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# DESIGN AND INSTALLATION OF A LARGE PNEUMATIC DOME IN BRAZIL

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**Key words:** Pneumatic Dome; Membrane Structure; Design and Installation; Construction details.

**Summary.** This paper presents the design and production of a set pneumatic domes recently installed in the south of Brazil, intended for theater performances and 3D cinema projections, during the 2022 Christmas and 2023 New Year celebrations. The domes are constituted of single layer polyester-PVC envelops, with the larger unit reinforced by a set of 40 steel cables arranged radially, converging to a cable ring at the top of the dome and anchored to a perimetral base ring made of reinforce concrete. Since the main dome was intended for high-resolution cinema projections, the creases of the membrane surface should be as small as possible, and the reinforcements cables were installed with low prestress forces. However, the location is susceptible to intense wind gusts, requiting that the domes to be designed for a normal operation wind speed of 70km/h and an ultimate wind speed of 130km/h.

## 1 INTRODUCTION

Pneumatic structures are paradigms of tension structures, since only in them it is possible to have all structural elements working exclusively in tension. Practical applications of pneumatic structures started at the beginnings of the 20th century, to become rather customary nowadays, in many distinct areas, as large stadia roofs, building façades, or everyday furniture, like sofas, boats and toys. The use of large, insufflated pneumatics for permanent applications has been largely superseded by other light structural systems in the last decades, but a few large pneumatic structures are still proposed for special applications[1].

This paper presents the design and installation of a set of pneumatic domes recently produced in the south of Brazil, intended for theatre performances and cinema projections, during the 2022 Christmas and New Year celebrations. Conceived by entrepreneur Edson Erdmann, designed by Arch. Carlos Bauer and produced by ArtFlex Coberturas, with a diameter of 60m and a height 30m, the main dome is one on the largest pneumatic structures built so far for entertainment applications.

The city of Canela is a favorite touristic spot in the south of Brazil, and the exhibitions under de domes, which have a capacity of about 2000 spectators, attracted large audiences during the Christmas/New Year's season.

## 2 DOME DESIGN AND CHARACTERISTICS

The theatre complex in composed by a set of three pneumatic domes, all constituted of single layer, 0.63mm thick polyester-PVC envelops. The larger unit, hosting the theatre hall, is hemispheric, with a diameter D=60m and a height H=30m. A semi-toroidal dome (D=15m, L=115m), hosts a foyer sector. A smaller hemispheric dome (D=25m) hosts the ticket office and entrance gates. The main dome is reinforced by a set of 40 steel cables arranged radially, converging to a cable ring at the top of the dome and anchored to a perimetral base ring made of reinforce concrete. Since the main dome was intended for high-resolution 3D cinema projections, the creases of the membrane surface should be as small as possible, and the reinforcements cables were installed with low prestress forces. Nonetheless, the location is susceptible to intense wind gusts, requiring that the domes were designed for a normal operation wind speed of 70km/h and an ultimate wind speed of 130km/h. Figure 1 displays the general lay out of the domes and their facilities. Figure 2 displays the original architectonic rendering. Figures 3 and 4 show the installed dome and its surroundings. Figure 5 shows some stages of the domes assembling and inflation process.

