

DESIGN AND WIND SIMULATION OF STEEL STRUCTURES IN A PARAMETRIC ENVIRONMENT

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Abstract

Nowadays, parametric design and various simulation methods are gaining ground in almost every engineering and creative profession. This paper investigates the practical applicability of the combination of these methods, by analysing a specific free-form structure with Grasshopper 3D and OpenFOAM and points out the differences between the results of a CFD simulation and the recommended methods of the Eurocode, highlighting the new perspectives that are opening up in the field of structural design, especially in the examination of wind effects.

Keywords: *parametric structural design, wind simulation, computational fluid dynamics.*

1. Introduction

The ordinary practice of structural design is based on the use of many empirically introduced safety factors and statistical approaches, considering and applying different standards. As a result, the geometrical design of buildings and the loads acting on them can often change significantly because of simplifications, especially if the geometry of the structure is freeform, which is practically impossible to accurately model and analyse with standard tools. However, deviating from reality can be a legitimate concern for a structural designer.

Although one of the main characteristics of today's architecture is the use of bold, yet fragile looking shapes. We are increasingly encountering so-called freeform structures, which provide structural design engineers tasks that require serious professionalism.

Structural engineers must be able to respond to the needs mentioned above. However, a parametric environment helps the engineer to create a controllable model. A module called Grasshop-

per, integrated into CAD software called Rhino 3D, is perhaps the most flexible modelling tool of its kind [1]. Its own visual programming language allows for so-called algorithmic modelling, which is a key factor in increasing the efficiency of certain design processes.

During the design of the steel structure shown in **Figure 1** beginning with the structural design and analysis of the model, through the detailing of the main structure and the secondary cladding structure, to the production and installation, parametric design was applied in every phase, showing an increased efficiency [2, 3].

Wind simulation methods were also used to study the loads acting on the structure, which is the main topic of the study. However, it can be stated that generally these methods/tools, (primarily the different types of simulations, in contrast to other industries), are far from widespread in the construction industry, especially not in the case of structural designers. However, after 2D and then 3D modelling techniques, this has perhaps the greatest untapped potential for the future of structural design.

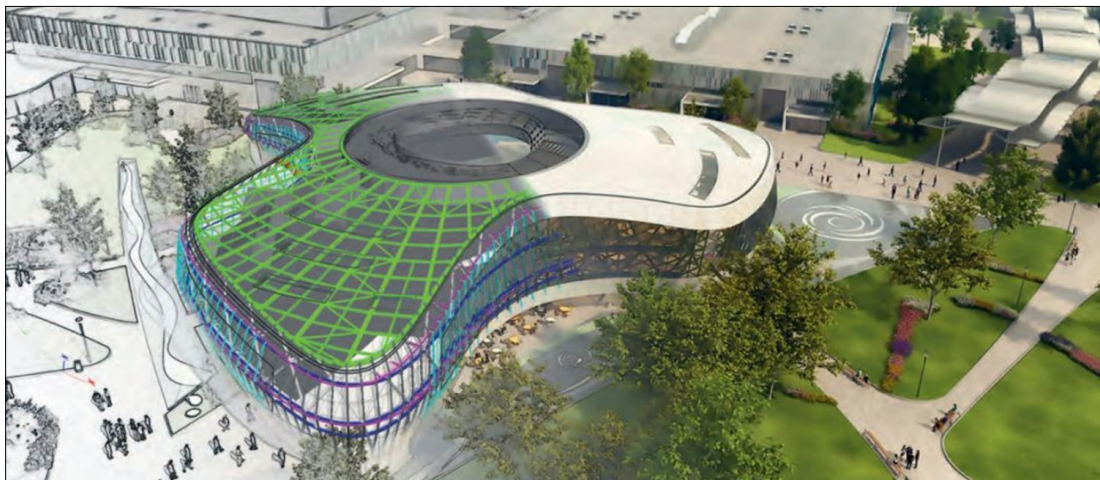


Figure 1. Reception hall of Hungexpo Congress and Exhibition Centre Budapest. Structural model (left), architectural rendering (right).

2. Parametric design of the examined structure

In terms of its functionality, the examined building is the reception hall of the Budapest Congress and Exhibition Centre with office space and showrooms.

The uniqueness of the lattice façade is ensured by the adaptation to the three-level concrete support structure with different floor areas, while the special shape of the roof structure is ensured by the fact that it fits to a spherical surface.

