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Original scientific paper

The Effect of Cylindrical Canopy on Atrium Buildings: Experimental Study

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Abstract: The research presented in this paper shows the changes in wind pressures after constructing a cylindrical canopy over an atrium of a historical building. Architectural interventions on existing buildings must be carefully built, considering various aspects, such as wind pressure and airiness. The wind pressure analysis presented in this paper aims to show the changes in the atrium walls, the surrounding roof, and the cylindrical roof over the atrium to expand the knowledge about existing regulations. The research uses the following methods: wind tunnel experiment, numerical analysis, and comparison to existing regulations, following the Eurocode design guide for wind action. The hypothesis is that this research will emphasise the importance of wind tunnel experiments for specific locations, especially for architectural interventions on heritage buildings since it will draw attention to limitations of existing technical regulations regarding atrium buildings. This paper discusses the effect of the cylindrical canopy design on atrium buildings, and the conclusions set the basis for expanding the existing design guide for wind action.

Keywords: CFD analysis; historic buildings; pressure coefficients; wind action; wind tunnel experiment

1 INTRODUCTION

Atriums formed by residential and business buildings in old city centres and atriums within large buildings represent places of the city whose space can be activated. Such areas prevail in the old city centres, where the city began to expand, often turned into pedestrian zones, with a ban on heavy traffic in the immediate vicinity [1]. The limited space of the entrance to the passageways represents difficulties in constructing the canopy. This research proposes a timber lamella vault with a textile membrane as a canopy for the atrium of Belgrade's Technical Faculties building. Lamella structures are suitable for such spaces because the whole structure can be delivered with a small delivery vehicle which can easily approach any location, and the construction method does not require heavy mechanisation [2]. The textile membrane would be suitable as a roof cover because its level of transparency allows enough light not to disrupt the atmosphere of the atrium and provides protection from the sun [3].

Every type of intervention on the existing building affects the building itself, and this paper will analyse the impact of the canopy on the roofs surrounding the atrium and its walls under the canopy. Regulations that define wind effects on buildings define general load cases that do not fully consider the context in which they are built. The calculated values of the coefficients that define the wind direction, the terrain's roughness, the building's height and the like do not provide enough information about the actual picture of the impact on the location [4]. Eurocode [5] defines different pressure coefficients (c_p) according to the surface on which they act. The dimensions of the vertical walls on the building perimeter define the c_p for walls. Walls in atriums could be observed as walls between the row of buildings since the Eurocode does not include the c_p values for walls in atriums. A similar method was shown for analysing multi-span roofs [6] and the roofs of buildings in proximity [7]. The Eurocode defines the c_p values for pitched and hipped roofs regarding the shape and incline of the roof and the wind direction. In contrast, the c_p values for cylindrical roofs change with the height at which the roof is located, the ratio of the building height to the span of the roof and the roof rise to the height of the building [5]. These values are given for free-standing buildings and do not consider other building typologies.

Over the years, various authors have conducted experiments for wind load cases not properly presented in the design guides. Kasperski [8] presents a specification of the design wind load based on wind tunnel experiments explaining the steps of the analysis needed to formulate the wind load code. Uematsu and others [9, 10] researched the wind loads on different form canopies. Their most recent research [11] discusses vaulted canopy and presents the wind pressure coefficients for angles of 0º, 45º, 60º and 90º. This research shows the most critical maximum and minimum peak wind force coefficients among all wind directions important for the cladding design of the vaulted canopies, which are not defined in the design codes. Colliers [12] emphasises that existing wind load standards do not cover the topologies of membrane and shell structures and that wind load testing should be used to obtain representative wind loads for these structures. The research is conducted for a hyperbolic paraboloid canopy structure and proposes a wind tunnel analysis methodology.

Other research on the effect of change in existing buildings is related to the increase in the energy efficiency of building roofs, such as the addition of solar panels [13] or the positioning of thermosyphon solar collectors [14]. This paper aims to show the changes in pressure coefficients on existing roofs after the construction of the canopy because it could increase the wind vulnerability of the roof [15].

Canopies over atriums are a common architectural intervention, and this paper will present a cylindrical structure placed over an atrium of a historic building. The analysis is conducted as experimental and numerical research for the building roof and atrium with the cylindrical canopy to compare the results and derive conclusions. Pressure values on the canopy of the atrium and on the part of the building of the Technical Faculty affected by the intervention were obtained by experimental and numerical analysis, an investigation used in the analysis of building structures [16]. Since the atrium building typology is not included in the Eurocode wind design guide, this research aims to expand the knowledge about wind pressures on atrium walls and surrounding roofs. This paper presents a wind tunnel experiment in Section 1, computational fluid dynamics (CFD) analysis in Section 2, the results of experimental and numerical analysis in Section 3, a discussion in Section 4 and a conclusion in Section 5.