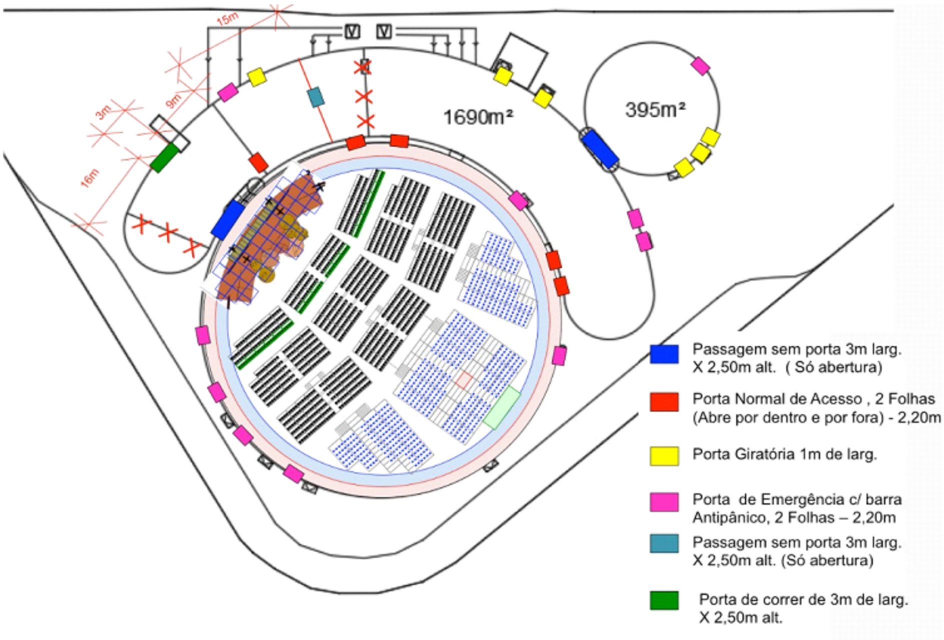

Figure 1: General lay-out of Canela’s Megadome, Brazil (2022).

The pressure system is composed of 8 axial fans with 5hp of power each. The two smaller domes were inflated in one hour, and the main dome in two hours, using the full power of the eight fans. One electric generator of 150kVA was used to feed the fans during assembling. A series of other generators, designed for the operation of the complex, can be used if back-up is required, but in idle times, the fans are fed directly from the public electrical grid.

The complex is equipped with six revolving doors for access of the public, tree air-lock gates for people using wheelchairs, nine double-wings emergency doors with anti-panic bars, three internal double-sized doors for circulation between the domes, and one sliding door for materials and services. In normal operational conditions, during the times of maximum public circulation through all access doors, 5 to 6 fans are required to withstand the internal pressure.

The dimensions of the Megadome place it among the largest pneumatic domes in the world, and while there are domes with larger diameters, those that reach its height and aspect ratio are rare. It is common for large spherical domes to be reinforced by cables, with the most frequent option being a radial arrangement, although in some cases, cross-cable arrangements are also used. The option of pneumatic envelopes without reinforcement cables is less frequent, limited to domes with smaller diameters, such as Canela's foyer and ticket office domes.

**Table 1:** Engineering information of spherical inflatable membrane structures. Adapted from Cheng et al.[2]

| Engineering Project | Span L (m) | Rise H (m) | Rise/Span H/L | Cable configuration |
|---|---|---|---|---|
| Canela's Megadome | 60 | 30 | 0.5 | Radial cable |
| Nalati Horse Dance Performance Hall | 80 | 30 | 0.38 | Radial cable |
| SOCT Children's Paradise | 54 | 15 | 0.38 | Cross cable |
| Jinxiu Water Sports Carnival | 100 | 25 | 0.35 | Radial cable |
| Yanjing Shenmuyuan Water Park | 110 | 35 | 0.32 | Cross cable |
| Jiaozhou Sports Center | 108 | 33 | 0.31 | Radial cable |
| Junmei Gymnasium | 90 | 23 | 0.25 | Cross cable |
| Zibo Intl. Convention and Exhibition Center | 98 | 35 | 0.36 | Cross cable |
| Xiangshawan Desert Art Museum | 100 | 30 | 0.30 | Radial cable |
| Large granary, Liaoning | 40 | 20 | 0.50 | Without cable |
| Zhongwei Starry Sky Theater | 60 | 25 | 0.42 | Radial cable |
| Inflated Airform for Pabco Gypsum, Las Vegas | 65 | 23.5 | 0.36 | Without cable |
| The Double Membrane cover, Exeter, Maine | 44 | 11 | 0.25 | Without cable |

Figure 2: Architectural rendering of Canela's Megadome, Brazil (2022)

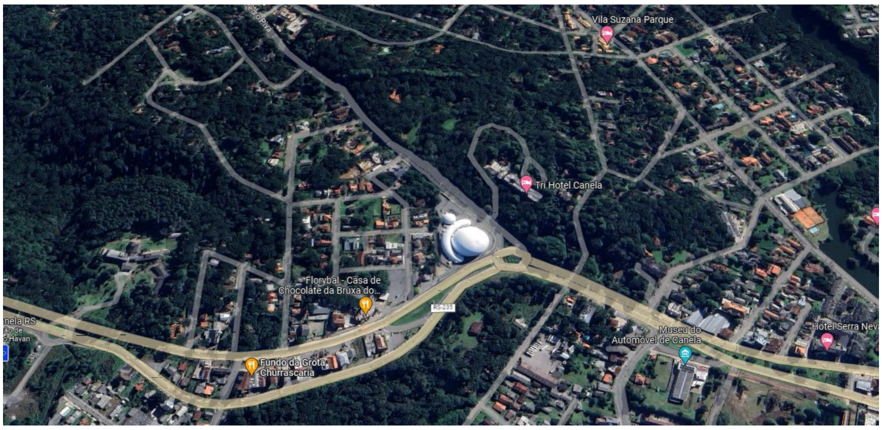

Figure 3: The Canela's Megadome and its surroundings

Figure 4: The Canela's Megadome, Brazil (2022)

Figure 5: Canela’s Dome Assembling and Inflation (2022)

## 3 NONLINEAR ANALYSES OF PNEUMATIC STRUCTURES

In previous papers[3,4,5], we presented a simple formwork to the analysis of pneumatic structures, of easy implementation and yet able to cope with a broad range of civil and architectural applications, which usually employ (almost) impermeable fabrics or films. Typical materials present nonlinear, anisotropic, and hysteretic behaviors, very much dependent on the fabric internal structure and load history. However, the orientation of orthotropy directions in double curvatures surfaces is not a trivial matter, not least because fabric patterning usually aims to minimizing waste, a conflicting objective with optimizing the yarns lay-out. Consequently, industry strives to provide the market with fabrics the more isotropic and linear elastic as possible, and so follow design and analysis software. Furthermore, wind loads might induce wrinkling on the pneumatic envelope, and practical strategies to cope with wrinkling supersede concerns about other types of nonlinear material behavior.

The Newton-Raphson Method (NRM) usually yields the best algorithm for the solution of non-linear static equilibrium of cable and membrane structures, since it then presents quadratic convergence rate, in a sufficiently narrow vicinity of the solution. However, cables and membranes have no bending stiffness and in the absence of a proper tension field, the structure’s tangent stiffness matrix may become non-positive definite, frequently leading to divergence of the method. This is usually the case of large, insufflated domes under high wind loads, where wrinkling areas may appear on the envelope. In these cases, NRM must be supplemented with additional stabilization or continuation methods such as penalty or arclength methods.

In many cases, the Dynamic Relaxation Method (DRM) offers a convenient alternative, to NRM, replacing the equilibrium problem by a pseudo-dynamic analysis, where fictitious mass and damping matrices are arbitrarily chosen to control the stability of the time integration process. The definition of an arbitrary damping matrix may be circumvented by the process of *kinetic damping*, whereby the undamped movement of the system is followed until a maximum of the total kinetic energy is reached, whence all the velocity components are cancelled, and the analysis is restarted, until new kinetic energy maxima (usually smaller than the precedent ones) are found, and all velocities are zeroed again. Although DRM shows no advantage for small to medium sized problems, whenever NRM shows good convergence, there might be economy for large problems.

Both methods have been implemented into a coherent computational framework named SATS – A System for the Analysis of Taut Structures, which has been applied to several problems involving the shape finding and analysis of cable and membrane structure. Details can be found in previous references[3,4,5].

## 4 STRUCTURAL ANALYSIS OF CANELA’S MEGADOME

The main concern regarding the structural performance of the Canela’s Megadome were the high wind loads that may occur in the region. Although the dome was designed to remain on-site only from mid-December 2022 to the end of January 2023, after the high wind season (basically September to October), the dome was designed to withstand the site highest wind speeds, but with a reduction factor, allowed by the definition of different operational conditions.

Only the main dome (D=60m, H=30m) was analyzed. The inside pressure was guaranteed by a set of fans with enough redundancy and capacity to vary the internal pressure for different operational scenarios. The pneumatic envelope is constituted by a single layer of PVC-polyester fabric, 0.64mm thick, reinforced with 40 meridian steel cables anchored to a perimeter concrete ring.

Although the response of pneumatic domes to wind actions is a dynamic phenomenon, the consideration of equivalent static analyses is reasonable for typical dimensions[2]. Moreover, we considered constant inside pressure, since in reference[3] we concluded that this hypothesis suffices for large, insufflated domes.

The meridian cables converge to a parallel upper cable ring, with a diameter of 5m. The spacing between the cables varies from 4.7m at the base of the dome to 0.40m at the top. Although a larger number of smaller diameter cables might be desirable to increase the rigidity of the dome and minimize the wrinkles of the membrane, they would also significantly increase the practical difficulties of detailing and assembling the structure. Recent research by Chen et al.[2] indicates that a cross-cable layout provide a higher stiffness to the structure, however they also introduce a more complex installation and significantly higher costs, corroborating the option for a more simple, radial layout for the Canela’s Megadome.

The internal surface of the Megadome was designed for cinematographic projections, and to avoid significant creases in the pneumatic envelope under normal operational conditions, the reinforcing cables should be installed with small initial loads, which should however suffice to prevent cable slippage, under normal operating conditions. Moreover, the inside pressure under normal operational conditions should not be too high, to avoid an excessively scalloped surface.

## 4.1 Wind loads

The location of Canela's city is indicated with a red rectangle in Figure 6, which shows the chart of basic wind speeds of Brazilian national standard NBR-6123. A basic wind velocity $v_0 = 45 m/s$ is adopted for Canela's region. According to NBR-6123, the characteristics design speed is given by $v_k = v_0 S_1 S_2 S_3$, where the topographic factor is taken as $S_1 = 1.0$ (at the foot of a hill), the terrain rugosity is taken as $S_2 = 1.0$ (suburbs with low, sparse edifications), and the statistic factor is taken as $S_3 = 0.83$ (temporary constructions). The characterization of the structure as temporary is alloed by the definition of different operational conditions, with public access restricted if daily wind forecasts predict local wind velocities $v > 30 m/s$ (=70km/h).

There results a characteristic velocity $v_k = 37 m/s$, and a characteristic dynamic wind pressure $q = 0{,}83 kPa$. This wind pressure is associate to the maximum design wind speed, and other load scenarios, with lower wind speeds but larger safety factors have also been considered.

The external pressure coefficients were assumed by considering an envelope of the coefficients provided by the NBR-6123 and reference[2], see Figure 7.

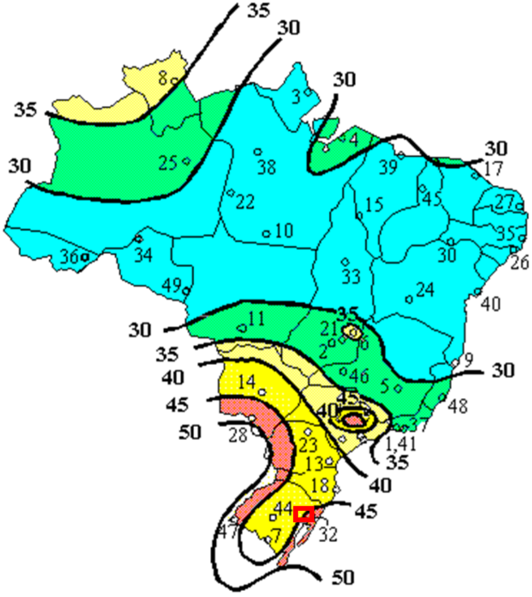

Figure 6: Wind velocities in Brazil, according to NBR-6123 standard; Canela's region is indicated by a red rectangle in the southernmost region.

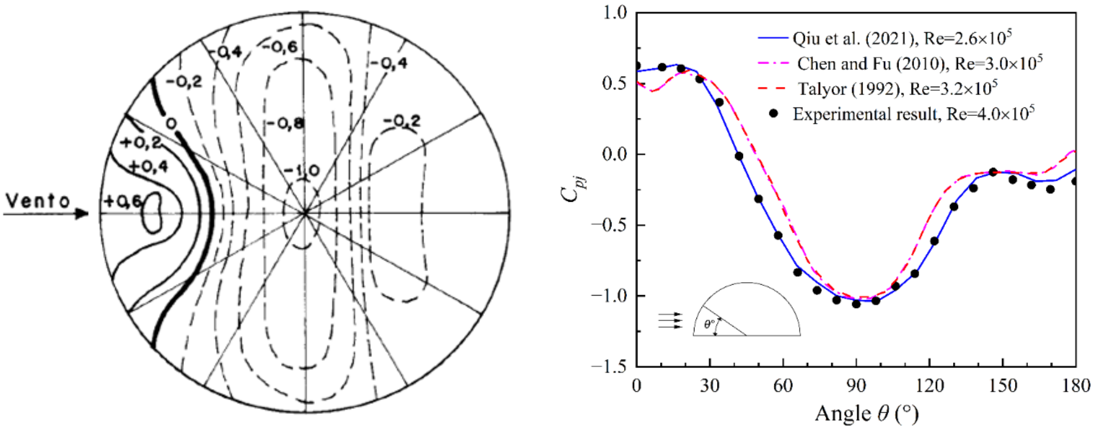

Figure 7: Wind pressure coefficients for a semispherical dome; (a) NBR-6123 standard; (b) Chen et al.[2].