In general, parametric design requires a well-structured set of rules (Figure 2). At the beginning, all the constraints and extremities have to be clarified, together with the basic conceptual principles, for instance the setting of the parameters. This is followed by data processing, which can mean dimensioning, modelling, or even detailing.

From an architectural point of view, the geometry of the designed steel structure is basically adjusted to the following fixed elements, so the whole structure should be arranged according to them (Figure 3):

- the rotationally symmetrical edge curves, with constant heights, but different length in every level (blue);
- rotationally symmetrical outer roof edge curve, with different heights along its length, due to the fact that it fits to a spherical surface, (green);
- horizontal and circular inner ring (orange).

Therefore, from the structural designer's point of view, the duty is to adapt to the above mentioned geometrical constraints, besides the load-bearing capacity, manufacturability and mountability. However, the primary task of the structural engineer was to develop the optimal load-bearing system, meaning the configuration and segmentation of the steel members, in addition to the global static inspections of the entire steel structure and

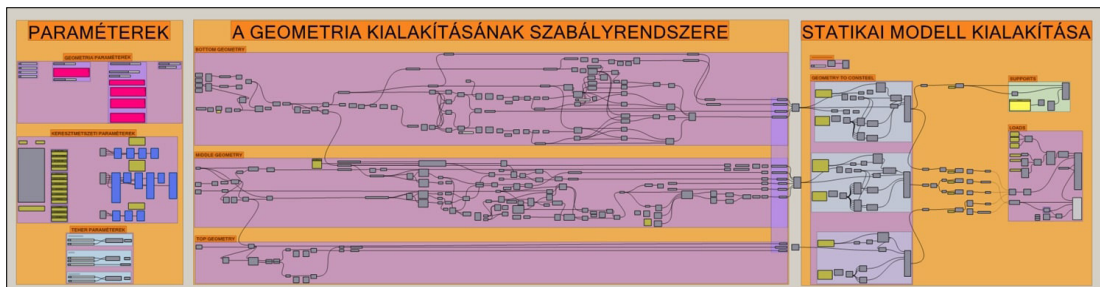


Figure 2. Example parametric algorithm in Grasshopper.

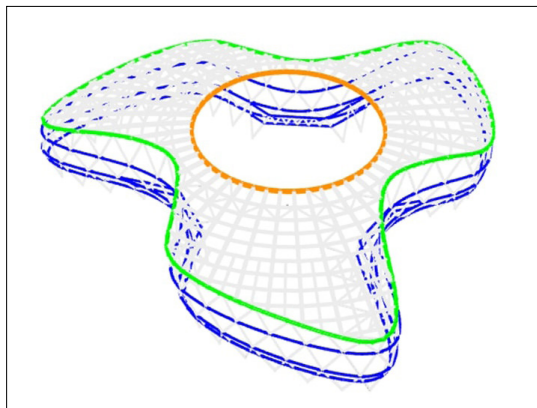


Figure 3. The final structural analysis model, highlighting the architectural base geometry.

the calculations of the joints. Several structural designs (Figure 4 and 5) emerged, which were also examined in a parametric way [4] according to the following aspects: total weight, utilization, stability, deflection and node complexity (number of individual and uniform nodes).

After the examination, the final roof structure was chosen, where the outer and inner edge rings are connected by radial main girders, curved in their plane, acting as a traditional simply supported beam. The main girders are connected to each other by straight beams, resulting in a quadrilateral field. Certain fields are stiffened by braces and secondary radial beams.

Overall, working with Grasshopper during the design of the structure showed huge advantages, as it made it possible to control the entire workflow, where the key is the coordination and interconnectivity with other software necessary for design (Figure 6). In this workflow, Grasshopper, as a focal point, provided input data for predimensioning (Karamba plug-in), global structural analysis and design (ConSteel), connection design (IDEA Statica), detailing (Tekla Structures) and also to perform wind simulations (OpenFOAM).

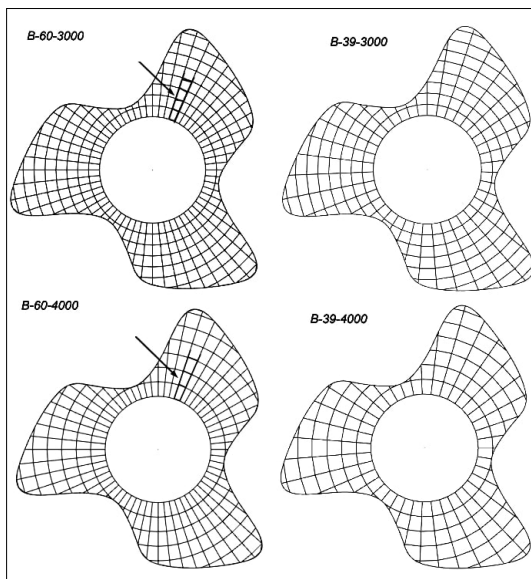


Figure 4. Roof configuration with radial girders.