2 WIND TUNNEL EXPERIMENT

2.1 Atrium Characteristics and Canopy Design

The Technical Faculties' building was built in 1931, and it stretches for approximately 150 m, enters the block 66 m, the height is 25 m, has four floors and an attic, a centrally placed grand hall with monumental stairs and four atriums. The atrium dimensions are 13.6/22.4 m at the base, and the height is 24.4 m. The lamella structure of the canopy has the geometry of a segment of a right circular cylinder envelope and spans 13.6 m. The 3 m long arched lamellae are made of glued laminated timber and are connected by steel plate joints bolted to the lamellae [17]. The gable arches are designed as three-hinged glued laminated timber arches. At half the length of the canopy, at 11.2 m, another three-hinged arch is placed, according to the recommendations of engineers Scheer and Purnomo, that the ratio of span to length in lamella structures should always be 1:1 [18].

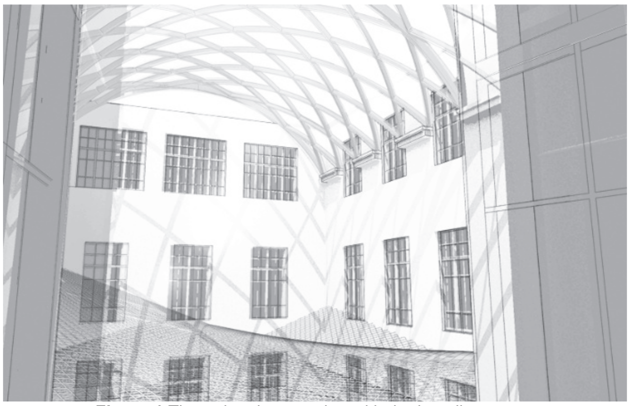

Figure 1 The atrium intervention with the lamella canopy

2.2 Model Description

To analyse the wind pressure on the roof of the building of the Technical Faculties and the interior facade in the atrium, a model of the segment of the building was made. The model scale is 1:100 to fit on the rotating platform of the wind tunnel test section. It is constructed as a volume with no openings, but the roof planes were precisely shaped since their shape and slope affect the experiment results. The lamella structure was 3D printed, and the textile membrane was simulated with transparent foil glued to the lamellae.

The measuring points were placed on (1) the roof of the building surrounding the atrium, (2) the newly designed canopy and (3) the atrium walls. Three measuring points were placed on each of the planes. Three measuring points were placed on the canopy in the middle of the canopy length. Each measuring point was drilled to place the measuring instruments - copper tubes Ø3 mm with extensions at the ends. The silicone tubes connected the measuring points on the model to the manometer to measure the wind pressures.