## 4.2 Operational conditions

Different operational conditions assumed in the analyses, associated to daily wind forecasts. Instant reaction to wing gusts or sudden changes of weather is unfeasible, in the case of large pneumatics, therefore the operational conditions must be defined many hours ahead. Several conditions have been considered, including Testing, Installation, Maintenance, Normal Operation, Attention, Concern and Preservation, with different safety factors affecting each condition. The Concern condition corresponds to ‘Storms’ on the Beaufort Scale and, in anticipation of that forecast, the structure must be closed to the public, with access allowed only to the maintenance team. In the Preservation conditions, corresponding to ‘Violent Storms’, the inside pressure must be increased to $p_0$=0.4kPa, the structure must be sealed, and access allowed only to tackle with the envelope’s jeopardy. At Conservation conditions, the membrane will be under high stresses, and tear propagation cannot be precluded.

We remark that, in general, even moderate winds can generate projectiles such as fallen tree branches[9], which might puncture the pneumatic envelope, but with low probability of tearing the membrane, under normal operational conditions. The exposure to flying debris is of particular concern in the present case, since the Canela’s Megadome is surrounded by Araucaria woods, as can be seen in Figure 3. The Araucaria (Figure 8) is a genus of evergreen coniferous trees, a very ancient tree which evolved during the Jurassic and Cretaceous periods, now a protected but endangered species in Brazil. Living up to 500 years, fully grown araucarias are large trees with a massive straight stem, reaching heights over 50m and diameters over 2.5m. Younger specimens (up to 20-30 years old), have a conical pine-like treetop, but as the tree matures, the branches progressively spread horizontally, with leaves concentrated at their ends. The older branches finally break under their own weight or intense winds, giving the distinguishable shape of a champagne coupe glass to the mature trees. Branches detached by windstorms might become large flying debris, and the owner of a large pneumatics located in such a region must be aware of the intrinsic susceptibility of any large pneumatic structure to debris collision.

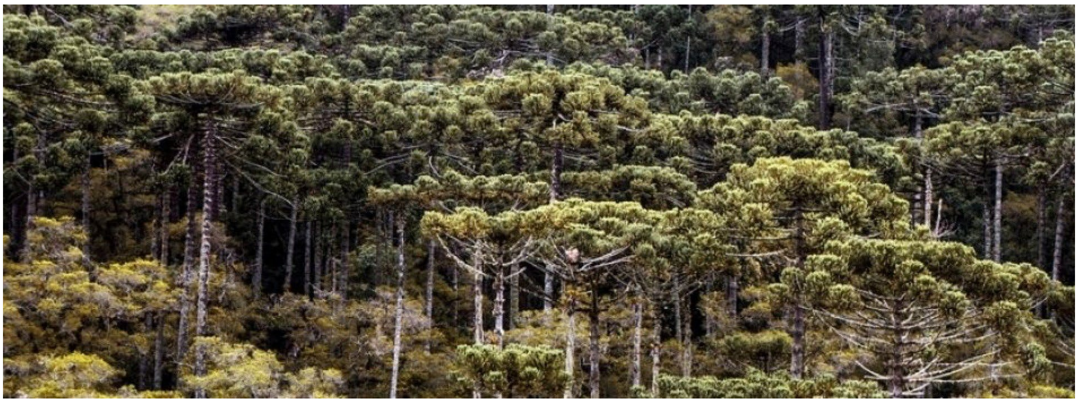

Figure 8: Typical araucaria woods

### 4.3 Results

The structural response of the Canela’s Megadome dome under several load conditions was analysed using nonlinear the nonlinear finite element models shown in Figure 9(a).