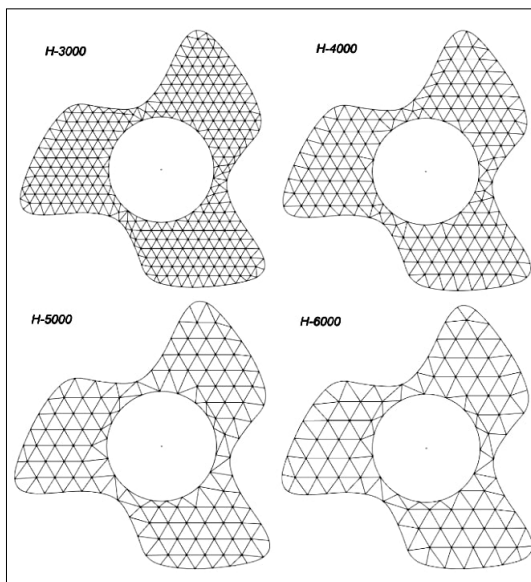


Figure 5. Roof configuration with triangle panels.

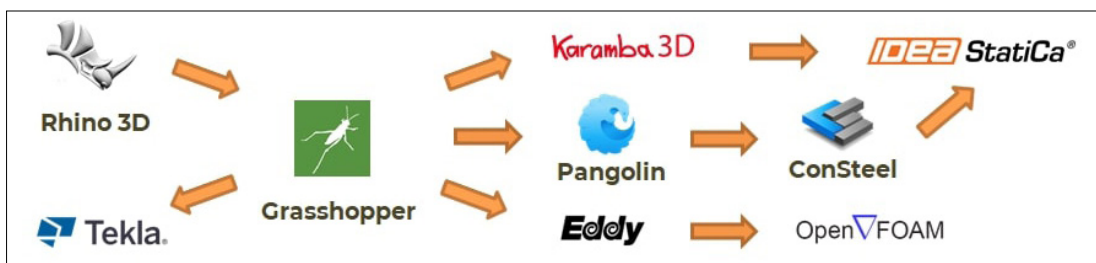


Figure 6. Parametric design workflow.

3. Wind loads according to Eurocode

The effect of the wind acting on a structure can be calculated from the average wind speed and the fluctuating wind speed generated by the turbulence around the building [5]:

$$V(z, t) = v_m(z) + v(z, t) \quad (1)$$

However, EN-1991-1-4 [6] defines the wind-generated effects as simplified surface pressures for the calculation of wind loads acting on structures, taking into account the shape of the structure, its location, the roughness of the terrain, etc. Thus, the wind loads can be considered as a quasi-static pressure equal to the effect of turbulent wind with maximum speed.

$$q_p(z) = \frac{1}{2} \rho v_p(z)^2 \quad (2)$$

The effective surface pressure instead (pressure or suction), can be determined as the result of the product of the peak pressure (at z height above the ground) and the pressure coefficients belonging to the building considered to be rigid:

$$w_e = q_p(z_{ref}) \cdot c_{pe} \quad (3)$$

In the case of the structure already presented, the main challenge, taking into account the methods of the codes, is to determine the appropriate pressure coefficients. For the sake of simplicity, the study is limited to the determination of the external pressure factors, in which case the code basically covers several regular shapes: flat roofs, different pitched roofs, vaulted roofs, domes, etc. Due to the relatively low roof slope of the structure, the pressure coefficients for a flat roof with curved eaves, or even for a mono-pitched roof, can be "falsely" used. For the sake of safety, by assuming the pressure factors corresponding to a roof with a 5° slope, the pressure distribution on the structure shown in Figure 7. can be assumed.

Of course, this assumption is highly debatable for several reasons. It is more logical to consider the structure under study as a dome (due to the fact that it fits to the surface of a sphere). In this case, the standard gives 3 characteristic values in a relatively cumbersome way (Figure 8), depending on the eave height, roof height and diameter of the building.

Along the sectioning circles created by planes parallel to the wind direction, the values between A, B and C can be estimated by linear interpola-

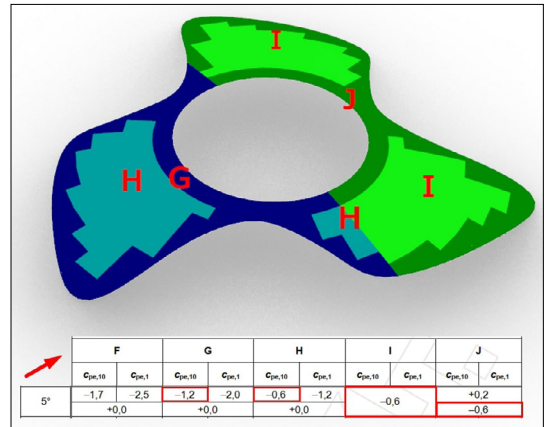


Figure 7. Pressure coefficients on the roof. 1st case.

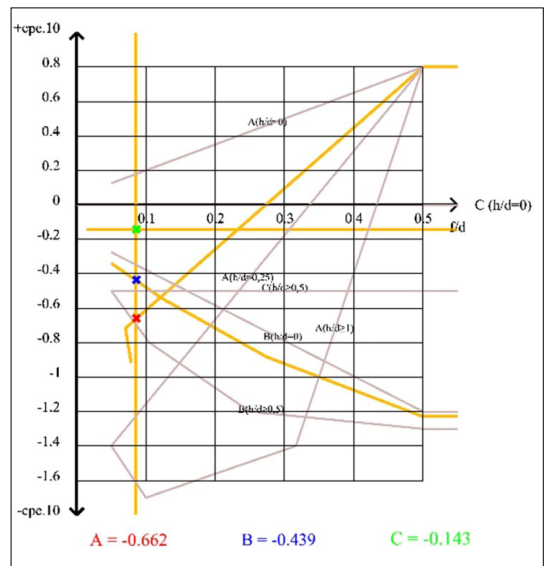


Figure 8. Function evaluating the pressure coefficients. 2nd & 3rd.

tion, thereby the following values shown in Figure 9 can be taken into consideration.

However, due to the complexity in plan, this is also debatable. If the roof structure is considered by examining the pressure coefficients for a circle written around the entire surface (Figure 10), then maximum suction is assumed only at the nearest points of the windward side.

It is more reasonable to divide the structure into several segments, assuming more circles written around these sub-surfaces, so the pressure coefficients are different, as shown in Figure 11). In this case, substructures with different diameters must be assumed.

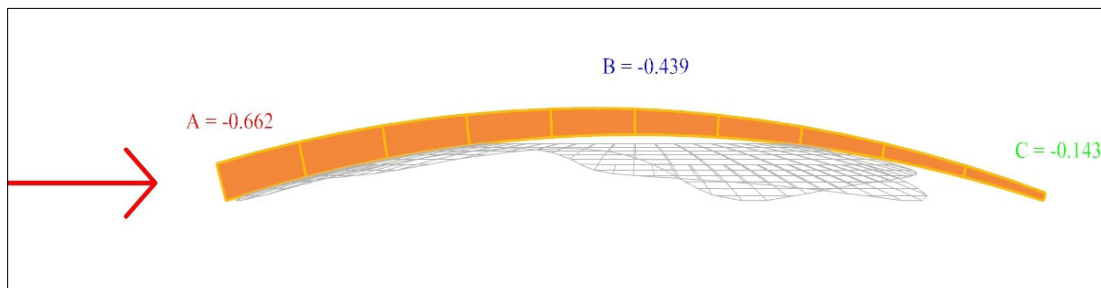


Figure 9. Pressure coefficient diagram of the roof.

The determination of the dominant wind direction is also a topic to be examined in terms of the dimensioning of the entire structure, which means at least 6 wind directions. However, the present study only covers the case when the closest panels to the windward side are also the lowest in terms of roof height, as this has proved to be the governing case especially from the point of view of the roof structure. This is also confirmed by Figure 12, which shows the smaller pressure values obtained in a similar way to the previous cases, with a wind direction rotated by 60°.

