Mean loads on vaulted canopy roofs: tests in boundary layer wind tunnel

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ABSTRACT

The vaulted canopy roof (VCR) is a widespread structure in vast areas of South-America, especially in parts of Argentina, Brazil and Paraguay. Information about the aerodynamics of VCRs however, is scarce in the open literature. This paper presents the results of mean wind loads coefficients on VCRs obtained in boundary layer tunnel tests, which constitute a firm base to assess wind loads on the structure.

INTRODUCTION

The vaulted canopy roof (VCR) is a widespread structure in vast areas of South-America, especially in parts of Argentina, Brazil and Paraguay where the climate is warm. They can be seen across both urban and rural areas, in a wide variety of uses. For instance, a common landmark in the north-east of Argentina, is a carpenter’s workshop sheltered by a VCR. Information available in the specialized literature about the aerodynamic behavior of VCRs is scarce. Cook [1] summarized this situation when he wrote: “There are only a small amounts of data for curved canopies and these are all early data obtained in smooth uniform flow. For example Irminger and Nokkentved included a barrel vault canopy with a rise of r = W/4 in their studies published in 1936, and Blessmann included domed canopies with rises W/4 y W/8 in his 1971 studies. The validity of the loading coefficient is open to question in the light of current techniques, however the general loading characteristics may be still be useful.”. This situation is also reflected in the codes of practice. The authors of this work found only two codes that provide loads coefficient values for VCRs: the French code NV 65 [2] and the Argentinean code CIRSOC 102 [3]; the former having been superseded by the Eurocode and the later being superseded by a new version that will be shortly come into effect [4]. Both codes suggest using the same mean pressure coefficients of planar canopy roofs while keeping the same relation rise/span. Marighetti et al. [5] though, showed that this approximation is incorrect in their presentation of wind tunnel results of mean pressure distributions on VCRs which they compared with the those corresponding to a planar canopy roof with similar dimensions. Fig. 1 reproduces two figures from their work, corresponding to incident wind angles of 45º and 90º relative to the ridge. It can be seen that the contour plots have different patterns as well as different values, which is not surprising taking into account that it is hardly possible that the flow over a surface with sharp edges would be similar to the flow over a relatively smooth curved surface. Reports on boundary layer wind tunnel tests related to these structures have also not been found in the literature, apart from those of Natalini et al. [6, 7, 8]. Regarding computational modelling the situation is similar, though there have been recently some promising results reported by Balbastro et al. [9, 10, 11].
Considering the lack of reliable data sources for state-of-art wind engineering and that the structural designer needs design aerodynamic coefficients, the subject was the object of a wind-tunnel-based studio in the Laboratorio de Aerodinámica de la Facultad de Ingeniería de la Universidad Nacional del Nordeste (UNNE), Argentina. This paper presents results of mean wind loads coefficients on VCRs obtained in boundary layer tunnel tests. The first problem approached was the selection of the most suitable technique for modeling pressures on curved surfaces. Once the modeling conditions were established, local and global wind load coefficients were determined on models of six VCRs of different geometry using wind simulation.

WIND TUNNEL MODELING TECHNIQUES

The study of these structures through wind tunnel tests presents difficulties inherent to both free-standing canopies and bodies with curved surfaces, for which it was necessary to develop specific modeling techniques. The first problem approached was the selection of the most suitable technique for modeling pressures on curved surfaces. The issue of modelling wind loads on VCRs was approached by Natalini et al. [6], who based in previous work of Ribeiro [12], Cheung and Melbourne [13], Batham [14], Blackbourn and Melbourne [15], Blessmann and Loredo Souza [16] and Blessmann [17], tested three 1:75 scale models of similar geometry but different roughness over the roof. As a result, sand of appropriate size was added to the upper side of the roof of the models. On the other hand, Natalini et al. [18] reported a study on the modelling of mean pressures on planar canopy roofs. The paper presented wind tunnel results of tests on scale models of the full-scale Dutch barn tested by Robertson et al. [19] at Silsoe, UK. The comparison between both full and reduced scale barns showed that severe distortions can appear which are linked to scale effects if the size of the model is below a certain level. In the case of the UNNE tunnel such distortion did not manifest when using a 1:75 scale model [20]. Based in these experiences the scale 1:75 was adopted for all the models used in the present study.
EXPERIMENTAL ARRANGEMENT

MODELS

The geometry and size of the six models that were tested were adopted on account of the range of dimensions of the VCRs more frequently found in the north-east of Argentina, and the size of the models of enclosed buildings appearing in the literature. Fig. 2 and Table 1 summarize the geometry of the models.

