On the reduction of the wind-load on buildings by using cantilever parapets

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ABSTRACT: The high wind loads on building roofs are normally associated with very intense vortex formed close to the windward roof eaves, which cause intense suction loads on the roof elements. The effect of cantilever parapets on the wind-load on buildings' roofs has been studied. A cantilever parapet consists of a short and flat plate located along the edge of the roof and just over it (slightly detached from the roof surface and parallel to it). The analysis has been performed by wind tunnel testing of different model geometries, including flat and curved roofs of low-rise buildings and covers of stadium-grandstands. Models were rigid, so that no aero-elastic phenomena were accounted for. The different model surfaces under study were equipped with pressure taps on the roofs, and the time averaged pressure signal at each tap measured at 100 Hz sampling rate, the cases studied being stationary. Experimental results reveal that the air stream formed between the parapet and the building blows away the conical vortices from the roof surface, reducing the suction created on them by the wind.

1 INTRODUCTION

It is well known that the new design concepts in architecture and civil engineering introduced in the 19th and 20th centuries were the consequence of the natural evolution of the technical skills in both disciplines. New materials like steel, reinforced concrete or composites have allowed architects and engineers to build bigger, more slender and lighter structures. But as these new concepts in design were being applied to construction a new problem appeared: the wind action could hardly damage the buildings and constructions in general. Some codes of practice have been developed (Eurocode 1, ASCE 7-98...) in the recent decades to take into account the wind effect on buildings and other civil constructions, wind-tunnel research being required or at least highly recommended in some specific cases (wind action on skyscrapers, long-span bridges, pedestrian comfort...).

It is possible to identify some steady aerodynamic effects that result in pressure changes when the wind meets an obstacle like a building: acceleration or deceleration of the wind-flow; attachment, detachment and reattachment of the flow; and finally the development of conical vortices next to the surface of the building. In addition, non-steady aerodynamic effects are also important and must be taken into account when the frequency of the mentioned aerodynamic effect is close to one of the frequencies of the building's structure, or there could be a coupled action between the structure oscillation and the wind-forces like flutter or galloping (Pindado, 2003; Meseguer et al, 2001).

The most damaging steady aerodynamic effect for a building is the conical vortex, which is normally responsible for very high local suctions on roofs. Conical vortices are developed in low-rise building's roofs when an oblique to the eave wind reaches the roof's eave, see Figures 1 and 2. Also, other forms of conical vortices can be developed in high buildings (Kawai, 2002). The conical vortices are aerodynamic phenomena that have been widely studied in the literature, their effects on the local suction on the building's roofs being quite well known today (Lin et al, 1995; Marwood & Wood, 1997; Hoxey et al, 1998; Peterka et al, 1998; Banks et al, 2000; Wu et al, 2001; Banks & Meroney, 2001; Franchini et al, 2005; Kawai & Nishimura, 1996; Kawai, 1997; Hoxey et al, 1998).

The use of solid parapets positioned at the roofs' eaves has been studied in order to reduce the suction created by the conical vortices on the roofs' surface (Kramer et al, 1979; Kind, 1986; Baskaran & