WIND ACTION ON SHELLS OF THREE SUPPORTS

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ABSTRACT

The free form shell structures, which are very thin, are known for its slenderness and load bearing capacity due to its own form. These shell structures, built in ultra-high performance concrete, can have extremely thin thickness, giving them an image of slenderness and beauty. The complexity of the architectural forms of these shell structures requires a more accurate description of the wind action and interaction with these structures.

This paper presents a study on the aerodynamic behaviour of prefabricated thin shells in ultra-high performance concrete, with triangular shape. The goal is to evaluate the interaction between the shell and the wind for different wind angles, and the influence of the number of facades incorporated in the model. In order to determinate the internal and external wind pressure coefficients on the shell surface, experimental tests on a scale model were performed in a wind tunnel of the National Laboratory of Civil Engineering (LNEC), characterized by a uniform wind speed profile, 20 m/s. There were analysed three different model configurations: i) without facades, ii) with one facade and iii) with two facades. The experiment results are presented in the form of isobaric curves representing values of resulting pressure coefficients for different wind incidence angles and model configurations.

Key-words: Shell structures; Scale model; Wind tunnel; Pressure coefficients; Free form

1 INTRODUCTION

During the 50's and 60's many concrete shells were built, standing out the work of the Swiss engineer Heinz Isler (1926-2009). The high resistance of these structures and their architectural freedom are two important characteristics that contributed to its popularity (Peerdeman, 2008). There are remarkable works of shell structures from 1950 to 1970, designed by Pier Luigi Nervi (1891-1979), Ove Arup (1895-1988), Eduardo Torroja (1899-1961) and Félix Candela (1910-1997). Despite the huge potential shown by this type of structures, in the last decades of the twentieth century there was a decrease in the design and construction of concrete thin shells, related to the high cost of falsework and labour, particularly in developed countries (Peerdeman, 2008). Currently, these shell structures have been design in several free forms, highlighting the importance of studying the interaction of these structures with adverse natural phenomena such as atmospheric wind (Ferreira, 2013).

This work focuses on the aerodynamic behaviour of thin shells, of an experimental model developed with three supports and different configurations depending on the number of facades. In this study it is determined experimentally in wind tunnel tests, pressure coefficients due to wind action, identifying the surface areas and critical angles of incidence when the shell interacts with wind.

2 SHAPE DESIGN OF SHELL STRUCTURES

A shape of a shell structure, with any kind of curvature, can be designed using either a geometric or a non-geometric process. While the geometric definition is based on mathematical equations, the non-geometric method is associated with natural processes, commonly known by form-finding, assuming that the form is determined by the active load.

Heinz Isler was the author of the widely explored form-finding concept, associated with the non-geometrical processes. Of the three unconventional methods of form-finding: Freely shaped Hill, Membrane under pressure, and Hanging cloth reversed, the last stands out (Isler, 1961 cited in (Chilton, 2012). Isler indicates 39 potential forms of shells and says that there is still an infinite number to discover (Chilton, 2009). His first and most important shells were built based on the Hanging cloth reversed and Membrane under pressure methods. The technique used to load the fabric, which simulates the shell, was to put plaster in order to maximize the suppleness of the wet fabric and maintain a constant thickness (Chilton, 2012).

Heinz Isler referred that the key factors that influence the form of a shell structure are: i) functionality, ii) form, iii) artistic expression, iv) static, v) construction, and vi) cost. The shape and size of the initial surface influence on the reactions at the supports and the state of internal tensions of the shell (Chilton, 2012).

The typical scale to obtain the coordinates x, y, z, in order to built real size shell structures, is 1:50 or 1:100. According to Isler, obtaining the coordinates manually is the most important and critical step of the whole process (Chilton, 2012).

It is possible to have a wide range of shapes, with different support conditions and loading, changing the number of support and its position (Cardoso, 2008). The Hanging cloth reversed method is the most interesting one from the point of view of the relationship between the bearing capacity of tensile fabric fibres and the compression bearing capacity of the concrete. Figure 2-1 illustrates Isler studies in physical models through the Hanging cloth reversed method.