In the case of wind loads acting on the façade, they can also be separated into different wind zones, only according to a specific, intuitive principle, as the standard only provides guidance for vertical and rectangular walls. It is obvious that the separation of a minimum of 3 types of zones is justified: windward, leeward, and suctioned side zones, perpendicular to the wind direction. The generated panels of the cladding can be considered as direct load-transfer surfaces. By dividing each panel in half, the created triangles are defining planes, each having a normal vector of which it can be decided that the wind direction is more “perpendicular” or more “parallel” to the given panel, according to the angle defined by the two vectors, compared to 45° (Figure 13).

4. Wind Simulation

Computational Fluid Dynamics (CFD) is a branch of fluid mechanics which is the basis of widely used simulation methods. It is used in several fields, such as aerodynamics, natural sciences, weather simulations etc. There are several computer tools / methods for different air, liquid, heat or gas flow analyses.

OpenFOAM [7] (Open Source Field Operation and Manipulation) is a free C++ toolkit suitable for this type of numerical fluid dynamics calculations (Figure 14). In essence, it allows applications

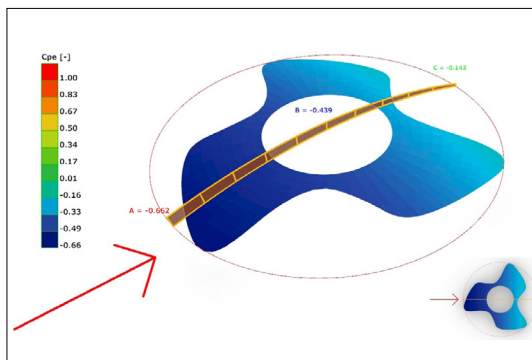


Figure 10. Pressure coefficients on the roof, 2nd case.

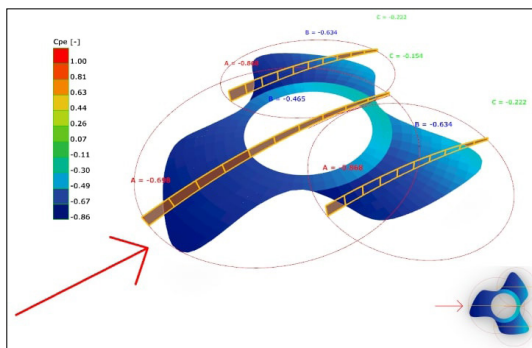


Figure 11. Pressure coefficients on the roof, 3rd case.

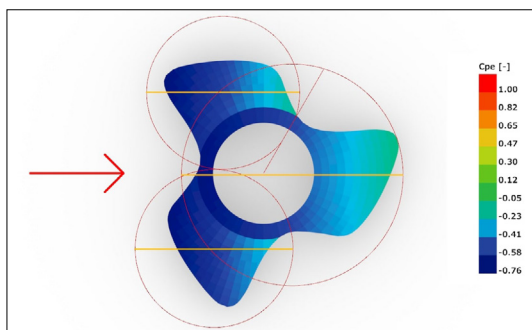


Figure 12. Pressure coefficients on the roof, 3rd case, wind acting rotated with 60°.

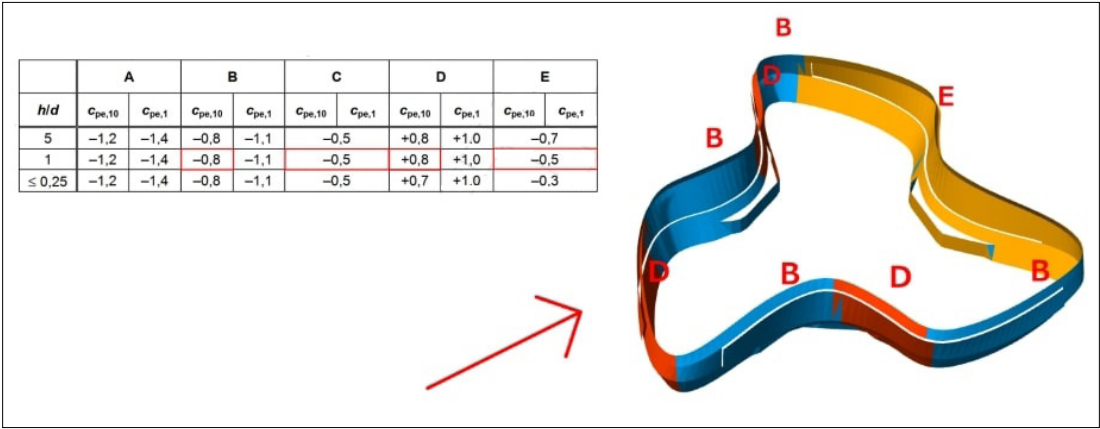


Figure 13. Pressure coefficients on the facade

to be made and executed to simulate different fluid behaviours and their environments. There are basically two main types of applications that can be created. Solver-type applications are suitable for solving specific solid or liquid body mechanical problems, while utilities can be used for data management.