![Geometry of the models](image)

**Fig. 2: Geometry of the models.**

<table>
<thead>
<tr>
<th>Model</th>
<th>Absolute dimensions</th>
<th>Relative dimensions</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>r [cm]</th>
<th>α</th>
<th>Re x 10^5</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>60 [cm] 15 [cm] 6 [cm] 3 [cm]</td>
<td>0.25</td>
<td>0.40</td>
<td>0.20</td>
<td>0.5</td>
<td>10.88</td>
<td>43°58’</td>
<td>2.09</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>60 [cm] 15 [cm] 4 [cm] 3 [cm]</td>
<td>0.25</td>
<td>0.27</td>
<td>0.20</td>
<td>0.75</td>
<td>10.88</td>
<td>43°58’</td>
<td>1.96</td>
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<td>C</td>
<td>60 [cm] 15 [cm] 2 [cm] 3 [cm]</td>
<td>0.25</td>
<td>0.133</td>
<td>0.20</td>
<td>1.50</td>
<td>10.88</td>
<td>43°58’</td>
<td>1.68</td>
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<td>D</td>
<td>30 [cm] 15 [cm] 6 [cm] 3 [cm]</td>
<td>0.50</td>
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<tr>
<td>E</td>
<td>30 [cm] 15 [cm] 4 [cm] 3 [cm]</td>
<td>0.50</td>
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<td>0.75</td>
<td>10.88</td>
<td>43°58’</td>
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<tr>
<td>F</td>
<td>30 [cm] 15 [cm] 2 [cm] 3 [cm]</td>
<td>0.50</td>
<td>0.133</td>
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</table>

The rise, f, and the span, b, was kept similar in all models. Basically, two kinds of models were built, the deep models (A, B and C) and the short models (D, E and F), which allowed the assessment of the influence of the depth. By varying the height of the eves, h, (2, 4 and 6 cm), the six models were produced. It is clear that models C and F, with a h dimension that corresponds to 1.5 m at full-scale, do not represent any real situation. They have been included in the tests in order to observe the trend that pressures follow when varying the height of the eves. Wind load coefficients were measured under wind blowing at angles of 60°, 75° and 90° relative to the ridge line since, as demonstrated by Natalini et al. [8], these directions produce the most severe loads.

The roof of the models was made with a 2 mm thick aluminium plate, and the columns with a 2.5 mm diameter steel rod (except one column, the farthest one from the area where taps were placed, which had a square cross section of 10 x 10 mm). As the models have two axes of
symmetry, only a quarter of the models' roofs had pressure taps in place, in this way reducing the number of tubes needed. In addition, all the tubes were led towards the farthest column, through which they reached the floor. In this way, the scale distortion in both columns and roof thickness and the possible interference of the tubes upon the measurements were minimized.

In order to obtain a flow in transcritical conditions, sand was added to the upper side of the roof of the models, being the relative roughness, \( \frac{k}{d} \), equal to \( 3.30 \times 10^3 \).

**Wind Simulation**

The wind tunnel tests were undertaken in the “Jacek P. Gorecki” wind tunnel at the Universidad Nacional del Nordeste. This is an open return wind tunnel with a working section of 22.4 m in length \( \times \) 2.4 m in width \( \times \) 1.8 m in height and a maximum flow velocity of 25 m/s when the working section is empty. Further details are given by Wittwer and Möller [21]. All the models were tested under a wind simulation corresponding to a suburban area. The simulation hardware consisted of two modified Irwin’s spires [22] and 17.1 m of surface roughness fetch downstream from the spires. In this way, a part-depth boundary layer simulation of neutrally stable atmosphere was obtained. Mean velocities, when fitted to a potential law, give an exponent of 0.24. The length scale factor determined according to Cook’s procedure [23] was about 150. The local turbulence intensity at the level of the roof is 0.25. De Bortoli et al. [24] gave further details of this simulation, including size, geometry and arrangement of the hardware and design criteria.

**Pressure Measurement System**

Pressures were measured using a differential pressure electronic transducer Micro Switch Honeywell 163 PC. A sequential switch Scanivalve 48 D9-1/2, which was driven by means of a CTLR2 / S2-S6 solenoid controller connected the roof pressure taps to the transducer through PVC tubes of 1.5 mm in internal diameter and 400 mm in length. No resonance problems were detected for tubes of that length (the gain factor being around one) therefore restrictors of section were not used for filtering. The DC transducer output was read with a Keithley 2000 digital multimeter. The integration time operation rate of the A/D converter was set to produce mean values over 55 seconds.

Simultaneously to the pressure measurements being taken on the roof, the reference dynamic pressure, \( q_{ref} \), was measured at the eaves height with a Pitot-Prandtl tube connected to a Van Essen 2500 Betz differential micromanometer of 1 Pa resolution. The probe stayed beside the model at a distance of about 70 cm to avoid mutual interference. The reference static pressure was obtained from the static pressure tap of the same Pitot-Prandlt tube.

**Results**

**Pressure Coefficients**

The net pressure coefficient, \( c_p \), was obtained by subtracting the internal pressure coefficient, \( c_{pi} \), from the external pressure coefficient, \( c_{pe} \). The two last coefficients are the rate between the pressure on the tap, \( p \), which can be either an external or internal pressure, and \( q_{ref} \), which is the reference dynamic pressure measured at the reference height. Here, the tap pressures are relatives to the static reference pressure, \( P_{ref} \), which is obtained from the static tap of the same Pitot-Prandlt tube used to measure \( q_{ref} \). Following the usual convention, negative values of both
$c_{pe}$ and $c_{pi}$ indicate actions directed out from the surface (suctions). Accordingly, positive values of $c_{p}$ indicate actions directed into the building. In this work, the most positive and negative values of a set of pressure coefficient will be referred as the maximum and minimum values of that set.

The whole set of contour plots were given by Natalini [25], including figures of internal, external and net pressure coefficients. When comparing pressures on deep and short models, at first glance they show more similarities than disparities. However, two differences can be noted, though they are restricted to the central area of the roofs. On the one hand, external pressures are slightly higher near the upwind eave of the deep models and the zero pressure coefficient line is shifted towards leeward; on the other hand, internal negative pressures are lower (that is bigger in absolute value) near the ridge of the deep models. The second difference can be better appreciated in figures 6 to 8, which show the profiles of the pressure coefficient distribution on a cross section in the middle of the roof (section II). In contrast, figures 3 to 5, which show the pressures on a cross section located 5 mm inwards the upwind edge (Section I), present virtually the same figures for both models.

![Diagram](image_url)

**Fig. 3:** External, internal and net pressure coefficients profiles. $\theta = 60^\circ$. Upwind edge.

![Diagram](image_url)

**Fig. 4:** External, internal and net pressure coefficients profiles. $\theta = 75^\circ$. Upwind edge.
Fig. 5: External, internal and net pressure coefficients profiles. $\theta = 90^\circ$. Upwind edge.

Fig. 6: External, internal and net pressure coefficients profiles. $\theta = 60^\circ$. Central section.

Fig. 7: External, internal and net pressure coefficients profiles. $\theta = 75^\circ$. Central section.
Theses differences occur because in the deep models the flow tends to be bidimensional in the central area. Let us do the following thought experiment: divide the deep model plots in four parts by means of normal-to-the-ridge vertical planes, remove the two central pieces and join the two remaining parts. The plots obtained in this way are almost the same than the corresponding to short models. It shall be seen in the following section how these differences propagate into the global coefficients.

