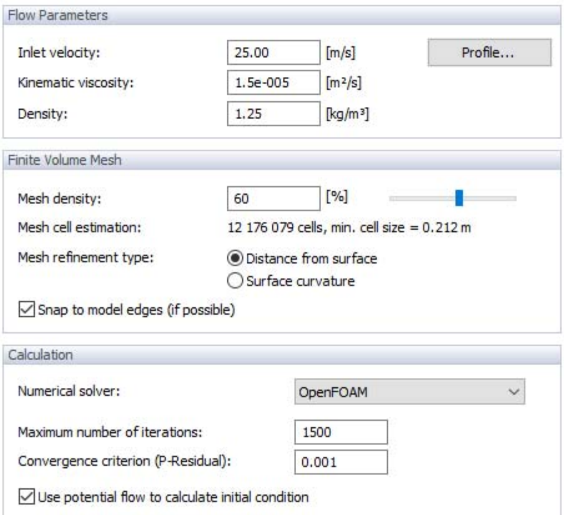

Fig. 6 Simulation setting in RWIND.

The main input data of the simulation are wind flow characteristics. These include the inlet velocity, kinematic viscosity ($\nu = 15 \cdot 10^{-6}$ m²/s) and air density ($\rho =$ 1.25 kg/m³). These values were inserted (see Fig. 6) in accordance with the standard [7]. The inlet velocity is set as a basic wind velocity 25 m/s and is defined by its profile. In order to be able to insert the profile of wind velocity, the height $z_{max} = 200$ m was divided into 401 parts (i.e., the height of one part is 0.5 meters). For each part, the appropriate wind velocity was calculated using equation (3) based on the height at which it is located. Fig. 7 shows the inserted profile in RWIND. Comparing this graph with Fig. 2, it can be seen that the profile determined in Chapter 3 corresponds to the profile used in the numerical simulation.

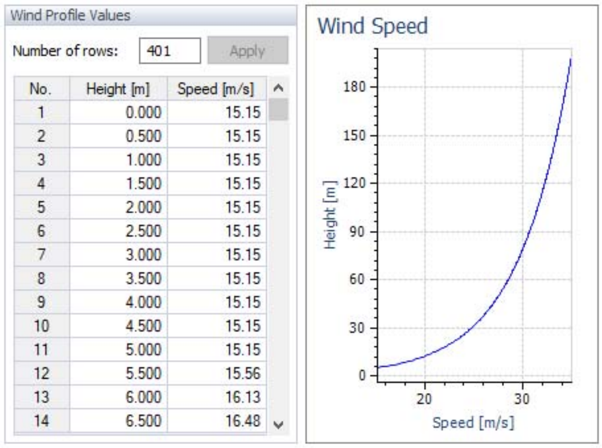

Fig. 7 Profile of wind velocity in RWIND.

The same procedure was used to create the profile of turbulence intensity. For each of the 401 parts, the turbulence intensity value was calculated according to equations (4) and (5). The calculated profile shown in Fig. 8 is again identical to Fig. 3 from Chapter 3.

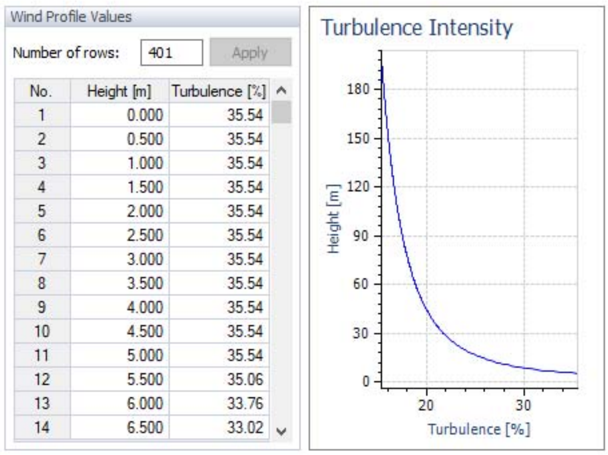

Fig. 8 Profile of turbulence intensity in RWIND.