To prepare a CFD-based simulation, the following main steps can be identified:

- Enter input parameters (wind speed $v_p(z)$, corresponding to the peak value of the wind pressure, wind direction, roughness length z_0 , boundary conditions [8], etc.),
- Preliminary mesh generation processes
- Selection of turbulence model
- Solver selection.

The most important task before effective wind simulation is to decompose the investigated building and the environment into finite elements. The mesh generation must meet certain criteria to provide a valid and consequently accurate solution or result. The basic or preliminary mesh generation can be performed manually,

which in the present study was done according to the principles developed within Grasshopper, in order to obtain the resultant surface pressure values in the appropriate positions when it comes to converting them to loads (Figure 15). Furthermore, in this way we can control the complexity of the geometry and consequently to simplify the partial differential equations to be solved, but keeping in mind the expected physical behaviour.

The great advantage of OpenFOAM is that during any run it checks whether the pre-mesh complies with the validity constraints, corrects it in case of an error, creating the final mesh of the structure based on the given desired mesh sizes, and also decomposes the environment into so-called blocks.

The different turbulence models and solving algorithms all assume the media and the objects within it are in accordance with specific principles. The most commonly used [9] also utilised in this case solves the partial differential equations of the kinetic energy and the energy distribution rate ($k-\epsilon$ model), while as a solver, SimpleFoam