Note the role that internal pressures play in the resulting net pressures. The contribution of the internal pressures ranges from 29% to 69% of the net pressures. Internal pressures are highly dependant on blockage conditions, and as the results presented here correspond to models with no blockage, loads can be expected to be significantly different under any degree of blockage.

Figures and plots show that high pressures occur near the edges and the ridge. Table 2 presents the highest and lowest pressures near the edges of every model, from the records of pressure taps while Table 3 presents the highest and lowest pressures near the ridge.

### Table 2: Maxima and minima pressure coefficient near edges.

<table>
<thead>
<tr>
<th>Wind direction</th>
<th>Model</th>
<th>Max</th>
<th>Min</th>
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<th>Min</th>
<th>Max</th>
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<tr>
<td>60º</td>
<td>A</td>
<td>1.8</td>
<td>-1.8</td>
<td>1.7</td>
<td>-2.0</td>
<td>1.6</td>
<td>-2.0</td>
<td>1.8</td>
<td>-1.8</td>
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### Table 3: Maxima and minima pressure coefficient near the ridge.

<table>
<thead>
<tr>
<th>Wind direction</th>
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<tr>
<td>60º</td>
<td>A</td>
<td>0</td>
<td>-1.2</td>
<td>-0.3</td>
<td>-1.3</td>
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<td>A</td>
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<tr>
<td>90º</td>
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<td>-0.2</td>
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</table>
**FORCE COEFFICIENTS**

The roof of the models were divided into four zones as shown in figure 9. Force coefficients were determined by integrating the pressures on the four areas and on the whole roof.

![Diagram showing force coefficients](image)

**Fig. 9: Reference areas.**

As force coefficients are associated with directions, a convention on the reference axes must be formulated. The conventional axes most commonly used in aerodynamics are wind axes and body axes. In this work, body axes are used, as displayed in figure 9. The force coefficients are then defined as

\[
C_{yi} = \frac{F_{yi}}{q_{ref} A_{yi}} \quad i = 1,2,3,4
\]

\[
C_{zi} = \frac{F_{zi}}{q_{ref} A_{zi}} \quad i = 1,2,3,4
\]

\[
C_y = \frac{F_y}{q_{ref} A_y}
\]

\[
C_z = \frac{F_z}{q_{ref} A_z}
\]

Where $C_{yi}$ is the partial force coefficient on zone “i” in $y$-direction (horizontal), $C_{zi}$ is the partial force coefficient on zone “i” in $z$-direction (vertical), $F_{yi}$ is the force on zone “i” in $y$-
direction, \( F_{zi} \) is the force on zone “i” in z-direction, \( A_{yi} = \frac{a.f}{2} \) is the vertical reference area for zone “i”, \( A_{zi} = \frac{a.b}{2} \) is the horizontal reference area for zone “i”, \( C_y \) is the total force coefficient in y-direction, \( C_z \) is the total force coefficient in z-direction, \( F_y \) is the force on the whole roof in y-direction, \( F_z \) is the force on the whole roof in z-direction, \( A_y = a.f \) is the total vertical reference area and \( A_z = a.b \) is the total horizontal reference area.

The reference dynamic pressure, \( q_{ref} \), was measured at the eave eight, as described before. Table 4 shows the force coefficients acting on every zone (partial coefficients) and the overall roof (total coefficients). The force coefficients are positive when the action is directed in the positive direction of the corresponding reference axis (fig. 9).