In the case of these simulations, the turbulent model K-ε was chosen. Software RWIND offers the possibility of inserting the characteristics of turbulent flow directly by the values of kinetic energy K and turbulent dissipation ε. This option was not used, and the turbulence was set as the $I_v(z)$ = 15.4 % at the highest point of the building and defined by the profile of turbulence intensity described above. The setting is shown in Fig. 9.

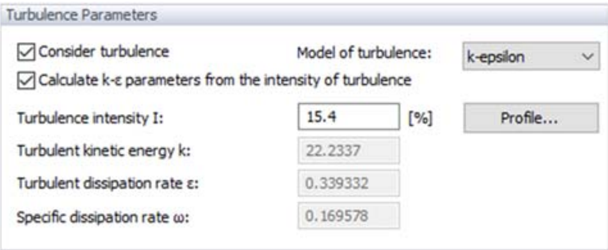

Fig. 9 Turbulence parameters.

The setting of the wind flow characteristics is complete. The next step is to set up the mesh and solver. Software RWIND uses a triangular element mesh to define the model boundaries. This mesh must be correct because its quality directly influences the simulation. For the purpose of creating the correct mesh, the software adds the possibility of using the so-called simplified model. Its task is to simplify the details that are not important for the simulation but may cause a deterioration in the convergence of the solution. The simplified model actually represents a special mesh "shrink-wrapping" the original model [10]. This achieves the creation of a correct mesh on the model boundary. User has the option to change the quality of the simplified model by increasing or decreasing the density of the mesh elements in percent and by selecting the level of detail. Increasing of the density value leads to the creation of a larger number of elements. In the case of the analyzed model, the network density is chosen to be 60% (see Fig. 9). This means that the created mesh is consisted of approximately 12 million elements with a minimum size of 0.212 meters. However, with the same density setting, the number of elements may differ for each of the eight simulations (see Tab. 3). The difference between the original and the simplified model is shown in Fig. 10. Furthermore, the mesh refinement type is set to the distance from the surface, which provides a fine mesh over the entire boundary area.

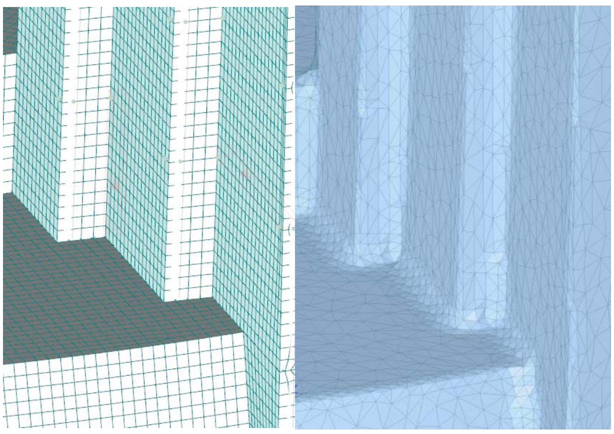

Fig. 10 Comparison of the original (left) and simplified (right) models.

RWIND in the current version only offers the possibility of calculation by the OpenFOAM solver (see chapter 4.1). This solver uses residual pressure as a convergence criterion. The convergence criterion value is set to 0.001. The maximum number of iterations was also limited to 1500 steps (see Fig. 6). The dimensions of the wind tunnel have not been adjusted. Its dimensions were automatically created by the program and the same for all simulations.

4.4. Simulation results

One of the results of the simulation is the surface pressure on the model. These are shown for each of the wind directions in Fig. 11, Fig. 12, Fig. 13, Fig. 14, Fig. 15, Fig. 16, Fig. 17, and Fig. 18. It is possible to notice the difference in the maximum and minimum values of pressure, which occur locally and are caused mainly due to the diversity of model shape. RWIND also calculates the resultant of the force in the direction of wind flow for all directions. Its values, the number of mesh elements, the number of iterations, and the duration of the calculation are written down in Tab. 3.

