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DEVELOPING A CFD NUMERICAL MODEL FOR WIND ANALYSIS OF BUILDINGS WITH ARCHED ROOF

Abstract:

Wind action on engineering structures can cause significant consequences. Arched structures covered with textile membranes (balloon halls) are particularly vulnerable. This paper presents a study of wind action on structures with arched roofs and flat gable walls. The analysis was conducted using Computational Fluid Dynamics (CFD), with variations in parameters that may influence structural response, for two representative wind directions: along-wind and crosswind. The selected output parameter, the pressure coefficient (*Cp*), is validated and compared with values provided in relevant standards. The aim of this research is to contribute to the dissemination of knowledge and experience related to CFD methodology, as well as to support the development of regulatory databases concerning pressure coefficients for non-standard structural forms.

Keywords: wind load analysis, CFD, arched roofs, balloon halls

РАЗВОЈ НУМЕРИЧКОГ CFD МОДЕЛА ЗА АНАЛИЗУ ДЕЈСТВА ВЕТРА НА ОБЈЕКТЕ СА ЛУЧНИМ КРОВОМ

Сажетак:

Дејство ветра на инжењерске објекте може проузроковати озбиљне последице. Лучне конструкције покривене текстилним мембранама (балон хале), су посебно осетљиве. У раду је приказана студија дејства ветра на објекат са лучним кровом и равним калканима. Анализа дејства ветра је урађена CFD методом, уз варирање параметара који утичу на одговор конструкције, за два репрезентативна правца ветра, подужни и попречни. Одабрана излазна вредност, коефицијент притиска (*Cp*) је валидирана и упоређена са расположивим подацима у важећим стандардима. Циљ рада је ширење знања и искустава везаних за CFD методологију и допуна регулативне базе података о коефицијентим притиска при дејству ветра за нестандардне облике објеката.

Кључне риjечи: analiza dejstva vetra, CFD, lučni krovovi, balon hale

1. INTRODUCTION

The analysis of wind action has been continuously improved over the past century through advances in theory, practice, and regulations. In most developed countries, current standards represent the state of the art and are mandatory in the design of all types of structures. In parallel, civil engineering aerodynamics based on Computational Fluid Dynamics (CFD) has been developing rapidly. This discipline has emerged as a result of both theoretical advancements and the rapid development of engineering software capable of solving complex mathematical problems. Despite their comprehensiveness, existing regulations are not able to fully address wind effects on atypical structures, whether due to their geometry or material properties.

Structures with arched (vaulted or barrel) roofs covered with textile membranes, commonly referred to as balloon halls in the Balkan region, typically take the form of a half-cylinder or a segment thereof. These structures are widely used in agriculture and as storage facilities. In the Balkan region, they are also commonly used as sports facilities for schools. Their application has proven to be cost-effective and often represents the most practical solution for rural and suburban areas lacking adequate gym facilities.

Available studies on wind loading of such structures are relatively limited, although some date back to as early as 1928, when Bounkin and Tcheremoukhin [1] conducted wind tunnel experiments. Holmes [2] published research in 1984 on wind loads acting on a hangar with an arched roof, also based on wind tunnel testing, considering wind direction perpendicular to the longitudinal axis. The same author later presented results for mean pressure coefficients on an arched-roof building under similar wind conditions [3]. A similar structure, but with vertical longitudinal walls, was investigated by Catalina et al. in 2017 [4] through a comparative review of experimental studies and regulations. In 2022, Ding et al. [5] examined wind loads on an arched canopy roof, considering both longitudinal and transverse wind directions based on wind tunnel experiments, including dynamic effects caused by wind fluctuations. The same authors extended this research in 2023 [6] by combining wind tunnel testing with CFD simulations. Arched-roof structures are also addressed in national and international design standards. For example, the European standard EN 1991-1-4:2005 [7] provides recommended pressure coefficients for such roofs with varying geometric ratios, but only for crosswind conditions. In contrast, the American ASCE standard [8] does not explicitly address arched roofs, instead referring users to “other approved standards, special studies using applicable recognized literature pertaining to wind effects, or using the Wind Tunnel Procedure...”.

From this overview, it can be concluded that wind action on arched-roof structures has become a topic of increasing interest in both engineering practice and academic research. However, a comprehensive and systematic database of wind pressure coefficients is still lacking. Existing studies differ in several aspects, including structural type (closed or open canopy), geometry (with or without vertical sidewalls), and dimensional ratios (width-to-length, width-to-height, rise-to-span). These differences result in varying wind pressure distributions. Balloon halls introduce an additional level of complexity due to the use of membrane materials, which possess negligible bending stiffness and low shear stiffness. As a result, their structural behavior under wind loading may differ significantly from that of conventional rigid roof systems, making them particularly sensitive and vulnerable.

The widespread use of arched-roof structures, especially balloon halls, highlights the need for reliable and detailed design guidelines, particularly regarding wind loading. Current standards do not sufficiently cover this aspect. In this context, CFD represents a promising and increasingly accessible alternative to costly and time-consuming wind tunnel experiments. Based on the presented background, the motivation of this research is to provide a modern approach to wind action analysis for structures commonly referred to as balloon halls. Additionally, the study aims to contribute to filling the existing gaps in standards by generating data that may support the development of more specific design recommendations for arched-roof structures.

2. MODELLING AND ANALYSIS

2.1. GENERAL CONSIDERATIONS

The methodology for wind action analysis is generally based on long-term investigations, which include experimental tests on scaled models in wind tunnels and the acquisition of measured data in situ. All these investigations ultimately aim to provide reliable input data for practical design projects. Verified data are eventually incorporated into regulations and standards. However, the wide diversity of design cases, regarding location, meteorological conditions, building geometry, façade treatment, and other factors, makes it very difficult to encompass every possible scenario through experimental testing alone. A viable solution to this limitation is the application of numerical methods, where an appropriate numerical model can be tailored to a specific structure.

In this research, Computational Fluid Dynamics (CFD) was applied using the software package ANSYS Workbench CFX [9], which is based on the Method of finite volumes (MFV). This methodology requires defining a computational domain representing the flowing fluid, in this case, air. The CFD model developed in this study consists of one main domain and one subdomain. The dimensions of both were selected according to established recommendations [10], [11], [12], [13] and the overall dimensions of the analyzed structure, i.e., a typical school gym (Figure 1a). The accuracy of CFD analysis also depends on providing sufficient domain length downstream of the building to ensure the development of a stable airflow field. Based on these considerations, the following dimensions were adopted (Figure 1b): domain length Ld = 1108.8 m, domain width Bd = 550 m, domain height Hd = 60 m, subdomain length Lsd = 422.4 m, subdomain width Bsd = 231.5 m, and subdomain height Hsd = 30 m.

A hexahedral finite volume (FV) mesh was selected for both the domain and subdomain, as recommended in the literature, due to its lower truncation error and improved convergence characteristics [12], [13]. Within the subdomain, an equidistant mesh composed of elements of equal size was generated.

In addition to mesh and domain characteristics, several other parameters significantly influence the analysis process and results. Among them, the choice of turbulence model is particularly important, as turbulence is a common phenomenon in airflow around structures. Numerous turbulence models have been developed, but none is universally applicable to all problem types. In this study, the standard k-ε model was used, as it is one of the most widely applied models and is provided as a default option in the selected software [9]. Developed by Launder and Spalding in 1972 [14], the standard k-ε model is valued for its stability and computational efficiency, making it suitable for both research and engineering applications.

The wind velocity, as a key input parameter, was set to v = 20 m/s, corresponding to typical regulatory values for most locations in Serbia. Although wind velocity generally varies with height above ground and is often represented by an Atmospheric Boundary Layer (ABL) profile, a constant wind profile was adopted in this case due to the relatively low height of the structure (10 m).