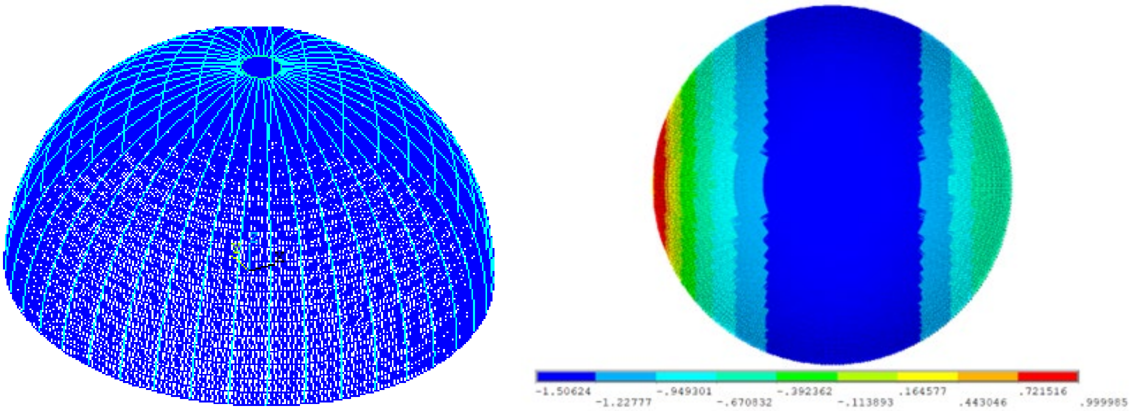

Figure 9: (a) finite element model of Canelas’s Megadome, reinforced with 40 streel cables. The base of the dome is supposed to be fully anchored; (b) distribution of the assumed external wind pressure coefficients.

For an intermediate wind speed of 100km/h, Figure 10 shows the overall spatial distribution of main quantities for Concern condition. Figures 10(a/b/c) show respectively the fields of the norm of the displacements and of maximum and minimum principal stresses on the membrane envelope. A maximum displacement $\|\mathbf{u}\| = 2.02\,m$ was observed at the windward side, and a maximum surface stress $S_1 = 18\,kN/m$ was observed at the top of the dome, with moderate wrinkling detected at the windward side. Figure 10(d) shows the normal loads action on the cables, with maximum loads with $N_{\max} = 88kN$ occurring at port and starboard sides and slackening occurring at the cables on the windward side. Of course, since the direction of the wind is arbitrary, all cables must be designed to withstand the maximum loads.

Maximum values, relevant to the design, are given in Table 2 for different operational conditions. Since the direction of the wind can be any, all the cables and anchorages must be designed to withstand maximum loads.