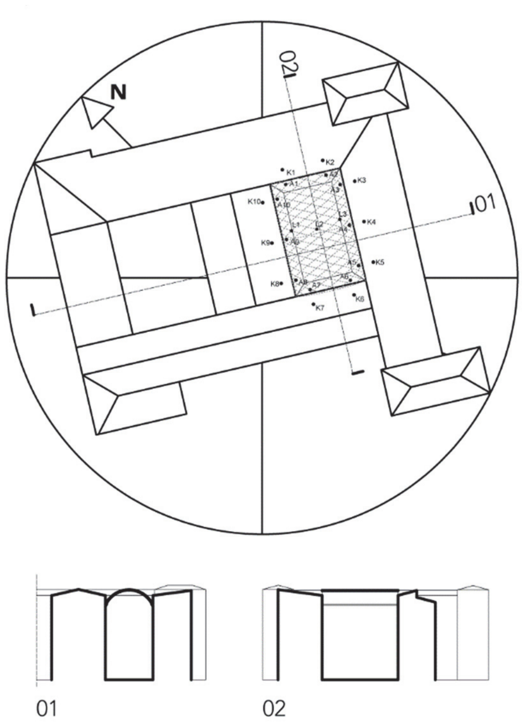

Figure 2 Model of the building, plan and sections

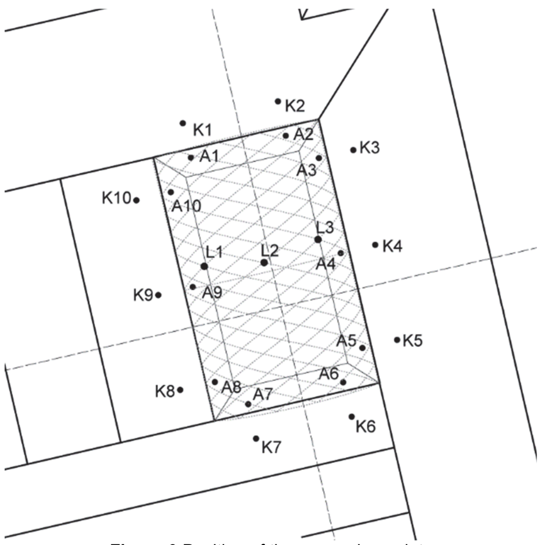

Figure 3 Position of the measuring points

All the elements were named in the model and on the manometer to follow the experiment results. The measuring points in the roof planes were called the letter K and numbers from 1-10, and those located inside the atrium, in the same direction, were given the letter A with the numbers from 1-10 (the measuring point A1 is located below the measuring point K1 so that the results could be more easily monitored). The measuring points on the lamella structure are called the letter L and the numbers 1-3. Following these positions, silicone tubes were also marked and connected with plastic ties depending on which plane they belonged to (K1 and K2 belong to one roof plane and are combined in one bundle). After that, the model was fixed to the rotating platform in the wind tunnel test section. An opening was formed on the platform to connect the tubes to the manometer. The length of each silicone tube exceeded 5.5 m to allow smooth rotation of the model on the platform in the wind tunnel. The manometer measured the pressure at the measuring points using 24 water columns. Each water column on which the pressures are read was marked with the name of the silicone tube connected to it and one water column was left for control and measured the atmospheric pressure.

2.3 Experiment

The experiment was conducted in the Aeronautical Institute of the Faculty of Mechanical Engineering, University of Belgrade. The institute has a subsonic wind tunnel, "Miroslav Nenadović", built in 1952/57 and renovated in 2013. It is a subsonic, closed-loop wind tunnel. The wind tunnel test section is 6.0 m long and has an octagonal cross-section 2.90 m wide and 2.10 m high. The wind tunnel is designed for aeronautical and environmental studies and research up to a speed of 60 m/s. The wind speed is measured by a PCM-PFM 2 digital anemometer connected to a stationary pitot tube installed in the wind tunnel's test section [19]. The wind tunnel is calibrated according to the regulations to have accurate experiment results, as suggested in the paper by Ockoljić et al. [20].

The experiment in the wind tunnel was carried out at a wind speed of 21 m/s, corresponding to the maximum wind speed of the "Košava" wind, which can be measured in the centre of Belgrade, as proposed in the Eurocode National Annex [21]. The model is positioned so that pressures can be measured at every 45º in a circle as the sides of the world: north/0º (N), northwest/45º (NW), west/90º (W), south-west/135º (SW), south/180º (S), southeast/225º (SE), east/270º (E) and northeast/315º (NE). The wind speed was tracked on a digital anemometer, and when stabilised, the results were read from the manometer.

Figure 4 Model position in the wind tunnel

The first experiments were carried out only for the segment of the Technical Faculties building, without a canopy, for a North wind. Then the platform was rotated 45º for each subsequent measurement. The procedure was repeated when the canopy rested on the crown of the atrium.

3 CFD SIMULATIONS

The CFD simulations are performed on the building model using Ansys Fluent. For the CFD simulation, four cases for wind directions azimuth (NW, SW, SE, and NE) were chosen, corresponding to 45°, 135°, 225°, and 315° positions in the wind tunnel experiments. For each case, geometry, grid generation, and computation performance were done using the same settings.

3.1 Computational Domain

The size of the computational domain is set up according to the guidelines by [22, 23]. Recommended blockage ratio should be below 3%, and to fulfil it, the distance from the building to the inlet, lateral sides, and upper side of the domain should be at least five times the height of the building, and the distance from the outlet is at least fifteen times of the height. Furthermore, to predict the flow field more correctly around the building, a hemispherical sub-domain is defined in the vicinity of the building model with a diameter of eight times the model height.

A mesh convergence study was performed for one case of the wind direction for uncovered building atriumin order to obtain an appropriate mesh density (number of cells) and the size of the hemispherical subdomain to ensure smaller simulation run time. The results have been applied to all remaining cases of the wind directions and canopy-building configurations. The domain is discretised using unstructured mesh for both the computational domain and sub-domain, with a maximum element size of 0.1 m and a minimum element size of 0.005 m, where an element size of 0.005 m was used for the faces of the building representing the roof surrounding atrium (and canopy). An element size of 0.01 m was used for the building's other faces. The total number of elements for the computational domain for each of the four cases slightly varies and is about 1.6 million, where nearly half are placed within the hemispherical sub-domain.

3.2 Setup and Solution

At the inlet, a "velocity inlet" boundary condition is defined. The applied wind speed profile is obtained from the earlier measurements in the same wind tunnel [24]. Non-slip conditions are applied for the building walls, roofs, and computational domain floor. Symmetry conditions are specified for the upper and lateral sides of the computational domain. At the outlet, the "pressure outlet" boundary condition was set as zero-gauge pressure. The values of turbulence quantities at the boundary were specified uniformly. Accurate profiles of these quantities are unknown, so the turbulent intensity and viscosity ratios were set as 1% at the inlet and 10% at the outlet.

The CFD simulations were done in ANSYS Fluent using a 3D steady-state, pressure-based solver, RANS approach with the Renormalization Group (RNG) k-ε turbulence model with curvature correction and production limiter. Choice of the turbulence model was based on the author's previous research of the wind influence on the buildings and literature recommendations [23, 24]. For the convective and diffusion terms of the governing equations, second-order discretisation schemes were used. The solution was initialised with hybrid initialisation with default settings.

