Numerical simulation of wind effects on the Church of Saint Francis of Assisi by Oscar Niemeyer

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Abstract. Numerical simulations are viable and reliable alternatives in the study of wind action in buildings. Using the *Ansys* Workbench software were estimated the effects of wind action on the Church of Saint Francis of Assisi, in Belo Horizonte, designed by Oscar Niemeyer, constituted of parabolic and circumferential generatrices. For validation, were determined the pressure coefficients considering monolithic domes according to Brazilian Standard ABNT NBR 6123. The wind effects on the Church of Saint Francis of Assisi by Oscar Niemeyer were simulated and, in a particular case, disregarding the slope. Here, were presented the visualization of the flow around the geometry from the streamlines and the analysis of external pressure coefficient isobaric lines.

Keywords: wind action, pressure coefficients, *Ansys,* Oscar Niemeyer.

1 Introduction

An area with a great range of applications and many open questions is the research on wind action in structures in Wind Engineering. Methods for the wind pressure distribution on buildings are experimental and numerical tools for predicting wind loading on buildings and cladding, air infiltration rates, and volumetric airflow rates through large openings.

In particular, were studied the wind effects in the buildings Oscar Niemeyer (1907-2012). For example, Soares, Azevedo, and Melo [1] analyzed the effects of wind action on the digital TV Tower nicknamed "Cerrado Flower" which opened in 2012, the last architectural project by Niemeyer in Brasília. The tower is 182 meters tall, of which 120 meters of reinforced concrete structure, more than 62 meters of steel structure, and has two glass domes. Based on the basic wind speed of the region, drag coefficients, dynamic pressure, and contact area, they concluded that the worst loading on the tower foundation was with a wind perpendicular to the support rod of domes with an incidence of 90°. Santos and Campos [2] analyzed the feasibility of *Ansys* software for calculating pressure coefficients in the Our Lady of Fatima Church by Niemeyer, the first masonry church in Brasília inaugurated in 1958. The authors noticed that the determined coefficients have physical coherence consistent with the structure under study. In this work, the effects of wind action on the Church of Saint Francis of Assisi, in Belo Horizonte, were estimated using the *Ansys Workbench* software.

2 Methodology

For geometry modeling, was used *Autodesk AutoCAD* software according to the dimensions proposed by Macedo [3]. The models were placed inside the domain according as stated by Franke *et al.* [4]. The boundaries are 5H from the inlet and both sidewalls, 6H from the base of model, and 15H behind the building to allow the flow development (Fig. 1). Here, H=9.16m is the maximum height of the building and boundary conditions and the non-dimensional parameters according to Table 1. For the representation of the slope, measurements provided by the *Google Earth Pro* software and a body of influence for local refining were used, having the length of the downstream region and half of this length upstream and also twice this dimension for the width and the height. For numerical simulations, were adopted the Fluid Flow (CFX) of the *Ansys Workbench* software and the *RNG K-Epsilon* turbulence model.

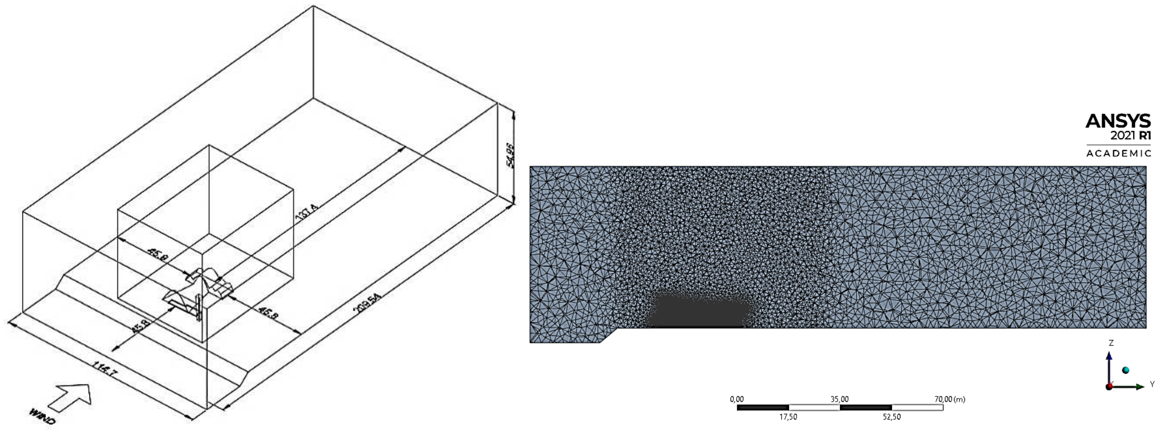


Figure 1. (a) Geometry and control volume and (b) geometry mesh and control volume used.

Table 1. Boundary conditions and non-dimensional parameters.

Condition	*Parameters*
Method of mesh	Tetrahedron
Reference pressure	101325 [Pa]
Air temperature	25 [°C]
Turbulence intensity	Medium (5%)
Flow regime	Subsonic
Inlet	40 [m/s] (*Application 1*)
	30 [m/s] (*Applications 2 and 3*)
Relative pressure of outlet	0 [Pa]
Wall - Lake	Free slip
Wall - Slope	Rough wall
Wall - Ground	Rough wall
Model wall roughness	Smooth wall
Roughness	0.0002 [m] (*Application 1*)
	0.01 [m] (*Applications 2 and 3*)

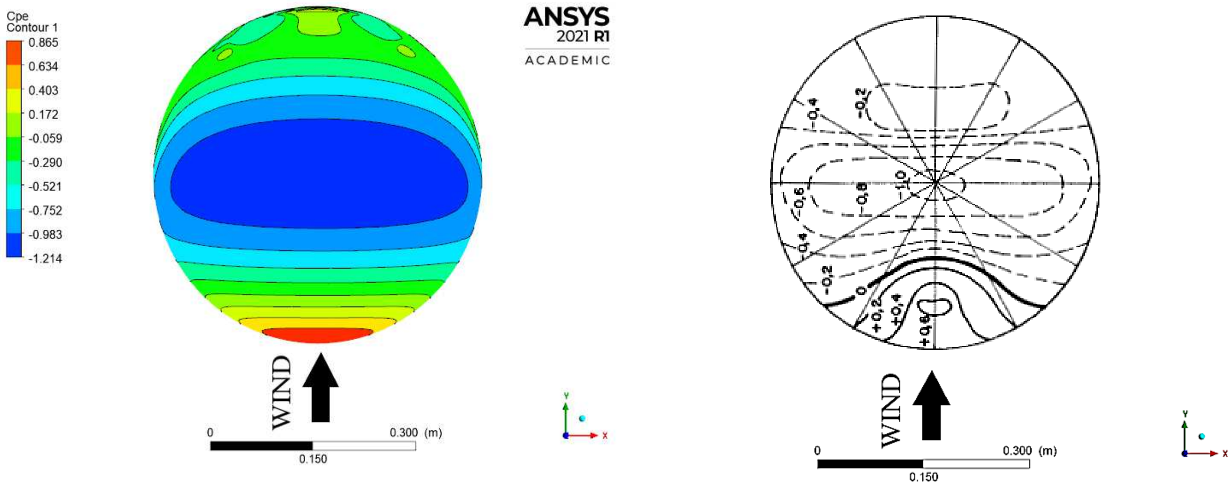
3 Numerical applications

Here, the pressure coefficients were determined considering monolithic domes according to NBR 6123 for the methodology validation. In another case, were calculate the pressure coefficients to the Church of Saint Francis of Assisi by Oscar Niemeyer. In this particular case, the slope was disregarding.

Application 1 (*Monolithic domes*): The monolithic domes are structures built entirely in the dome form whose basic geometric parameters are the diameter and the rise, denoted by d and f, respectively. Here, the monolithic domes present in ABNT NBR 6123:1988 [5] with the f/d=1/2 were adopted. The mesh, formed by tetrahedrons of 0.06 m in the fluid domain, 0.025 m in the body of influence, and 0.005 m in the dome face, resulted in 1876714 elements and 332008 nodes. Here, were adopted a pressure of 101325 Pa, the roughness of 0.0002 m on the ground, and a basic wind speed of 40 m/s for the boundary conditions. For the analysis, was embraced the *RNG K-Epsilon* turbulence model.

The dome wall was defined smooth. In three applications, for comparison were calculated the local pressure coefficients, defined by $Cpe=\Delta p/q$ where Cpe is the external pressure coefficient; Δp is the difference in external pressure coefficient, and q is the dynamic pressure.

In Figure 2, can be seen an agreement between the isobaric lines [5] and the generated by *Ansys* in this work.



(a) Present work

(b) NBR 6123:1988.

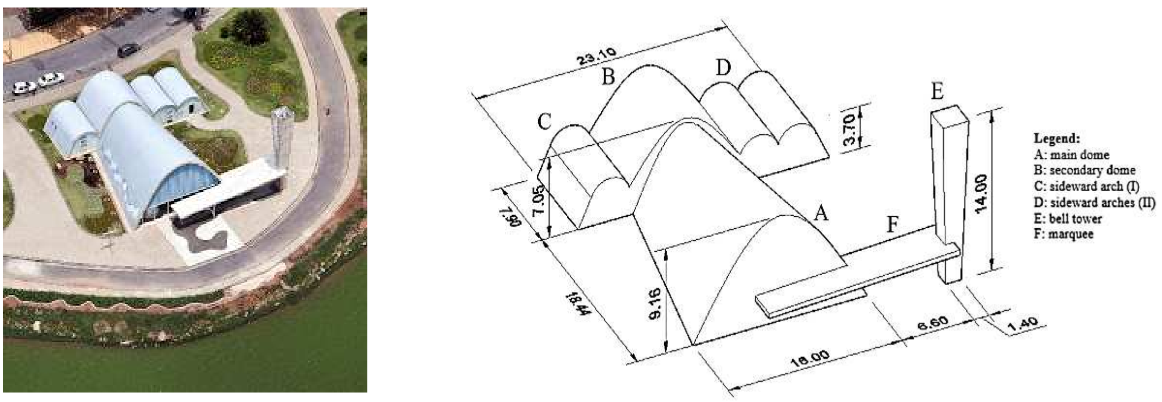
Figure 2. Top view of (a) external pressure coefficients via numerical analysis, and (b) isobaric lines of external pressure coefficients for *f*/*d* = ½.

Table 2 shows results with the one decimal place precision. In the 1st boundary was seen the highest difference between the NBR 6123 [5] and the present work. In the 8th boundary, the values coincided.

Table 2. External pressure coefficients for the monolithic domes considering *f*/*d*=1/2.

Boundary	1st	2nd	3rd	4th	5th	6th	7th	8th	9th
NBR 6123 [5]	0.6	0.4	0.2	0.0	-0.2	-0.4	-0.6	-0.8	-1.0
Present work	0.9	0.6	0.4	0.2	0.1	-0.3	-0.5	-0.8	-1.2
Difference	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.0	0.2

Application 2 (*the Church of Saint Francis of Assisi*): Application 2 (the Church of Saint Francis of Assisi): In this application, was simulated the flow of the Church of Saint Francis of Assisi in Belo Horizonte. Inaugurated in 1943 and designed by Oscar Niemeyer, its structure is composed of reinforced concrete arches forming two parabolic domes. The use of the parabolic shape - perhaps inspired by the airship hangers by Eugène Freyssinet architect, at Orly, near Paris, and dialogizing with the mountains of Minas Gerais and Rio de Janeiro (Underwood [6]) - allowed a single element to form the canopy and the walls, without resorting to independent structures. The bell tower and the marquee at the entrance (Fig. 3a) appear as structures independents.

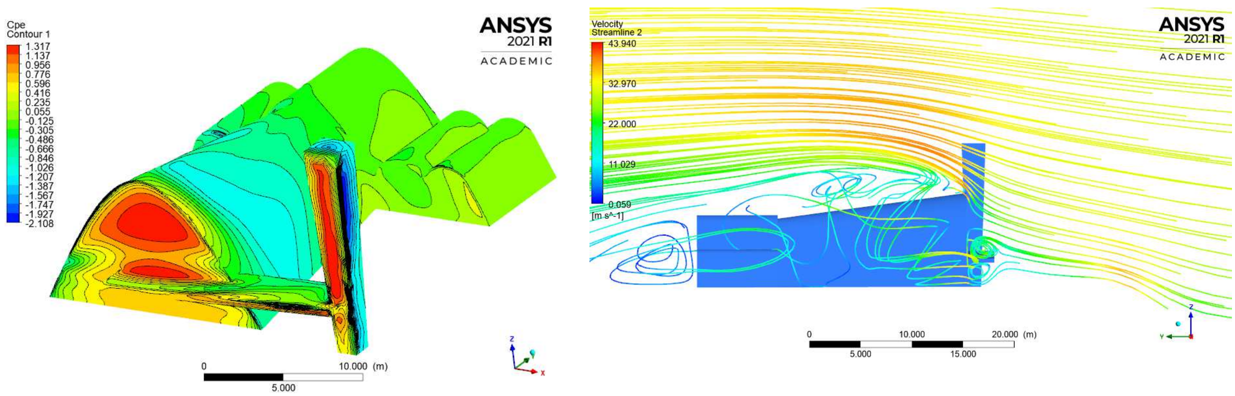


(a) (b)

Figure 3. (a) Aerial view of the São Francisco de Assis church, (b) dimensions and architectural elements

For the numerical simulation, a basic wind speed of 30 m/s, according to Vallis [7], was adopted. The mesh used was composed of tetrahedrons, with dimensions of 3.5 m in the fluid domain, 1.7 m in the body of influence, and 0.15 m in the faces of the building resulted in 1.826.728 elements and 331.175 nodes. In the entrance face (A in Fig. 3b), the wind was considered orthogonal and accelerated when passing over the slope and reaching the building. Vortices formed on the marquee (F in Fig. 3b) created a suction region. Figure 4a shows the distribution of pressure coefficients along the outer surface of the structure. The color hue represents the pressures acting on the surfaces corresponding to the ranges of the pressure coefficients: warm colors represent overpressures, while cold colors represent suctions. Figure 4b shows the behavior of streamlines in the YZ-plane. Similar to the distribution of pressure coefficients, warm colors represent higher velocities, and cold colors represent lower velocities.

The highest suction peak occurred (Cpe_{max}=1.317) (Fig. 4a) in the main dome incident face (A in Fig. 3b), made with glass and brise soleil, and the detachment point occurred at the intersection of the main dome inlet face with the parabolic shell of the main dome (Fig. 3b). Therein occurred a suction zone in structure A (Fig 4a) generated by the acceleration of the fluid. Note in the dome secondary (B in Fig. 3b), low values for *Cpe* and, downstream of the building, a recirculation zone with low wind speeds, thus generating negative pressure coefficients in the last wall orthogonal to the flow (Fig .4b).



(a) (b)

Figure 4: (a) Distribution of pressure coefficients in the building and (b) streamlines in the YZ-plane.

Application 3 ***(disregarding the slope of the Church of Saint Francis of Assisi):*** This application analyzed the influence of the topography surrounding, disregarding the slope of the building was. The mesh used was composed of tetrahedrons, with dimensions of 3.5 m in the fluid domain, 1.7 m in the body of influence, and 0.15 m in the faces of the building resulted in 1881663 elements and 342552 nodes. Here, were considered the boundary conditions described in Table 1. And, was disregarded the slope whose length, in projection, was 6.00 m and height of 5.00 m. The wind reached the main face of the main dome (A in Fig. 3b), causing an intense positive pressure near the marquee. The flow separation occurred at the intersection of the windward face with the main dome cover shell (A in Fig. 3b) due to the reduction in cross-section (Fig. 5b). At the top of the building occurred the detachment point and a reduced pressure region (*Cpe*= -1.656), characterizing suction, more intense than that observed in Application 2 (*Cpe*= -1.207) (Fig. 5a). The regions of the secondary dome (B in Fig. 3b) and sideward arches (C, D in Fig. 3b) did not present positive pressure coefficients. Downstream of the building, a recirculation zone can be observed.

Table 3 presents a comparison of fluid velocity and pressure coefficients with Application 2. The highest difference between the external pressure coefficients for the edification considering and disregarding the slope occurred in Cpe_{min} in the shell. Also, observed minor differences in the maximum and minimum velocities in the fluid domain.

Table 3. Comparison of fluid velocity and pressure coefficients with Application 2.

	Main dome (A) face	Main dome (A) shell	Fluid domain	
	Cpe_{max}	Cpe_{mix}	V_{max} [m/s]	V_{min} [m/s]
Edification considering the slope	1.317	-1.207	43.940	0.028
Edification disregarding the slope	1.082	-1.656	44.737	0.059
Difference	0.235	0.449	0.797	0.031

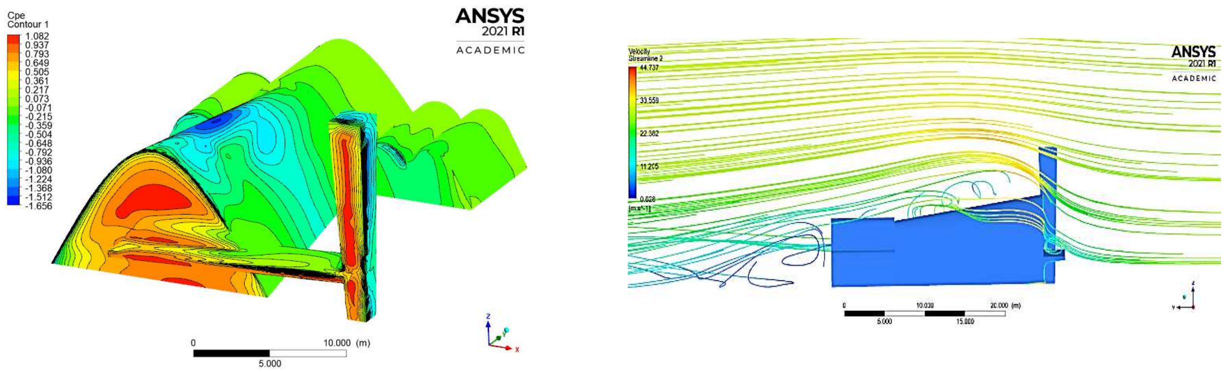


Figure 5: (a) Distribution of pressure coefficients in the building and (b) the streamlines in the building.

4. Conclusions

The effects of wind action on the Church of Saint Francis of Assisi were estimated using the Ansys Workbench software.

Considering monolithic domes were determined the pressure coefficients according to NBR 6123 for validation of the methodology. In the 1st boundary was seen the highest difference between the NBR 6123 and the present work. In the 8th boundary, the values coincided.

In another case, were calculate the pressure coefficients to the Church of Saint Francis of Assisi by Oscar Niemeyer. The highest suction peak occurred in the main dome incident face. At the intersection of the main dome inlet face with the parabolic shell of the main dome was located the detachment point. In the dome secondary, low values for Cpe and, downstream of the building, a recirculation zone with low wind speeds, thus generating negative pressure coefficients in the last wall orthogonal to the flow. The influence of the topography surrounding the building was too analyzed. In this case, the slope was disregarding. The wind incident in the main dome caused an intense positive pressure near the marquee. The regions of the secondary dome and sideward arches did not present positive pressure coefficients. Downstream of the building, a recirculation zone can be observed. The fluid velocity and the pressure coefficients compared with the previous case showed the highest difference between the external pressure coefficients, considering and disregarding the slope that occurred in Cpemin in the shell. Also, observed minor differences in the maximum and minimum velocities in the fluid domain.

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