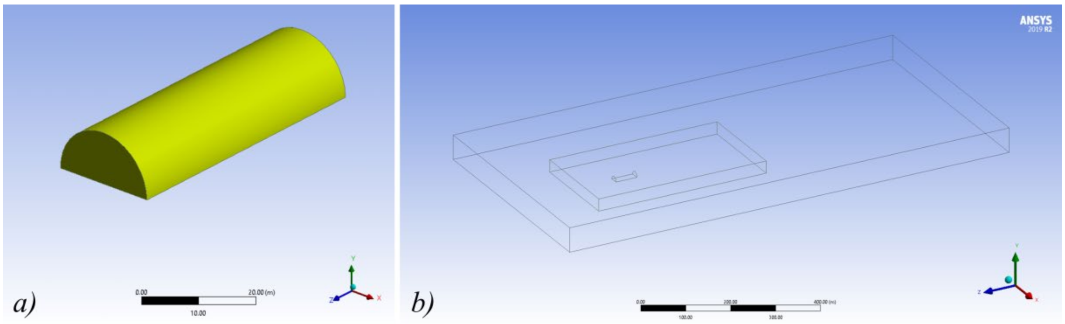

Figure 1. *a) Building shape and dimensions (l = 52.8 m, b = 20 m, h = f = 10 m; h/b = 0.5, l/b = 2.64); b) Geometry: domain, subdomain, and building (created by author).*

2.2. ALONG-WIND CASE

Wind direction at any location may vary, however, in design practice, two mutually perpendicular wind directions are typically considered. This approach was adopted in this study, analyzing both along-wind and crosswind cases.

To achieve an acceptable FV model, preliminary analyses were conducted with varying FV sizes (Table 1), following the recommendations of Ferziger and Perić [15]. In the along-wind case, the wind direction was defined as θ = 0°, meaning that the wind acts parallel to the longitudinal axis of the structure. A detail of the characteristic FV mesh is shown in Figure 2.

Table 1. Mesh FV size (wind direction θ = 0 °)

Mesh label	Domain FV size a_d [m]	Subdomain FV size a_{sd} [m]	Number of FV elements
CFX-011	5	2.5	614381
CFX-012	5	2	864573

CFX-013	5	1.5	1647058
CFX-014	5	1.15	2106159
CFX-015	5	0.9	2876307

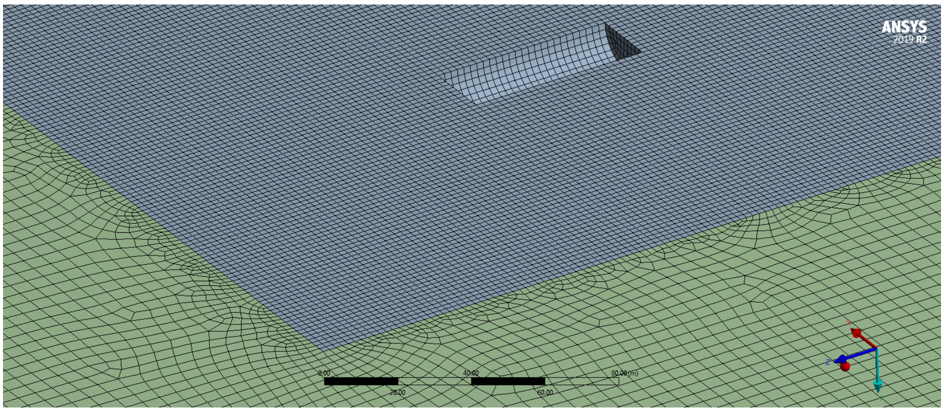

Figure 2. *FV mesh – detail (θ = 0°) (created by author).*

For this analysis, the pressure coefficient value *Cp*, commonly used in CFD studies, was selected as the representative output parameter (Figure 3).

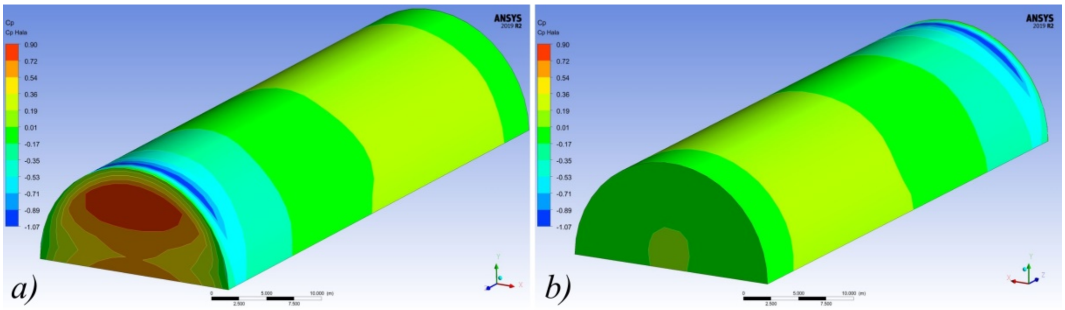

Figure 3. *Characteristic contours of the pressure coefficient Cp; a) windward wall and right side of the roof; b) leeward wall and left side of the roof (created by author).*