The convergence of the solution was reached when the solution monitor for outlet mass flow rate remained steady, using the criterion in order of 10^{-5}.

4 RESULTS
4.1 Experiment Data Processing

To analyse the experimental results, all data needed to be processed. The data from the manometer were expressed in millimetres of water, and the values of millimetres of water were translated into megapascals [MPa] according to the ratio 1 mm H_2O = 9.80665 Pa, to calculate the pressure onto each measuring point.

To calculate the pressure coefficients, it was necessary to calculate the difference between the measured pressures and the pressure of the undisturbed flow of air and then divide it by the dynamic pressure according to the Eq. (1):

$$c_p = \frac{p - p_\infty}{0.5 \cdot \rho_\infty \cdot V_\infty^2} \tag{1}$$

The results were differentiated by the plane's position with measuring points and the direction of the wind. The data was processed for the wind directions perpendicular (90º angle) to the planes, the NW, NE, SW and SE, which are, at the same time, in the direction parallel (0º angle) to the planes to be compared with the Eurocode design guide c_p values.

4.2 Experiment and CFD Simulation Results

The following diagrams show c_p values for all roof planes, all atrium walls and the canopy, both for the wind tunnel (WT) testing and the CFD simulation. To differentiate the results, the ones without the canopy are marked with "x", and the canopy are marked with "o", e.g., c_p WT x.