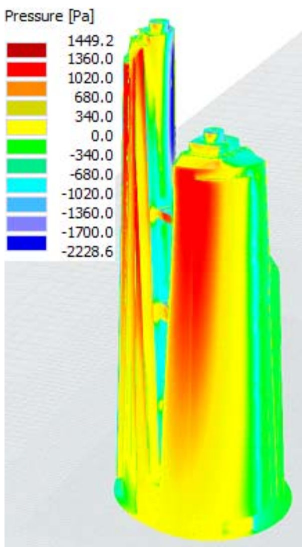

Fig. 11 Wind 0°.

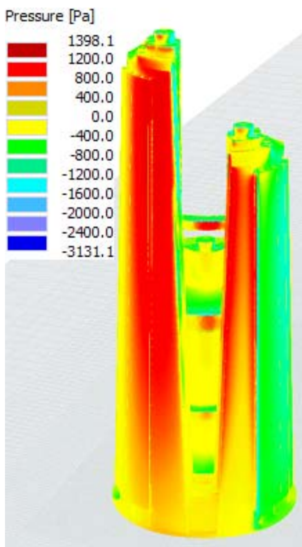

Fig. 12 Wind 45°.

Tab. 3: Simulation results.

Wind direction	Force [N]	Elements [in millions]	Number of iterations	Time [h:min:s]
0°	6064.54	11.952	498	4:09:48
45°	6643.86	12.869	464	4:23:26
90°	6499.29	11.081	610	4:30:25
135°	5314.71	11.179	668	4:54:12
180°	6496.97	11.953	733	5:51:49
225°	6958.97	12.869	794	6:17:15
270°	5887.74	11.082	706	4:49:6
315°	5680.20	11.178	652	4:37:25

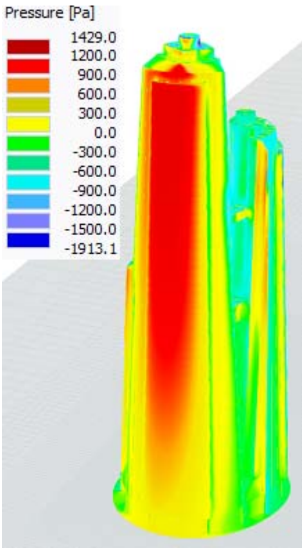

Fig. 13 Wind 90°.

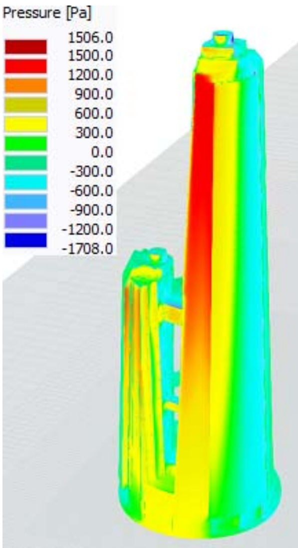

Fig. 14 Wind 135°.

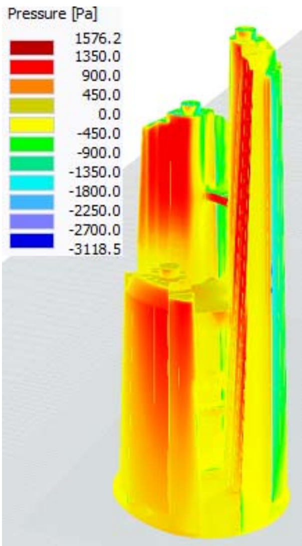

Fig. 15 Wind 180°.

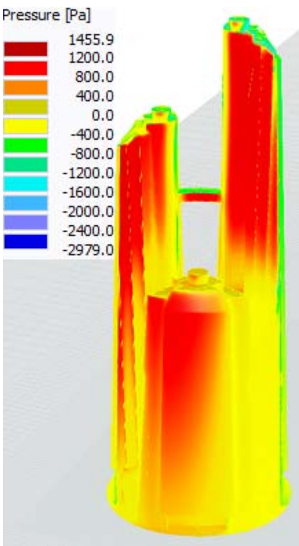

Fig. 16 Wind 225°.