### Table 4: Force coefficients.

<table>
<thead>
<tr>
<th>( \theta^\circ )</th>
<th>Parcial</th>
<th>Total</th>
<th>Parcial</th>
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<tr>
<td></td>
<td>( C_{y1} )</td>
<td>( C_{y2} )</td>
<td>( C_{y3} )</td>
<td>( C_{y4} )</td>
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<tr>
<td><strong>A</strong> h/b = 0.4</td>
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<td>0.31</td>
<td>0.43</td>
<td>0.65</td>
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<td></td>
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<td>0.43</td>
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<td>0.54</td>
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<td>90</td>
<td>0.35</td>
<td>0.35</td>
<td>0.45</td>
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<tr>
<td><strong>B</strong> h/b = 0.27</td>
<td>60</td>
<td>0.22</td>
<td>0.32</td>
<td>0.71</td>
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<tr>
<td></td>
<td>75</td>
<td>0.32</td>
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<td>0.64</td>
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<td>90</td>
<td>0.40</td>
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<td>0.52</td>
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<tr>
<td><strong>C</strong> h/b = 0.133</td>
<td>60</td>
<td>0.34</td>
<td>0.36</td>
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<td></td>
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<td><strong>D</strong> h/b = 0.4</td>
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<td>0.51</td>
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<td>0.51</td>
<td>0.51</td>
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<tr>
<td><strong>E</strong> h/b = 0.27</td>
<td>60</td>
<td>0.34</td>
<td>0.62</td>
<td>0.78</td>
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<tr>
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<td>0.39</td>
<td>0.58</td>
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<tr>
<td><strong>F</strong> h/b = 0.133</td>
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If the $C_y$ coefficients of short and deep models are compared, it can be observed that in general terms the ones corresponding to short models are about 10% higher for any $h/b$ relationship. This difference becomes even more evident between models B and E, where the disparity is 21%. It is interesting to view figures 10 and 11, which have been built with values extracted from Table 4. Figure 10 summarizes the variation of the total force coefficient in the $y$-direction for all models in regard to $\theta$ and $h/b$. The coefficients of the A, B and C models are at the left of the figure, clearly separated from those of the D, E and F models. The $C_y$ on the short models are higher than the corresponding ones of the deep models for every value of $\theta$ and $h/b$, and in this case they are not sensitive to $\theta$ and $h/b$, the values range between 0.98 and 1.04. Deep models proved to be more sensitive, being the most severe case when the wind direction is $75^\circ$.

In figure 11 the variation of the total force coefficient in the $z$-direction is shown. In this example, even though the curves follow the same trend but are inverted, they are not as clearly split up as the $C_y$ values in fig. 10. For $h/b = 0.27$ the values of $C_z$ are higher on deep models, but in the other two cases they are merged with the ones of the short models. Note that for $\theta = 90^\circ$ the variation is practically linear with $h/b$.

In the previous section, it was pointed out that in the central area of the deep models roofs, external pressures near the upwind eave are smaller than those of short models. This causes the net pressure on that area to be smaller on deep roofs, which contributes to both decreased $C_y$ and increased $C_z$ in regard to the short models. On the other hand, as internal negative pressures are lower (that is bigger in absolute value) near the ridge of the deep models, they contribute to decrease both $C_y$ and $C_z$. As both effects add up to influence on $C_y$, they explain the clear separation in figure 10, and as they have an opposite influence on $C_z$, they also explain the fact that $C_z$ figures are a bit entangled in figure 11.
CONCLUSIONS

Marighetti et al. [5] demonstrated that pressures on VCR are different from pressures on planar canopy roofs, for which reason it is a mistake to estimate the loads on VCRs by approximating them with those on planar canopy roofs, as advised in some codes of practice. In this paper, results of mean wind loads coefficients on vaulted canopy roofs obtained in boundary layer tunnel tests have been presented. These results constitute a firm base to assess wind loads on VCRs, though it must be noted that tests have been limited to models with a relation rise/ span f/b = 0.20, therefore estimating loads for others relation f/b is not straightforward.

Positive and negative pressures reach important values near the edges and the ridge. Tables 2 and 3 show the maxima and minima pressure coefficients in those zones of all models and for all the wind directions tested; they can be used to verify cladding and structural parts. Global coefficients given in Table 4 establish the total force acting on the structure, which is necessary information for the design of the immediately supporting structure.

Mean aerodynamic coefficients on VCRs are influenced by size relations. They vary with the column height and the relation span/depth. The maxima mean net pressure coefficients are higher on the short models, while the minima mean net pressure coefficients occur on deep models. The absolute value of pressure coefficients show a general trend to increase as the column height decreases. As for the global coefficients, $C_y$ values are higher on short roofs and $C_z$ values are, mostly but not always, higher on deep roofs.

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REFERENCES