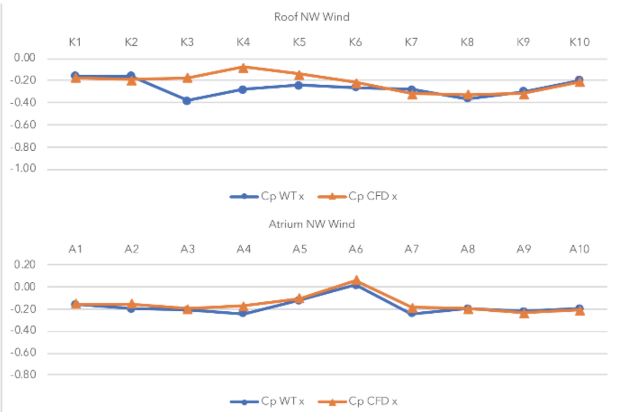

Figure 5 c_p values without the canopy for NW wind

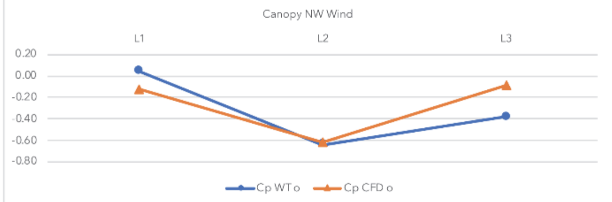

Figure 6 c_p values with the canopy for NW wind

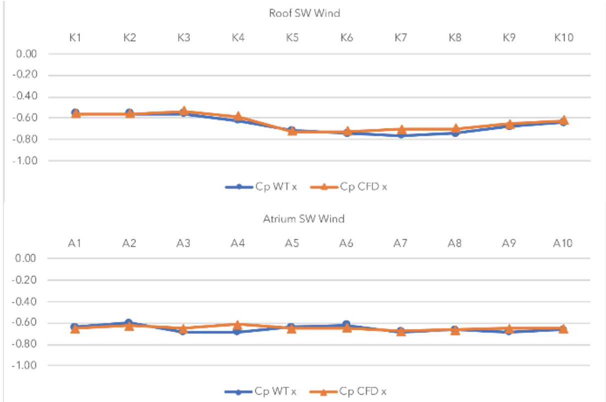

Figure 7 c_p values without the canopy for SW wind

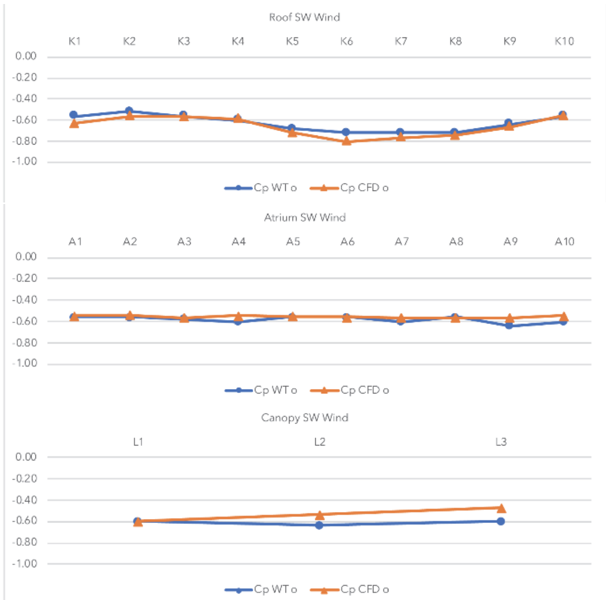

Figure 8 c_p values with the canopy for SW wind

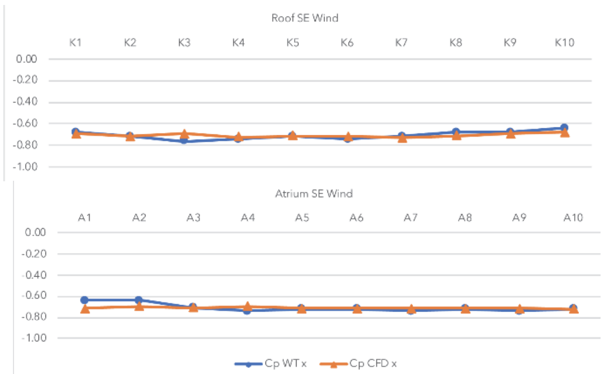

Figure 9 c_p values without the canopy for SE wind

The results have shown matching c_p values for SW and SE wind for both cases, without and with canopy (see Figs. 7 to 10). The maximum difference in values is 1.25 times. The NW wind without canopy results show different curves in measuring points K3-5, corresponding to one roof plane, and for the NW wind with canopy. The maximum difference between WT c_p and CFD c_p values is 2.25 times.

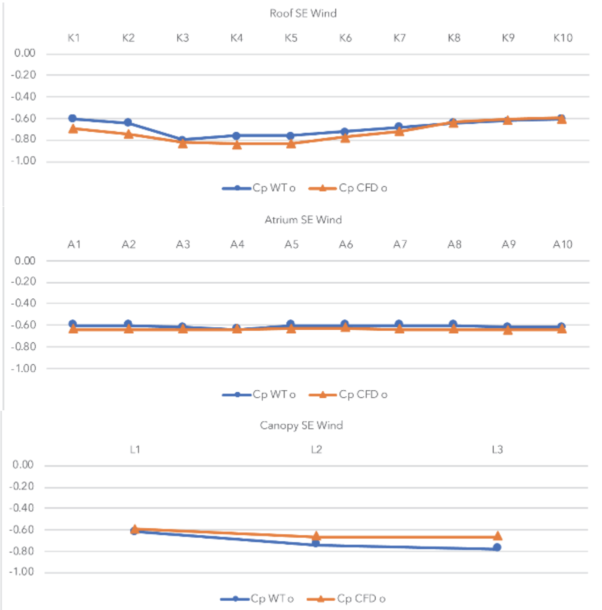

Figure 10 c_p values with the canopy for SE wind

The c_p values for NE wind show that the results from the WT give lower values for wind suction (the c_p is closer to 0) than the CFD values (see Figs. 11 to 12). The c_p values are all negative, except in the measuring point K10 for the NW wind with canopy, where WT $c_p(\mathrm{K10}) = +0.08$, but for the CFD c_p (K10) = –0.036.

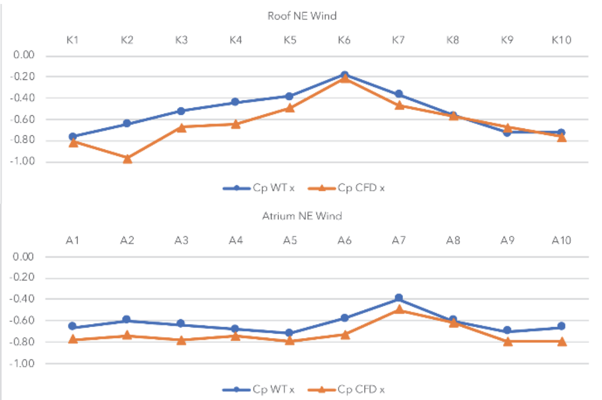

Figure 11 c_p values without the canopy for NE wind

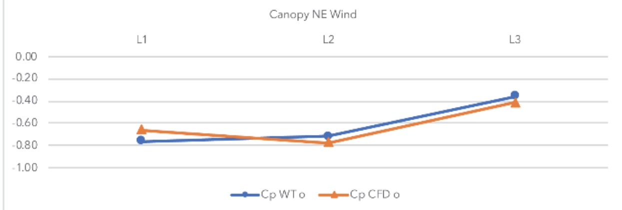

Figure 12 c_p values with the canopy for NE wind

5 RESULTS

The effect of the cylindrical canopy on the surrounding roofs and walls of the atrium can be observed by comparing c_p values without (x) and with (o) the canopy. The following diagrams show the SW and SE wind c_p values, which will be compared with the Eurocode design guide.

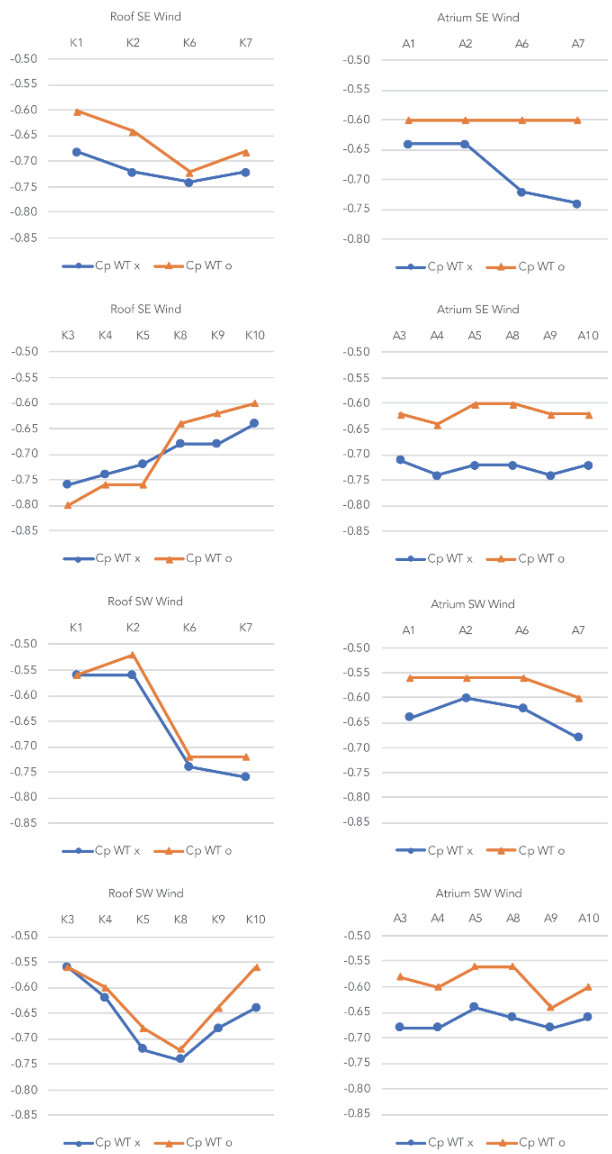

Figure 13 Comparison of c_p values without (x) and with (o) the canopy for SE and SW wind for different roof and atrium planes

The addition of the canopy generally decreases the wind suction, as observed in the c_p values on the diagrams. The wind flow over the roofs and the atrium wall is similar, except for the plane with measuring points K3-5 for the SE wind. Fig. 14 presents the wind flow in the CFD simulation for the SE wind.

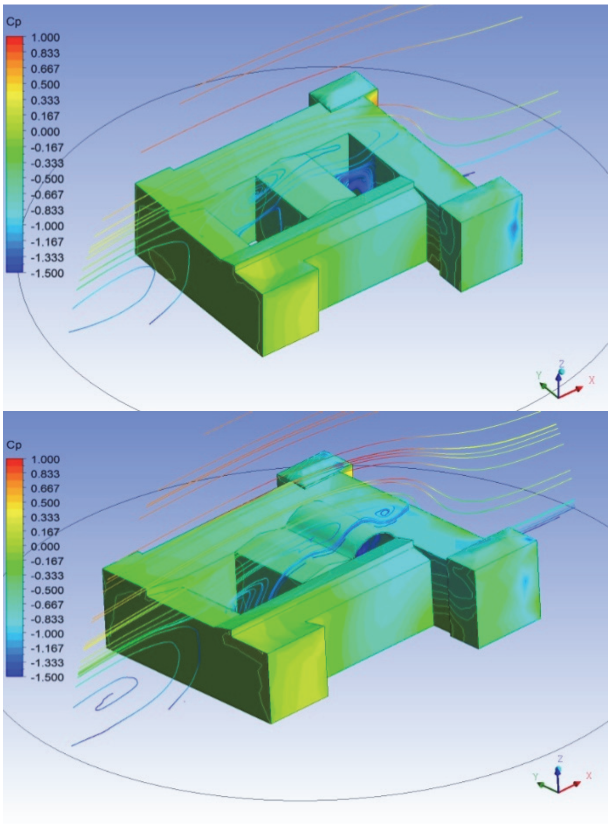

Figure 14 CFD simulation for the SE wind without canopy (up) and with canopy (down)

On the plane with measuring points K3-5, a wind whirl appears for the SE wind, increasing the suction of the wind on this roof plane.

The range of pressure coefficients is from –0.52 to –0.80. The maximum difference in the c_p values is 1.235 times when the wind suction decreases in the atrium (SE wind, measuring point A7).

With the addition of a canopy with an aerodynamical shape, the overall suction of the wind could be decreased on the surrounding planes of the atrium.

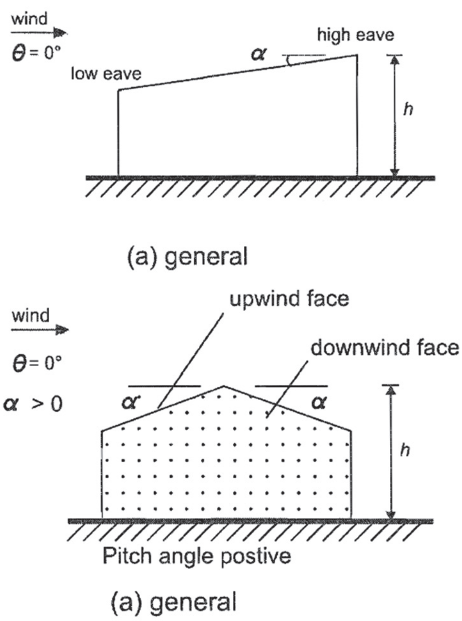

Figure 15 Mono- and double-pitched roof in EC [5]

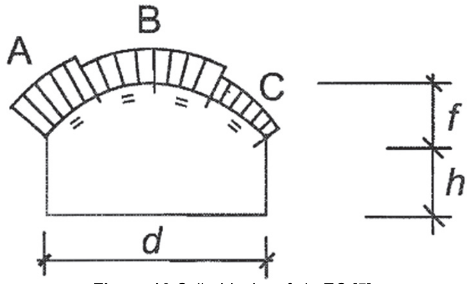

Figure 16 Cylindrical roofs in EC [5]

Since the atrium building typology is not presented in Eurocode (EC), the c_p values obtained from the analysis could be compared to those for pitched roofs. The measuring points K1-5 are placed on mono-pitched roofs, points K8-10 are on a double-pitched roof, and points K6-7 are on a double-pitched roof with an overhang (not included in EC so that it will be observed as a mono-pitched from the atrium side). The pitch angle of the roofs is approximately 5°. (Fig. 2) Tabs. 7.3a and 7.3b in EC [5] give recommended c_p values for mono-pitched roofs, while tables 7.4a and 7.4b give recommended values for double-pitched roofs. The external pressure coefficients, measured in this paper, are defined in EC as c_p for non-structural elements $-c_{pe,1}$ and for structures $c_{pe,10}$. (Fig. 15 and Fig. 16).

The direction of the SE wind is:

- $\theta = 0°$ for the roof plane with measuring points K8-10, and the peak c_p values are $c_p(\text{K8x}) = -0.68$ and $c_p(\text{K8o}) = -0.64$. The EC recommends the peak c_{pe} value for this zone $c_{pe,10} = -1.2$ and $c_{pe,1} = -2.0$, which is almost 2 times higher.
- $\theta = 180°$ for the roof plane with measuring points K3-5, and the peak c_p values are $c_p(\text{K3x}) = -0.76$ and $c_p(\text{K3o}) = -0.8$. The EC recommends the peak $c_{p,1}$ value for this zone $c_{pe,10} = -0.8$ and $c_{pe,1} = -1.2$.
- $\theta = 90°$ for the roof planes with measuring points K1-2 and K6-7, and the peak c_p values are $c_p(\text{K6x}) = -0.74$ and $c_p(\text{K6o}) = -0.72$. The EC recommends the peak $c_{p,1}$ value for this zone $c_{pe,10} = -0.6$ and $c_{pe,1} = -1.2$.

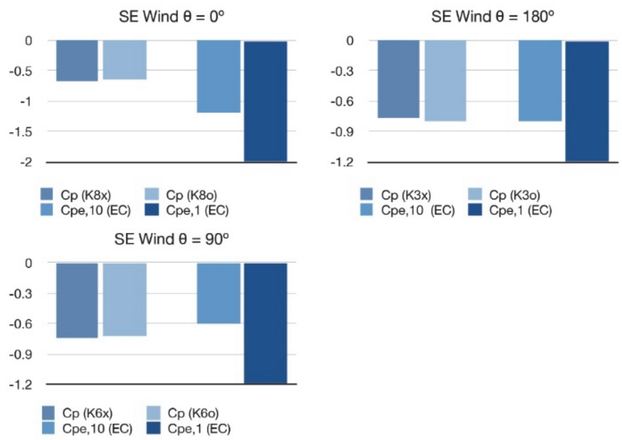

Figure 15 Charts presenting the comparison for the SE wind of the experimental peak c_p values and the c_p values proposed by Eurocode

The direction of the SW wind is:

- $\theta = 0°$ for the roof plane with measuring points K1-2, and the peak c_p values are $c_p(\text{K1x}) = -0.56$ and $c_p(\text{K1o}) = -0.56$. The EC recommends the peak c_{pe} value for this zone $c_{pe,10} = -0.6$ and $c_{pe,1} = -1.2$.
- $\theta = 180°$ for the roof plane with measuring points K6-7, and the peak c_p values are $c_p(\text{K7x}) = -0.76$ and $c_p(\text{K7o}) = -0.72$. The EC recommends the peak $c_{p,1}$ value for this zone $c_{pe,10} = -0.8$ and $c_{pe,1} = -1.2$.
- $\theta = 90°$ for the roof planes with measuring points K3-5, and the peak c_p values are $c_p(\text{K5x}) = -0.72$ and $c_p(\text{K5o}) = -0.68$. The EC recommends the peak $c_{p,1}$ value for this zone for mono-pitched roof $c_{pe,10} = -0.6$ and $c_{pe,1} = -1.2$,
- $\theta = 90°$ for the roof planes with measuring points K8-10, and the peak c_p values are $c_p(\text{K8x}) = -0.74$ and $c_p(\text{K8o}) = -0.72$. The EC recommends the peak $c_{p,1}$ value for this zone for double-pitched roof $c_{pe,10} = -0.6$ and $c_{pe,1} = -1.2$.