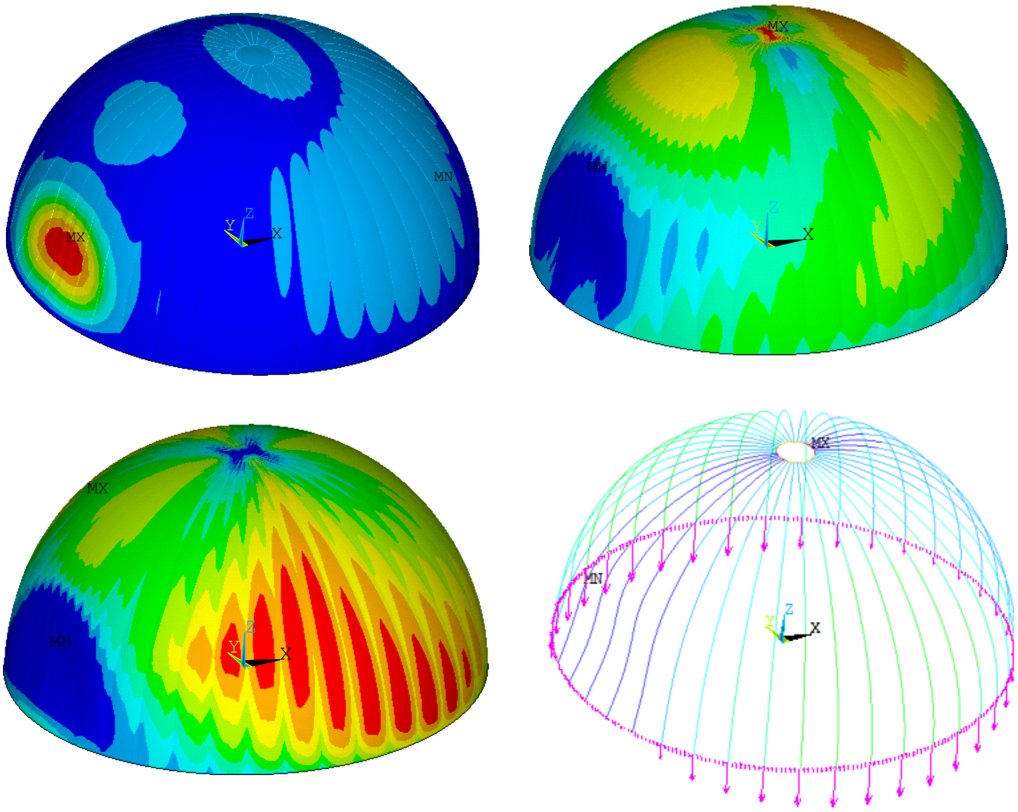

Figure 10: field distributions for Concern conditions: (a) norm of the displacements; (b/c) principal $\sigma_1$ and $\sigma_2$ stress fields; (d) normal loads on cables and anchorages.

**Table 2**: Some selected maximum results for different operational conditions

| Conditions | Beauford wind Scale | $v_{op}$ [km/h] | $p_0$ [kPa] | Membrane displacements [m] | Membrane stresses [kN/m] | Max cable loads $N_{\max}$ [kN] | |
|---|---|---|---|---|---|---|---|
| | | | | $\|\mathbf{u}\|_{\max}$ | $S_1 = \sigma_1 \times t$ | Meridian | Ring |
| Assembling | -- | 0 | 30 | 0,03 | 4,7 | 0 | 0 |
| Attention | Fresh Gales | 70 | 30 | 0,36 | 11,4 | 23,4 | 37,6 |
| Concern | Storms | 100 | 30 | 2,02 | 18,0 | 47,4 | 87,9 |
| Preservation | Violent Storms | 134 | 40 | 2,70 | 25,0 | 87,8 | 196,6 |

## 5 CONCLUSIONS

We presented the design and installation of a set pneumatic domes recently produced in the south of Brazil, intended for theater performances and cinema projections, during the 2022 Christmas and 2023 New Year celebrations. The domes are constituted of single layer polyester-PVC envelops, with the larger unit reinforced by a set of 40 steel cables arranged radially, converging to a cable ring at the top of the dome and anchored to a perimetral base ring made of reinforce concrete. Since main dome was intended for high-resolution cinema projections, the creases of the membrane surface should be as small as possible, and the reinforcements cables were installed with low prestress forces. However, the location is susceptible to intense wind gusts, and thus the domes were designed for a normal operation wind speed of 70km/h and an ultimate wind speed of 130km/h.

The structure was used with much success during the last Christmas and New Year seasons, and although initially planned to be dismantled in February 2023, it is currently still in place, possibly to be used in the next season. However, carefully monitoring of the dome is required, since the transition from Winter to Spring seasons, especially in October, are particularly prone to high winds at the site of the dome, which is surrounded by Aracuaria trees, whose large branches are prone to detach during windstorms, possibility becoming large flying debris.

## REFERENCES

[1] Pauletti RMO. “Some issues on the design and analysis of pneumatic structures”. *Int J Struct Eng* 2010; 1(3/4): 217-240.

[2] Chen, Z.; Wei, C.; Li, Z.; Zeng, C.; Zhao, J.; Hong, N.; Su, N., Wind-Induced Response Characteristics and Equivalent Static Wind-Resistant Design Method of Spherical Inflatable Membrane Structures. Buildings 2022, 12, 1611.

[3] R.M.O. Pauletti, K.B. Rocha, “A simple finite element framework for modelling pneumatic structures”. *Engineering Structures* vol. 235 (2021) 111812 https://doi.org/10.1016/j.engstruct.2020.111812

[4] Pauletti, RMO. “Static Analysis of Taut Structures. in *Comput Meth Appl Sci 2008; 8: p.117-139. Textile Composites and Inflatable Struct II*, E. Oñate, B. Kröplin (eds). Springer, Dordrecht.

[5] Pauletti RMO, Guirardi DM. “Implementation of a simple wrinkling model into Argyris’ membrane finite element”. *VI International Conference on Textile Composites and Inflatable Structures 2013*; Munich.

[6] J. D. Holmes, Wind Loading of Structures, Taylor & Francis, London, 2001.