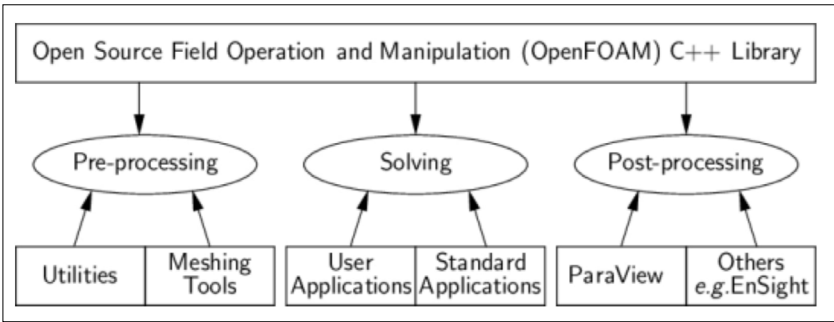


Figure 14. Overview of OpenFOAM Toolbox

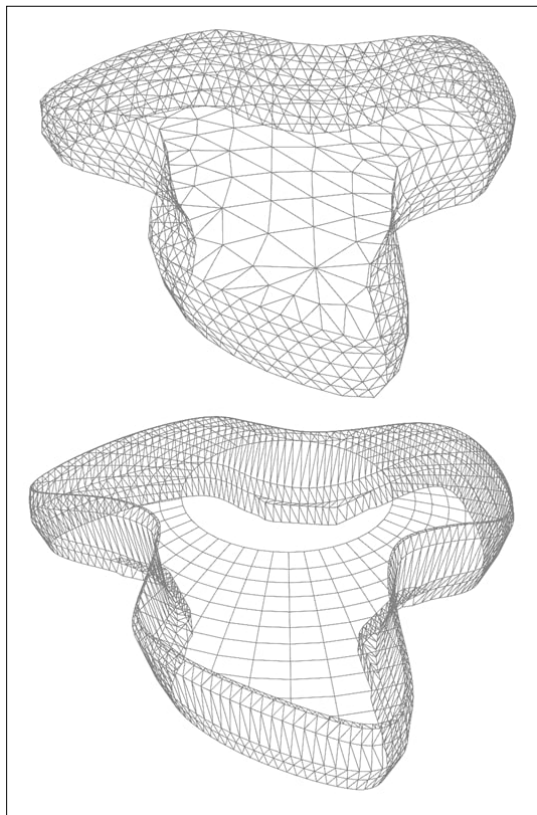


Figure 15. Pre-meshing

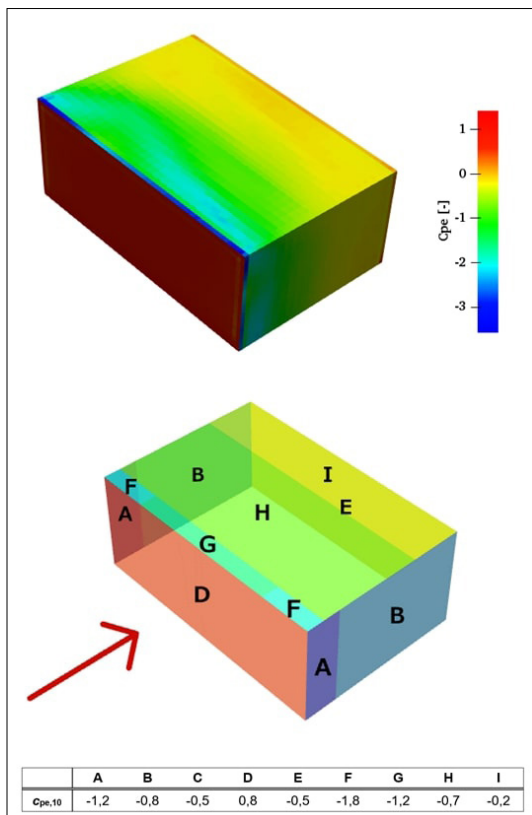


Figure 16. Pressure coefficients according to the simulation (top) and the code (bottom)

(SIMPLE = Semi-Implicit Method for Pressure Linked Equations) was selected. In this case, the simulation assumes the following conditions:

- Incompressible, rigid bodies;
- Turbulent flow;
- There is no physical time, quasi-static pressure.

Running OpenFOAM can also be controlled through Grasshopper. Thus, simulation models can be developed on a much more user-friendly interface, which can be part of a parametric system. The most commonly used extensions are Butterfly (Ladybug Tools) and the one used for this study, Eddy [10]. Both plug-ins' toolbars contain the commands needed to set up a complete simulation.

Performing numerical fluid dynamics calculations and determining wind loads by simulation is not commonplace in structural design practice. Thus, a preliminary study is warranted on a geometrically regular building (rectangular in floor plan, with a flat roof structure and with vertical walls). Based on this, the “enveloping” intention

of the values recommended by the standard is clearly obvious, the separated zones assume the maximum pressure values uniformly, while the simulation shows the real pressure change at the surface, taking into account the more intense local effects (Figure 16).

Interestingly, from a structural point of view, if the building is considered as a frame structure - as a typical steel hall structure, the difference in the behaviour of the structure can be well demonstrated on the basis of the two methods. With regard to the displacements, with 50-80% higher values can occur in the case of the methods proposed by the codes for specific nodes (column end, main girder midpoint). If the structure is to be dimensioned, utilization differences of about 10-20% can be found in favour of the simulation method. The extent of the deviations depends on how the given pressure values obtained at the specific points (at the corners of the finite elements) are interpreted, namely how it is converted to surface loads in a structural analysis. In

the case of a structural model, the most obvious is to define load-bearing surfaces (similar to the zones recommended by the standard) in which uniformly or variably distributed area loads can be defined, with an intensity given by the average or eventually the maximum of the corresponding pressure values (Figure 17).

Using the simulation methodology of the simple hall structure, the results of the examined freeform structure showed a more significant deviation when examining extreme values of the extracted pressures (maximum suction and pressure). In addition, the mesh generation parameters of the different models were recorded, based on which OpenFOAM performed the final mesh generation, and the time required to run the given simulation. Based on this, it can be shown that the “density” of the mesh has a major impact when examining local pressure concentrations and, of course, also in terms of analysis duration. Figure 18. shows the results of the last, most dense mesh, in accordance with Table 1, which summarizes the results of four highlighted simulations.

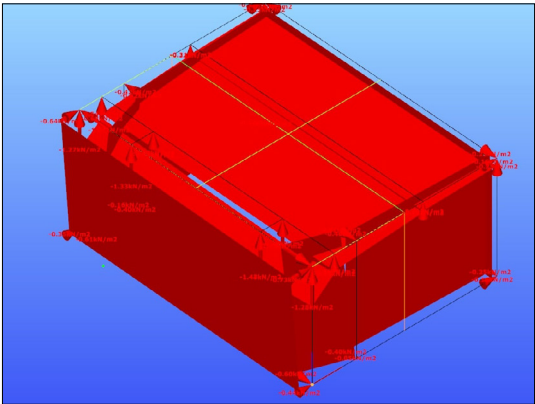


Figure 17. Pressure as surface loads in a structural analysis model (ConSteel).