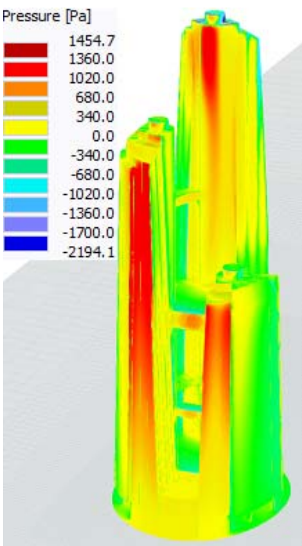

Fig. 17 Wind 270°.

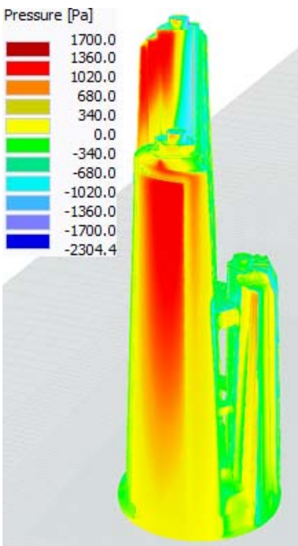

Fig. 18 Wind 315°.

The calculation time depends on the parameters of the computer on which the simulation is performed. In this case, the parameters are:

- CPU: Intel I5-6500 4x3.20 GHz,
- RAM: Kingston HyperX 2x8 GB DDR4,
- GPU: NVIDIA GeForce GTX 1060 6 GB,
- SSD: Kingston Now UV400 120 GB, read/write speed 550/350 MB/s, SATA III,
- HDD: Seagate Desktop HDD 1TB, 7200 RPM, 32 MB cache, SATA 6 GB/s (SATA III),
- Virtual RAM: 50 GBa on HDD.

Computing time was also affected by writing data to virtual RAM due to the insufficient size of 16 GB of physical RAM.

RWIND also allows you to view other results such as velocity vectors, pressure field, velocity field, turbulence k field, turbulence ε field, surface C_p coefficient, member forces or streamlines.

5. Results

In this article, the values of wind action on the structure were determined in two ways. The first way, described in Chapter 3, is a simplified procedure according to the standard of an approximated building model. This calculation was performed primarily in order to obtain the overall resultant of the wind force acting on the surface. These values serve as a control benchmark. The second way is to perform a CFD simulation on a numerical model of the construction. The simulation was performed for a total of 8 wind directions and its more detailed description can be found in Chapter 4. Comparison of the results is given in Tab. 4.

Tab. 4: Comparison of global resultants of wind forces.

Wind direction	Force F_w [kN]		Deviation [%]
	Norm	RWIND	
0°	6002.88	6064.54	1.03
45°	6002.88	6643.86	10.68
90°	6002.88	6499.29	8.27
135°	6002.88	5314.71	11.46
180°	6002.88	6496.97	8.23
225°	6002.88	6958.97	15.93
270°	6002.88	5887.74	1.92
315°	6002.88	5680.20	5.38

As can be seen, the largest deviation is achieved for the 225° direction, specifically 15.93%. The presence of deviations was expected. Apart from the simplifications made, described in the individual phases of the calculation, in the norm procedure is not taken into account the layout of towers in the space. In the normative calculation, it is also difficult to determine the results of wind forces for the other two global axes, which is not a problem in the case of CFD simulation.

6. Conclusion

Results obtained by simulations in the CFD software RWIND can serve to civil engineers as an easy, time-saving, and cost-effective obtaining of initial information about the behavior of the wind flow and its actions on the structure. When comparing the results of wind force obtained by simulation with the simplified standard calculation procedure, which neglected the exact value of the structural factor or the real layout of the skyscraper part, acceptable deviations were achieved. In the case of large-scale projects, it is appropriate to verify the calculated results by experimental measurements in a wind tunnel, the 3TOWERS skyscraper project would not be an exception. It can also be considered appropriate to perform a detailed evaluation of the simulations performed by the software RWIND and comparison with the measurement results on already existing constructions, which could be a logical step forward in the further research work of the author team.

Acknowledgements

This contribution has been completed thanks to the financial support provided to VSB-Technical University of Ostrava by the Czech Ministry of Education, Youth and Sports from the budget for the conceptual development of science, research and innovation for the 2021 year.