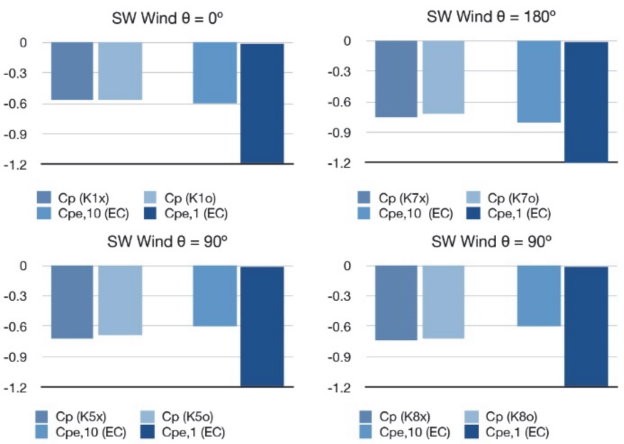

Figure 16 Charts presenting the comparison for the SW wind of the experimental peak c_p values and the c_p values proposed by Eurocode

The peak measured value for the cylindrical canopy external pressure coefficient for the SE wind is c_pWTo(L1) = –0.62, c_pWTo(L2) = –0.74 and c_pWTo(L2) = –0.78. The EC defines only the cpe,10 for the structure of cylindrical free-standing roofs/canopies. For structures whose rise f and span d ratio is between 0.2 and 0.3, according to the EC, it is necessary to calculate the wind pressure in the first third of the structure when the wind angle is $\theta = 90°$. The ratio of the rise to the span of the canopy is f/d = 0.288, while the ratio of the height to the span is h/d = 24.4/13.6 = 1.8. According to the EC, the pressure coefficients for the positions of the measuring points on the canopy are $c_{pe,10}$ (L3) = –0.5 for the negative value (wind suction) and $c_{pe,10}$(L3) = +0.2 for the positive value (wind pressure), $c_{pe,10}$ (L2) = –1.00, and $c_{pe,10}$(L1) = –0.40 for the wind at an angle of 90º to the cylindrical plane. The measured values in this research do not give positive c_p values, as EC proposes since the canopy in the experiment is surrounded by inclining roofs aimed towards it. The surrounding roof increases the wind speed and negatively affects the canopy. One of the possible directions for future research could be to use the experimental c_p values to conduct a static analysis of the canopy, as was done in the research presented by Damjanović et al. [25].

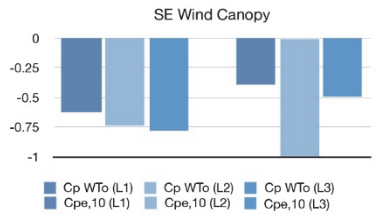

Figure 17 Chart presenting the comparison for the SE wind of the experimental peak c_p values and the c_p values proposed by Eurocode for the vaulted canopy

The measured peak c_p value on atrium walls without the canopy is $c_p\text{WTx}(\text{A4}) = -0.74$ for the SE wind. The canopy reduces the suction effect of the wind on atrium walls by 1.15 times since the values in EC Tab. 7.1 [5] are from –0.8 to –1.4.

It can be concluded that the Eurocode design guide proposes greater absolute c_p values than the ones measured in the wind tunnel.

6 CONCLUSIONS

Refurbishing historical buildings to improve their energy efficiency or adapt to a new function requires thoroughly analysing the existing structure and building envelope. The construction of a cylindrical canopy over the atrium in a historical building showed that the aerodynamic shape of the canopy improves the wind flow on the existing building planes, reducing the suction effect that the wind produces on the roof and wall planes for three-story buildings. Unlike free-standing buildings with pitched roofs, the atrium roofs protect one another and create a uniform wind flow, resulting in more favourable c_p values than proposed in the EC. The cylindrical canopy placed on the pre-existing atrium ridge before the annexe of the third floor is also protected by the outer roofs of the atrium, resulting in different c_p values than those proposed by the EC, especially in the zone of the first impact of the wind.

The wind tunnel experiment has shown that the wind producing the highest absolute c_p values (the highest suction effect) is the SE wind, corresponding to the direction of one of the strongest winds in Belgrade [26], and the CFD simulation confirmed the c_p values obtained in the wind tunnel experiment.

The conclusion is that a wind tunnel experiment should be done for the interventions on existing buildings, especially for the typologies not included in the EC.

In order to continue this research, new investigations should focus on the relation between the radius of canopy curvature and the inclination of the surrounding roofs and how it affects the changes in the c_p values.

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