The contour plots indicate that *Cp* values vary significantly along the gable walls (over height) and along the roof (over length). The results also show a symmetric distribution across the structure with respect to the vertical longitudinal symmetry plane, which can be considered an indicator of the model's quality. Based on these observations, three characteristic monitoring lines were defined on the structure (Figure 4).

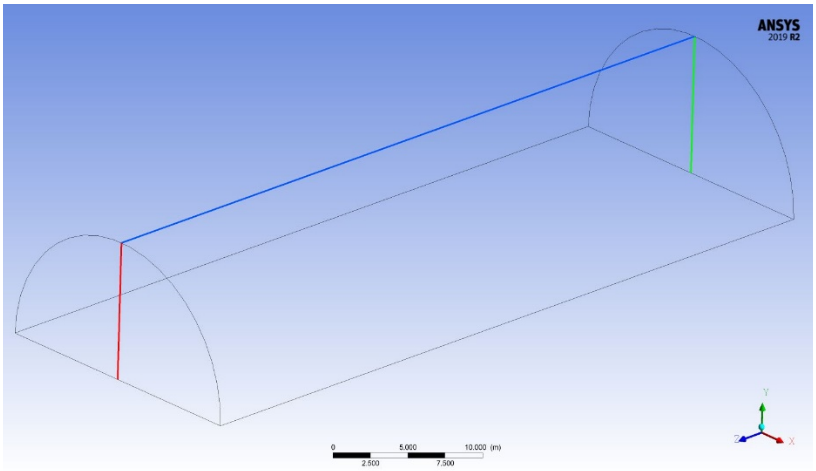

Figure 4. *Monitor lines: red - windward side, blue – roof, green – leeward side, wind direction: θ = 0° (–Z-direction) (created by author).*

The diagrams in Figure 5 present the distribution of *Cp* values along the windward monitoring line for three consecutive mesh densities. The distributions are similar for all analyzed meshes (Mesh 013, 014, 015), indicating stable numerical behavior. A deviation analysis between consecutive meshes shows that most deviations fall within ±5% (from −3.67% to 5.40%), which is considered acceptable [15]. Larger deviations, reaching up to 39.35%, occur near the top edge of the structure; however, such discrepancies are commonly observed in regions near geometric discontinuities and are typically excluded from detailed analysis.

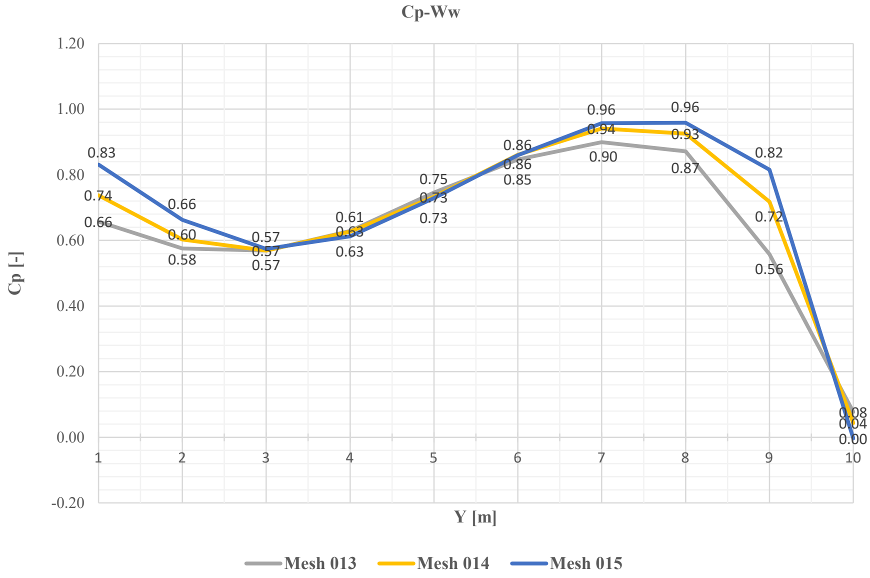

Figure 5. *Cp values on windward (Ww) monitor line (created by author).*

Figure 6 presents the *Cp* values along the roof monitoring line. Initial comparisons for coarser meshes (Mesh 011, 012, 013) revealed deviations exceeding acceptable limits. Therefore, further mesh refinement was performed (Mesh 014, 015), resulting in acceptable deviation levels and reliable results. Consequently, the finest meshes (013, 014, 015) were adopted for further analysis.

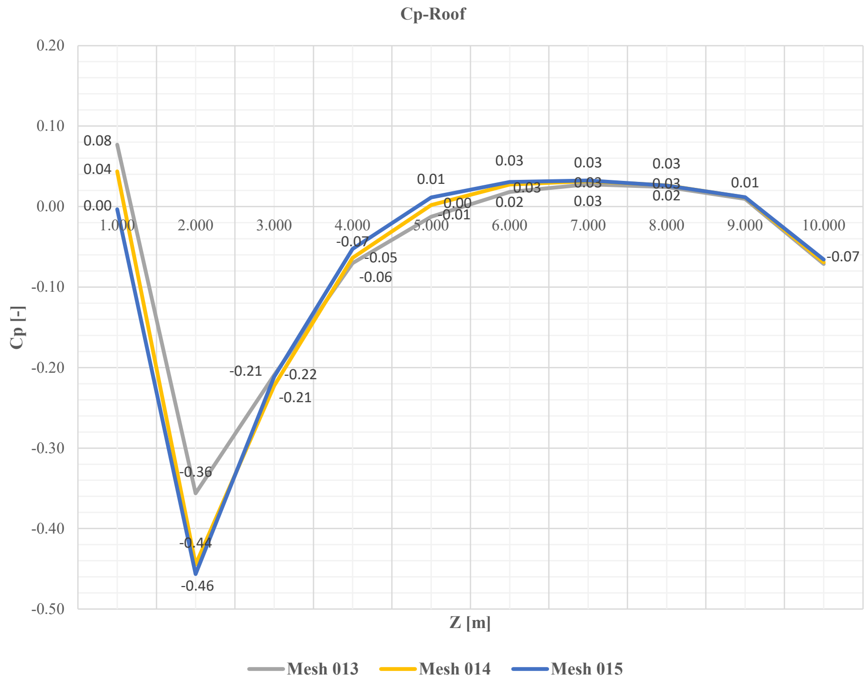

Figure 6. *Cp values on roof monitor line (created by author).*

The obtained distributions clearly illustrate the transition of wind action from positive pressure to suction and vice versa. However, it is noteworthy that many *Cp* values are very close to zero, indicating that the corresponding wind loads would be negligible in practical design.

Figure 7 shows the *Cp* values along the leeward monitoring line. The results demonstrate good agreement in the distribution patterns, with relatively small deviations. As in previous cases, larger discrepancies occur near the ends of the monitoring line. An isolated extreme deviation is observed near mid-height, corresponding to a region where *Cp* transitions between positive and negative values. In such zones, accurate numerical extraction of values is inherently challenging due to the proximity to zero.

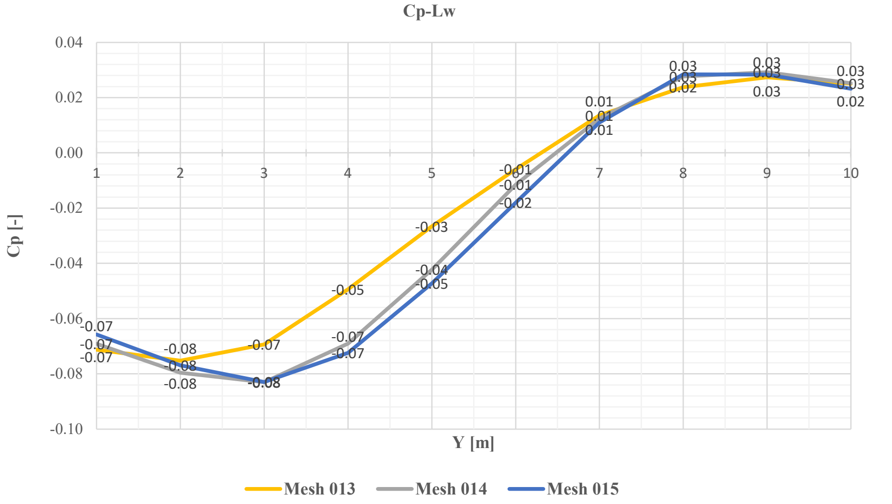

Figure 7. *Cp values on leeward (Lw) monitor line (created by author).*

2.3. CROSSWIND CASE

The crosswind case implied the wind direction that is perpendicular to the longitudinal axis of the building, that is, θ = 90°. Varying the FV size has been also done for this case (Table 2).

Figure 8 illustrates the wind velocity field along the vertical longitudinal symmetry plane using streamlines. A significant increase in velocity is observed above the structure, while a wake region forms downstream. These results are consistent with previously published studies [1], [16].

Figure 9 presents the contour distributions of the pressure coefficient C_p. The results show that $C_p$values are relatively uniform along the longitudinal direction. However, along the arch profile, the pressure distribution varies from positive pressure on the windward side, through strong suction near the crown, to moderate suction on the leeward side. This behavior aligns with expectations and is consistent with the pressure distributions provided in relevant standards [7]. A more detailed discussion of these results is provided in Section 4.

Table 2. Mesh FV size (wind direction θ = 90°)

Mesh	Domain FV size a_d [m]	Subdomain FV size a_{sd} [m]	Number of FV elements
021	5	3.25	608263
022	5	2.5	804890
023	5	2	1022445
024	5	1.5	1241044
025	3	1.15	1578975

Figure 8 illustrates the wind velocity field along the vertical longitudinal symmetry plane using streamlines. A significant increase in velocity is observed above the structure, while a wake region forms downstream. These results are consistent with previously published studies [1], [16].

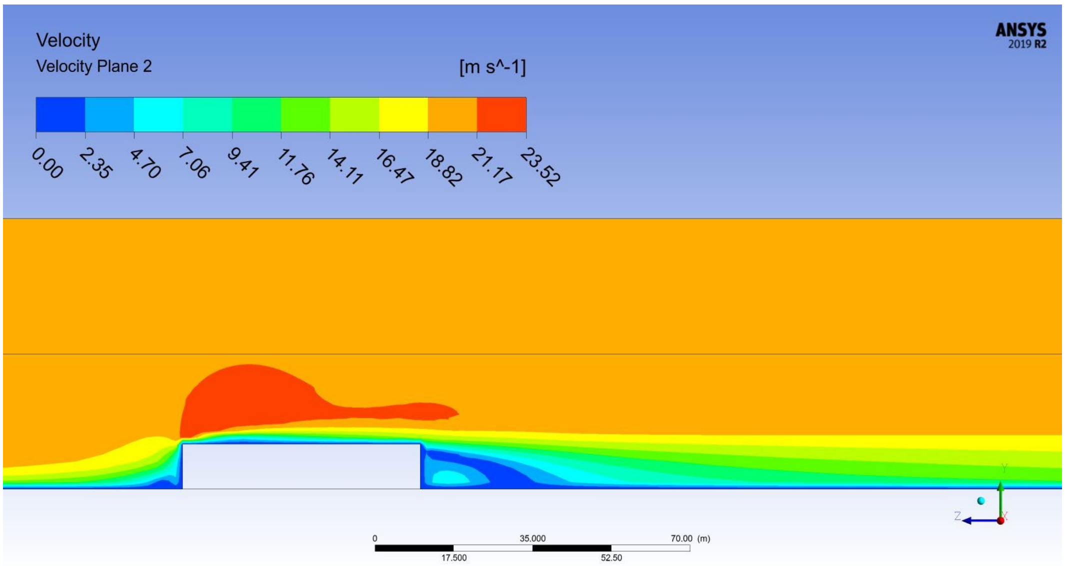

Figure 8. *Velocity field along the longitudinal vertical symmetry plane*

Figure 9 presents the contour distributions of the pressure coefficient *Cp*. The results show that *Cp* values are relatively uniform along the longitudinal direction. However, along the arch profile, the pressure distribution varies from positive pressure on the windward side, through strong suction near the crown, to moderate suction on the leeward side. This behavior aligns with expectations and is consistent with the pressure distributions provided in relevant standards [7]. A more detailed discussion of these results is provided in Section 4.

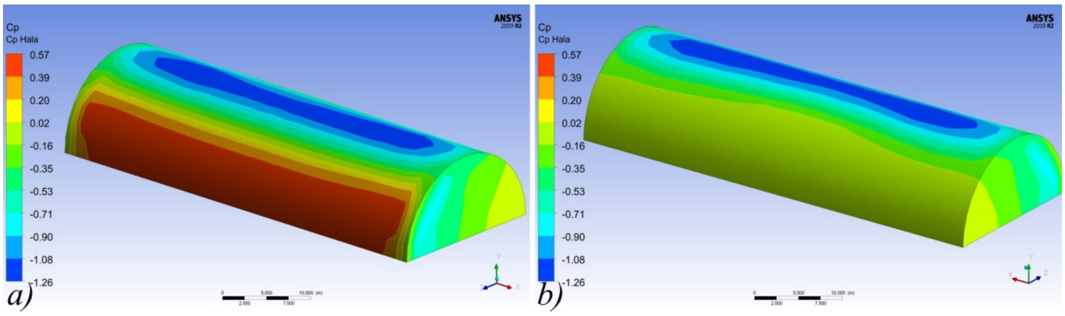

Figure 9. *Characteristic contours of the pressure coefficient Cp; a) roof (windward side) and right wall; b) roof (leeward side) and left wall (created by author).*

3. VALIDATION OF THE RESULTS

As previously noted, numerical methods provide approximate solutions, with varying margins of error. This is particularly true for CFD calculations, where the final output may exhibit noticeable sensitivity even to small variations in input data. For this reason, validation of results plays a crucial role in the application of CFD. Its importance is even greater when the objective of the research is to supplement or refine existing regulatory data.

Validation can be performed in several ways. The most direct, though technically and financially demanding, approach is through wind tunnel experiments. Field measurements on existing structures using pressure tap devices may also be employed. Finally, data from previously published research can serve as a valuable reference for comparison.

As noted earlier, published data on pressure coefficient distributions for the specific building geometry considered in this study are limited. Moreover, available studies often differ in terms of wind direction, presence or absence of walls, geometric proportions, and other relevant parameters, which complicates direct comparison.

Tables 3 and 4 present comparative results for the pressure coefficients (*Cp*) obtained in this research and those available from external studies and standards that most closely match the analyzed building and boundary conditions. For the along-wind case, *Cp* values are not provided in some of the most widely used standards [7], [8], while for the crosswind case, only standard [7] includes relevant data. This clearly indicates the need for expanding and refining the existing *Cp* database. The results obtained in this study are therefore proposed as a contribution toward that goal.

Table 3. Comparative results for Cp – along-wind case

Research / Method	**Ww (max)**	**Lw (max)**	**Arch-crown l=L/25**	**Arch-crown l=L/4**	**Arch-crown l=L/2**	**Arch-crown l=3L/4**	**Arch-crown l=9L/10**
Authors / CFD	≈ 0.90	-0.10	≈ -1.1	≈ -0.2	≈ -0.1	≈ -0.1	≈ -0.1
Holmes-Paterson [3] / CFD	0.5	-0.3	-1.6	-0.4	-0.3	-0.3	-0.3
Maraveas [14] / Standard	0.70	-0.30	-1.4	-0.37	-0.22	-0.2	-0.2
EN 1991-1-4 [7] / Standard	N/A	N/A	N/A	N/A	N/A	N/A	N/A
ASCE/SEI 7-16 16 [8] / Standard	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 4. Comparative results for Cp – crosswind case

Research Method	**φ=0-55º**	**φ=55-115º**	**φ=115-180º**
Authors / CFD	+0.55	-1.25	-0.30
Holmes-Paterson [3] / CFD	+0.50	-0.80	-0.20
Maraveas [17] / Standard	0.30	-1.20	-0.40
Mathews and Meyer [18] Soriano [19]	+0.3	-1.30	-
EN 1991-1-4 [7] / Standard	+0.80	-1.20	-0.40
ASCE/SEI 7-16 [8] / Standard	N/A	N/A	N/A

φ = central angle of the roof arch, starting from the bottom of the windward side [14]

4. DISCUSSION OF THE RESULTS

The analyzed arched roof structure was investigated under two characteristic wind directions: along-wind and crosswind. The pressure coefficient *Cp* was selected as the primary output parameter, as it is the most representative indicator of wind action on building surfaces. This coefficient is strongly influenced by the geometry of the structure, and arched roof forms differ significantly from conventional prismatic buildings, which are more commonly studied in CFD-based wind analyses.

The results are presented in two formats: contour plots and diagrams. Contour plots provide a spatial representation of the pressure coefficient distribution across the surface of the structure. They offer valuable insight into critical regions such as edges, the arch crown, and transition zones where *Cp* values shift from positive pressure to suction.

The use of diagrams requires the definition of specific linear paths, referred to as monitor lines, along which the variation of *Cp* is evaluated. The selection of these lines depends on the geometry of the structure and the wind direction. In the along-wind case, the monitor line was defined along the symmetry axis, covering both gable walls and the crown of the arch (Figure 5). This configuration aligns with the wind direction and captures the most significant pressure variations (Figures 6, 7, and 8).

For the crosswind case, a different approach was necessary. Here, the most pronounced variation in pressure coefficients occurs along the arch profile itself. Therefore, the comparison of *Cp* values (Table 4) was based on characteristic arch zones defined in [17], which provide the closest available reference for this type of structure.

As shown in Section 3, the obtained results demonstrate good agreement with available data from the literature. However, a complete comparison is not possible due to differences in geometry, boundary conditions, and analysis setups among the considered studies. This further confirms the need for additional research in this field, ideally under standardized and comparable conditions.

An important advantage of CFD analysis is the ability to generate detailed contour fields, offering a more refined representation of pressure distribution compared to design standards. In contrast, standards typically provide simplified distributions with abrupt transitions between predefined zones on roofs and walls.

The conducted investigation yielded meaningful results, validated against available external sources [3,17, 18,19]. To the best of the authors' knowledge, no additional data closely matching the present case were found. It should be noted that even small variations in geometry or proportions of seemingly similar structures can lead to significant differences in CFD results.

5. CONCLUSIONS

The motivation for this research stems from two key considerations: the lack of sufficiently reliable data for accurate wind action analysis of arched roof structures, and the potential of advanced computational methods in the field of building aerodynamics. The CFD analysis presented in this paper, although limited to a single case study, provides a foundation for more comprehensive investigations that should include additional influential parameters, such as alternative turbulence models, variable wind profiles, and multiple wind directions.

As with all numerical approaches, CFD results are inherently approximate. This study aims to improve the reliability of such analyses and to contribute to reducing uncertainty. Furthermore, it highlights the lack of detailed regulatory data for pressure coefficients applicable to arched roof structures. Existing standards, such as [7], provide only generalized values and do not cover all relevant loading cases, particularly the along-wind scenario. Other standards, such as [8], do not explicitly address this class of structures and instead refer designers to specialized studies or experimental methods.

The results indicate that the selected CFD model provides satisfactory performance. The adopted domain dimensions, subdomain configuration, and mesh density offer a solid basis for analyzing wind effects on arched roof structures.

It should also be emphasized that this research specifically addresses so-called “balloon halls,” which are widely used in the Balkan region. Future studies should extend the analysis to include additional parameters, particularly varying wind incidence angles, since directions between the principal cases ($\theta = 0^o$ and $\theta = 90^o$) may prove critical for certain structural configurations.

ACKNOWLEDGEMENTS

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