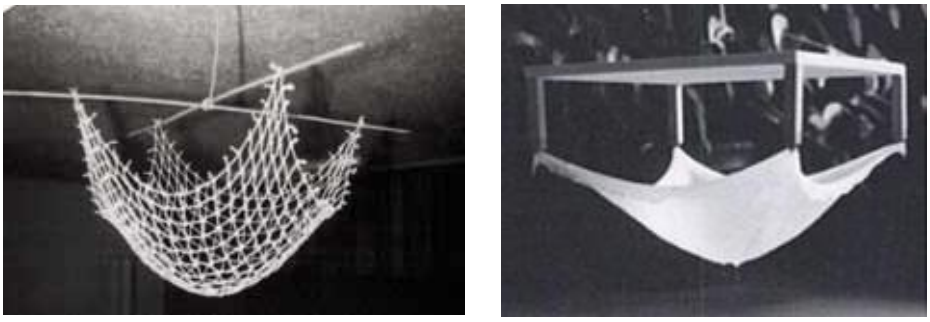

Figure 2-1- Physical model testing of the Hanging cloth reversed method, Isler (1994) (http://n0310093.weebly.com/)

3 WIND ACTION ON SHELL STRUCTURES

3.1 Non-dimensional parameters

There are some non-dimensional parameters that should be defined in order to analyse the interaction between wind flow and structures. Therefore, there are three non-dimensional parameters, pressure coefficient, Strouhal number and Reynolds number (Cook, 1985).

The value of the pressure coefficient at a certain point is defined in terms of the wind dynamic pressure, by the expression (Simiu & Scanlan, 1996),

$$C_p = \frac{p_s(x) - p_0}{\frac{1}{2}\rho\bar{U}^2} \quad (1)$$

Where, $p_s(x)$ is the static pressure over the object surface, p_0 is the reference conditions static pressure and $\frac{1}{2}\rho\bar{U}^2$ is the non-disturbed wind dynamic pressure at the reference high.

It has been considered a uniform flow around an infinitely long cylinder, and the ideal case of an inviscid flow. At the point where the centre line of flow rings the cylinder surface, the pressure coefficient is one, assuming the maximum value for this particular case (Cook, 1985). This point is called the stagnation point. In pressure zones, C_p takes positive values and in areas of suction takes negative values.

The Reynolds number, Re, characterizes the type of flow, and has influence on the phenomena which may occur resulting from wind-structure interaction. Represents the relationship between inertial forces and viscous nature forces, given by the expression,

$$Re = \frac{\rho_a UD}{\mu} = \frac{U.D}{\frac{\mu}{\rho_a}} = \frac{UD}{\upsilon} \quad (2)$$

Where, D is the characteristic dimension of the body, $\bar{U}$ is the mean flow velocity and ν is the kinematic fluid viscosity coefficient (for $20ºC$ temperature air takes value of $1{,}51 \times 10^{-5}\ m^2/s$).

3.2 Effects of the wind-structure interaction

Cook (1985) presents different analysis of the flow around obstacles for both uniform wind profile and bundary layer profile. When the flow touch the front face of a structure, the streamlines bypass the object through the sides and cover. In the case of a uniform profile incident velocities, the wind flows into the upper area of the front face and the pressure is maximum in the ground in the center of the face. The pressure decreases on the edges. In the other hand, for an increasing velocity profile the flow tend to go downward toward the ground. The descendants streamlines (which focuses less than 2/3 of the height of the front face) forms a vortex near the ground (Cook, 1985).

Cook (1985) also describes the trajectory of the flow over a flat roof when the wind flows perpendicularly to a front face of the structure. In the case of a uniform profile incident velocities, the stream lines do not return to the surface. On the contrary, for a non-uniform wind profile it creates a vortex over the roof and the second separation point is antecipated (Cook, 1985).

3.3 Previous studies about wind action on shells

Cheung & Melbourne (1983), Ganguli, Newman, & Shrivastava (1984), Taylor (1991), Meroney, Letchford, & Sarkar (2002) are some of the authors of experimental studies about shell structures.

Cheung & Melbourne (1983) concluded that wind tunnel tests in circular structures and flows characterized by Re <2x105, are highly dependent on the value of Re and the intensity of turbulence.

Ferreira (2013) studied the behavior of two different geometries of thin shells, hexagonal and pentagonal. Performed tests in a wind tunnel in order to determinate pressure coefficient on the surface of the models for various wind incidence angles. The tests were performed in open-circuit wind tunnel, with a section of 0.72 m2, boundary layer with velocity profile characteristics and turbulent equivalent to the peripheral region of a city (Ferreira, 2013). Ferreira (2013) analyzed separately the internal and external pressure coefficients for both laminar and turbulent flow conditions.

4 DESCRIPTION OF THE EXPERIMENTAL CAMPAIGN

The experimental campaign can be divided into 3 phases, Phase 1 – testing the model without any facade, Phase 2 –testing the model with a facade, and Phase 3 – testing the shell with two facades. The tests were performed in closed circuit wind tunnel with section 3,0x1,2x1,0 m^3 and continuously variable speed from 0 to 45 m/s, belonging to the Earthquake Engineering Centre and Structural Dynamics (NESDE), Structures Department, LNEC.

The scale model (Figure 4-1) has three supports, which form an equilateral triangle, with 500 mm side 160 mm maximum height, 20 mm wide in support (Thomas, Vizotto, & Julio, 2014). First of all, the model was printed (3D), then reinforced with fibre glass on the interior surface. The scale of 1:50 is considered appropriate for this free form geometry.

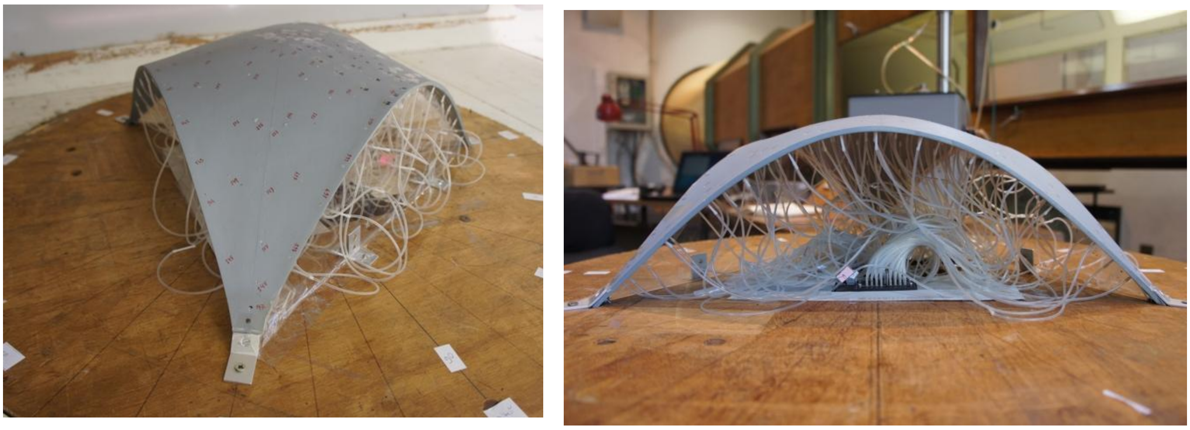

Figure 4-1- Free form shell model of three supports (LNEC)

There are two possible positions for the facades, without overhang or allowing an overhang, forming a small “flap". In order to study the behaviour of the shell for both structural solutions, it was decided that the model should have one side of the shell with overhang and one side without it (Figure 4-1).

4.1 Experimental design tests

Figure 4-2 illustrates the three cases studied, corresponding to the three shell model configurations.

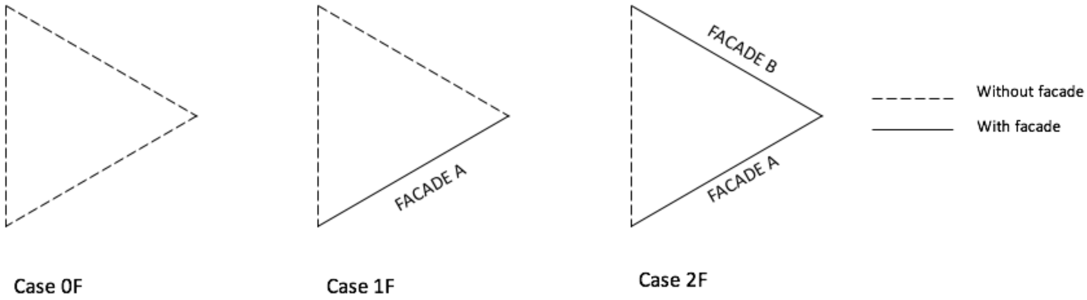

Figure 4-2- Scheme of the three cases studies. Case 0F - model without facades; Case 1F - model with a facade; Case 2F - model with two facades

In order to facilitate data process and analysis of the results the surface was divided according to Figure 4-3.

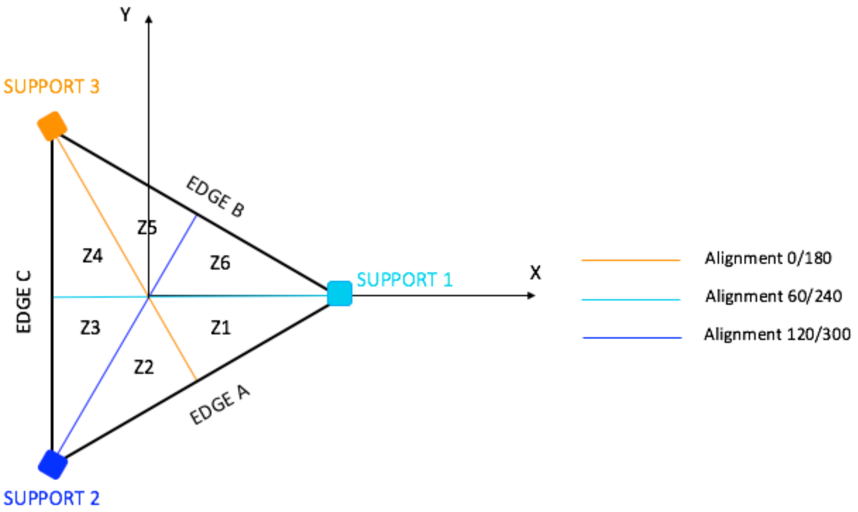

Figure 4-3 Triangular shell free form. Schematic illustration of the support, edges and model alignments in plan.

For the case 0F (Figure 4-2) the tests were performed under uniform velocity profile conditions, for a total of 119 pressure taps (TP) disposed in zone Z1 (Figure 4-3). From this set of taps was possible to obtain a fine distribution of pressure and evaluate the Re dependency, and also conclude on the test velocity. The sensitivity analysis of the number of TP reduced its number for the next tests. The model was tested for 19 incidences between 0º and 350º, varying constantly between 10 and 30, with results in the interior and exterior surface, separately.

For 1F and 2F cases were performed tests covering the whole surface of the shell, 124 pressure taps uniformly distributed. Facade A (Figure 4-2) was also tested, with 30 pressure taps distributed throughout the facade area.

The experiment conditions were the same for every case study, $V = 20\, m/s$ (wind speed), $\upsilon \cong 1{,}5 \times 10^{-5}\, m^2.s^{-1}$ (kinematic viscosity), therefore Reynolds number was $Re \cong 2{,}16 \times 10^5$.

5 RESULTS ANALYSIS

In this chapter, it is presented the experiment results, resulting pressure coefficient distributions (ΔCp), given by the difference between the value of the internal pressure coefficient (Cp_i) and the external one (Cp_e). The analysis is performed only for the most relevant wind incidence angles: 0º, 60º and 180º.

5.1 Incidence angle 0º

Figure 5-1 shows the values of ΔCp on the alignment 0/180, for wind incidence angle of 0º and for the three cases, 0F, 1F and 2F.

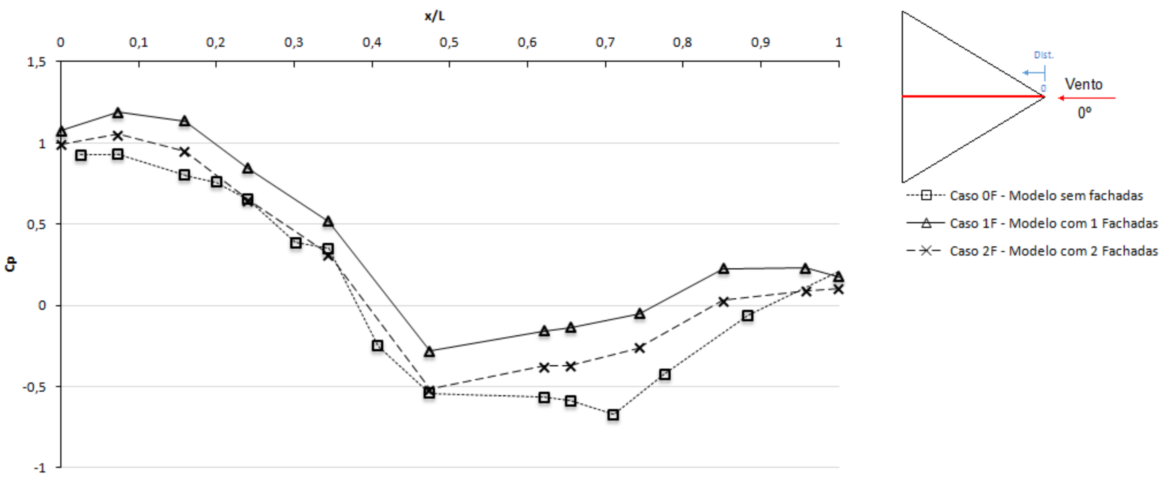

Figure 5-1- Resulting pressure coefficients in the shell surface for cases 0F, 1F and 2F, incidence angle 0º. Alignment 0/180.

In certain points of the shell surface, the value of ΔCp can be greater than 1 due to its open geometry, so tests were performed in internal and external surface. This phenomenon occurs precisely on the support 1 for the Case 1F (Cp = + 1.19), and can be explained by positive pressure from the outer side (+ Cp_{ext} = 0.71) and suctions from the inner side (Cp_{int} = -0.48).

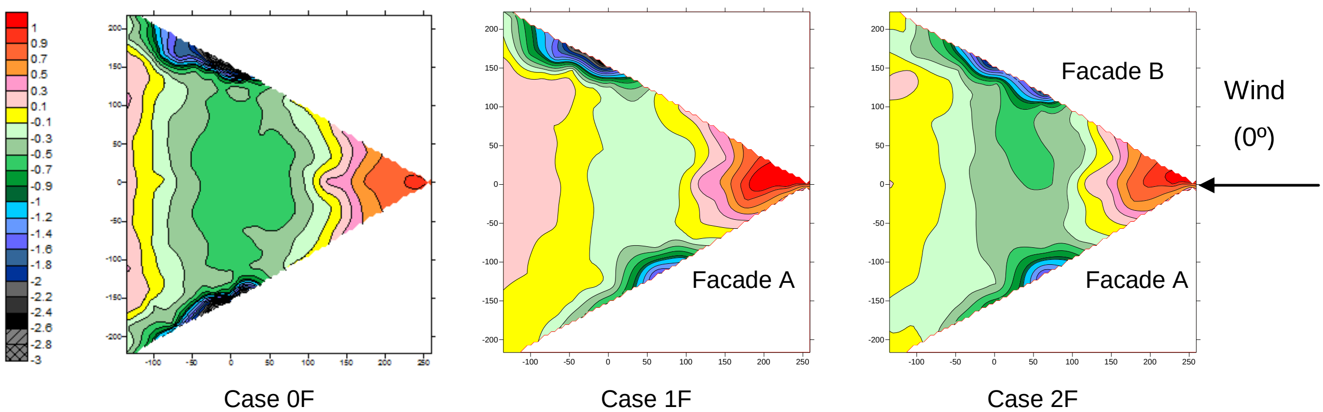

Figure 5-2- Pressure coefficient distributions at the shell surface for the cases 0F, 1F and 2F, and 0° incidence angle.

By analysing the different distributions of ΔCp (Figure 5-2) for the three cases it is possible to conclude:

- There are two symmetrical regions along the side edges at about x/L=0,75, characterized by strong suction values (ΔCp = -2.8), for the case 0F;
- Asymmetry of the ΔCp distribution due to the inclusion of one facade (case 1F) and strong suction zone in the edge without facade. On the central zone ΔCp values are less negative;

- For the case 2F would be expected a symmetric distribution. The asymmetry observed can probably be explained by a misalignment of the model or the overhang on the side of the facade, causing some asymmetry in the flow-model interaction and consequently in the ΔCp distribution. ΔCp values in the central zone are, as expected, among those recorded in other configurations.

These strong suctions, along the edges A and B, for the cases 0F and 1F are consequence of the shell shape and the absence of the facade, so the flow separates at the edges.

This study presents similar values for the results for the triangular shell model when compared with the values presented by Ferreira (2013), who analysed the values of internal and external pressure coefficients separately, for pentagonal and hexagonal shell models.

5.2 Incidence angle 60º

For the incidence angle of 60º, the wind flows perpendicularly to the opening in the case 0F, and perpendicularly to the facade A in 1F and 2F cases.

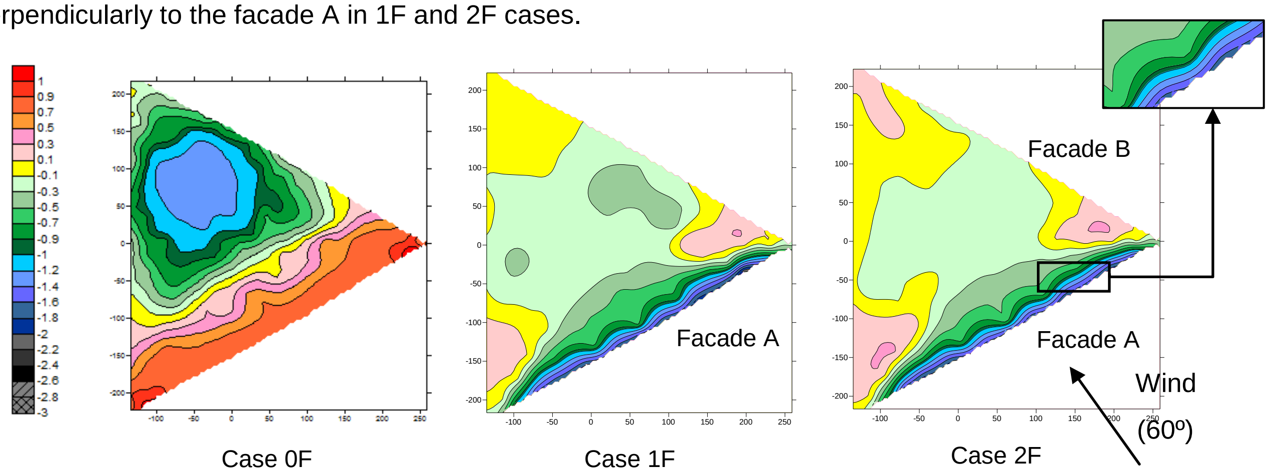

Figure 5-3- Pressure coefficient distributions at the shell surface for the cases 0F, 1F and 2F, and 60 ° incidence angle.

By observing the ΔCp distributions (Figure 5-3) for the three cases it is possible to conclude:

- The difference between model configurations for an incidence angle of 60° produces a very pronounced effect compared to 0º. This difference is more significant between the case 0F and the cases 1F and 2F, since the wind for the last cases flows toward the facade A;
- For case 0F, ΔCp distribution on the shell surface presents a well defined suction area of rounded geometry, with values up to (ΔCp = -1.4);
- The initial zone of the surface (in the flow direction), is under pressure for case 0F and under suctions for cases 1F and 2F. For cases 1F and 2F, the flow streamlines crash into the facade A causing suctions in the vast majority of the shell surface;

- For cases 1F and 2F the ∆Cp positive areas (under pressure) are very small and are at the back of supports 1 and 2.

5.3 Incidence angle 180º

Figure 5-4 illustrates ∆Cp distributions for the three model configurations when the wind incidence angle is 180º.