Table 1. The results of the simulation

Block size	FE Size	Min Cpe	Max Cpe	Meshing runtime	Simulation runtime	Post-processing runtime
[m]	[m]	[-]	[-]	[min]	[min]	[min]
10	1	-2.02	0.57	2	4	3
10	0.5	-2.26	0.43	4	5	3
5	0.5	-1.75	0.46	10	35	5
2	0.5	-5.72	0.83	16	50	12

5. Conclusion

Based on the study, the real potential of parametric design can be observed, mainly due to its versatility. The use of a parametric methodology can be an advantage in virtually any design process, but it is important to emphasize that setting up such a system is a time consuming task. Aware of this, adequate experience is required to estimate the degree of efficiency that can be implemented. In addition, it has become worthwhile to keep up with the developers behind different parametric design applications, because there is a constant progress with the emergence of new tools, making it easier to meet the need for automation. In fact, if the routine in everyday tasks is recognized any work can be made extremely efficient with little effort. In justified cases, it is also worthwhile to design such a parametric system for performing complex tasks, especially if the goal is optimization (since Grasshopper was basically developed for this purpose [11]).

However, the topic of wind simulation is much more complex. Experience basically shows that although CFD can be used to perform wind load tests for industrial use, its reliability is highly questionable. This is mainly due to the fact that it requires a serious fluid dynamics expertise and in case of improper use, contradictory results can be

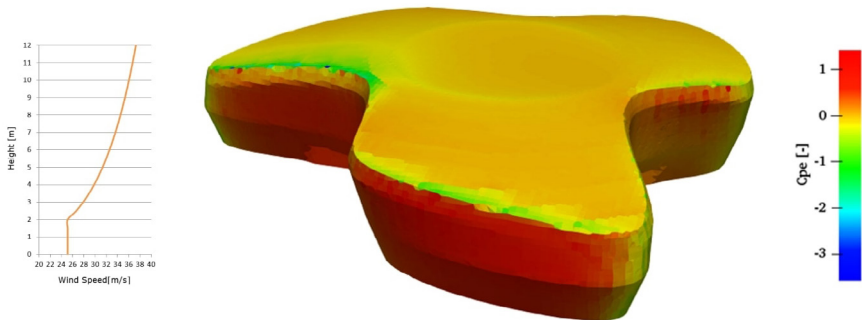


Figure 18. Wind profile (left) and the pressure coefficients according to the simulation (right).

easily obtained. Nevertheless, in justified cases, a simulation built in a parametric environment can replace the methods proposed by the codes, especially if the only way is to use the values of similar geometries, which can lead to a false interpretation, thereby the structure could be dimensioned improperly. In the case of the presented structure, it can be stated that quite different pressure values can be evaluated on the basis of the methods proposed by the codes. The most critical zones of the structure are the roof edges under suction at windward sides, where the values of the pressure coefficients determined in three different ways according to the standard are -0.66 , -0.86 , -1.2 , respectively. On the other hand, based on the simulation, it can be shown more precisely that in the case of local pressure concentrations, coefficients higher than the above values (around -2) can be evaluated, but as required by the standard.

Of course, it is not entirely advisable to rely on these data, but it can certainly give a general picture or guidance to the structural engineer in determining the pressure distribution and thus the wind loads on the building.

The golden mean between the codes and computer wind simulation may be laboratory wind tunnel studies, but here, too, some of the obstacles need to be highlighted. The primary consideration is also the expertise and technology, which is provided in a few cases, especially in our region, in the case of building wind simulation. As it is a relatively rare need - because few serious investments justify such studies - there is no know-how or even protocol for data communication between the laboratory and the client in the case of such a task. Another important consideration for a wind tunnel test is the amount of time spent, which in a few cases catches up with the rapid pace of the market. Because building a wind simulation model alone can take up to weeks, especially if a modular model is needed to simulate different construction phases. Thereafter, the evaluation of the measurements and the results can be a similarly lengthy process, so that the duration of a complete experiment can take up to 3-6 months, while the full global structural design of a structure, which can be considered complex, can be completed in just few months. Thus, in many cases, there is no data available during the initial design phase, to design more economically by overwriting the code recommendation with wind simulation results. Therefore, in the

early phase of designing a free-form structure, it is worth considering the use of wind simulation methods. This means that more studies and experiments are needed to be carried out regarding CFD analysis for civil engineering problems in order to develop reliable and validated simulation methodologies.

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