References

[1] LUKIANTCHUKI, M. A., SHIMOMURA, A.P., DA SILVA, F.M., CARAM, R. M.. Valuation of CFD simulations with wind tunnel experiments: pressure coefficients at openings in sawtooth building. Acta Scientiarum. Technology. 2018, 40(1), e37537. ISSN 18062563. Available at: DOI: 10.4025/actascitechnol.v40i1.37537

[2] LAURIKS, Tom, LONGO, Riccardo, BAETENS, Donja, DERUDI, Marco, PARENTE, Alessandro, BELLEMANS, Aurélie, VAN BEECK, Jeroen, DENYS, Siegfried. Application of Improved CFD Modeling for Prediction and Mitigation of Traffic-Related Air Pollution Hotspots in a Realistic Urban Street. Atmospheric Environment. Elsevier, February 2021, 246(2021), 118127. ISSN 1352-2310. Available at: DOI: 10.1016/j.atmosenv.2020.118127

[3] CHODE, K. K., VISWANATHAN, H., CHOW, K.. Numerical investigation on the salient features of flow over standard notchback configurations using scale resolving simulations. Computers & Fluids. Elsevier, October 2020, 210(2020), 104666. ISSN 0045-7930. Available at: DOI: 10.1016/j.compfluid.2020.104666

[4] BALOGH, M., PARENTE, A., BENOCCI, C.. RANS simulation of ABL flow over complex terrains applying an Enhanced k-ε model and wall function formulation: Implementation and comparison for fluent and OpenFOAM. Journal of Wind Engineering and Industrial Aerodynamics. Elsevier, May–July 2012, 104-106(2012), 360-368. ISSN 0167-6105. Available at: DOI: 10.1016/j.jweia.2012.02.023

[5] ZHU, Hongjun, LIU, Wenli, ZHOU, Tongming. Direct numerical simulation of the wake adjustment and hydrodynamic characteristics of a circular cylinder symmetrically attached with fin-shaped strips. Ocean Engineering. Elsevier, January 2020, 195(2020), 106756. ISSN 0029-8018. Available at: DOI: 10.1016/j.oceaneng.2019.106756

[6] RWIND Simulation - Wind Simulation: Generation of Wind Loads Based on CFD for Any Type of Structure [online]. Prague: Dlubal, 2021. Available at: https://www.dlubal.com/en/downloads-and-information/documents/online-manuals/rwind-simulation-1/01/01

[7] Eurocode 1: Actions on structures - Part 1-4: General actions - Wind loads. Ed. 2. Prague: Czech office for standards, metrology and testing, 2013.

[8] JURACKA, David. Skyscraper 3TOWERS (in czech) [online]. Ostrava, 2018. Available at: http://hdl.handle.net/10084/129034. Theses and dissertations of Faculty of Civil Engineering (FAST).

[9] MICHALCOVA, Vladimira, LAUSOVA, Lenka. Numerical calculation of aerodynamic roughness of chimney jacketed with corrugated sheets. Transactions of the VSB - Technical University of Ostrava, Civil Engineering Series. Ostrava, 2016, 16(1), 33-39. ISSN 1804-4824. Available at: DOI: 10.1515/tvsb-2016-0006

[10] RWIND - Simulation Generation of WindInduced Loads on General Models: User Manual [online]. Dlubal Software, October 2020. Available at: https://www.dlubal.com/en/downloads-and-information/documents/online-manuals/rwind-simulation-1/01/01

[11] ALFONSI, Giancarlo. Reynolds-Averaged Navier–Stokes Equations for Turbulence Modeling. Applied Mechanics Reviews. July 2009, 62(4), 040802-1 - 040802-20. Available at: DOI: 10.1115/1.3124648

[12] RFEM – FEM Structural Analysis [online]. Prague: Dlubal Software, 2020. Available at: https://www.dlubal.com/

[13] AutoCAD® - software CAD [online]. California, U.S.: Autodesk, 2020. Available at: https://www.autodesk.cz/products/autocad/overview