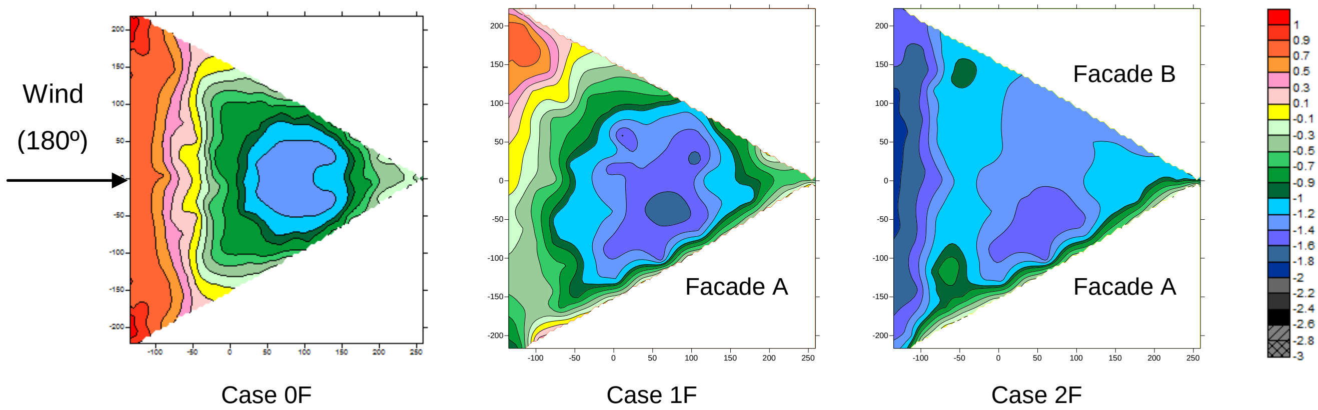

Figure 5-4- Pressure coefficient distributions at the shell surface for the cases 0F, 1F and 2F, and 180 ° incidence angle.

For ∆Cp distributions and this incidence angle stands out:

- A stain of ∆Cp negative values, suction, (∆Cp = -1.4), characterized by a round shape, for 0F and 1F cases. In the case 1F is found that the stain is bigger, has more negative values and moves toward the facade. This happens due to the presence of facade A which makes the ∆Cp distribution asymmetric;
- As expected, for 0F case the ∆Cp distribution is identical to the distribution for the incidence angle of 60 °, rotated 120° clockwise;
- For 2F case, ∆Cp distribution has more negative values compared to other cases. Wind flow enters the shell model and becomes confined between the two facades A and B, forming a huge suction bubble (∆Cp) extended to the whole surface (corresponding to positive pressures on the interior surface, Cp_{int}). The surface presents average values of (ΔCp_{med} = -1.5);
- Case 2F presents a non-symmetric distribution, it has a longitudinal strip along the facade characterized by ∆Cp values less accentuated, ranging between (∆Cp =-0,9) and (∆Cp =-0,1). As Façade A is positioned, an overhang is formed causing this particularity.

6 CONCLUSIONS

This paper experimentally analyses the aerodynamic behaviour of a shell structure with three supports. To achieve this goal, there were performed wind tunnel tests in order to determine pressure coefficients on a reduced scale model, analysing the variation for various wind incidence angles and three shell structure configurations (no facades, with a facade and with two facades).

It was considered that the situation producing more pronounced suction, and generalized to the entire surface of the shell, was the case with two facades when the wind flows at an angle of 180º. The influence of facades in the results is most conspicuous for 1F and 2F cases when the wind flows at an angle of 60º, and for the 1F at 300º. On the contrary, for 0º angle of incidence the facades have very low influence on the results. ΔCp distributions on the facades were found very uniform, with no major variations or abrupt value changes. In general, it was found that the presence of side facades changes substantially the pressures distribution, and the wind incidence variations influences mostly the configurations with facades.

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REFERENCES

Cardoso, F. H. (2008). Coberturas em betão armado e pré-esforçado: Solução estrutural tipo casca. *Dissertação de Mestrado Integrado em Engenharia Civil*. Instituto Superior Técnico. Universidade Técnica de Lisboa.

Chilton, J. (2012). Form-finding and fabric forming in the work of Heinz Isler. *ICFF, International Society of Fabric formwor (2012), 84-91*.

Chilton, J. (2009). Heinz Isler's infinite spectrum of new shapes for shells. Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia

Cook, N. (1985a). *The designer's guide to wind loading of building structures Part 1: Background, damage survey, wind data and structural classification.* London: Butterworths.

Ferreira, M. A. (2013). Análise de estruturas em cascas de formas livres sob ação do vento. Tese de Doutoramento . Faculdade de Engenharia Civil, Arquitetura e Urbanismo – Universidade Estadual de Campinas, Campinas.

Peerdeman, B. (2008). Analysis of Thin Concrete Shells Revisited: Opportunities due to Innovations in Materials and Analysis methods. *Dissertação de Mestrado em Engenharia Civil*. Delft University of Technology.

Tome, A. P., Vizotto, I., & Julio, E. N. (2014). Guidelines de apoio à produção de modelos reduzidos de cascas em betão para anáise aerodinâmica em túnel de vento. *5as Jornadas Portuguesas de Engenharia de Estruturas* .

Simiu, E., & Scanlan, R. H. (1996). Wind Effects on Strutures. John Wiley & Sons, Inc.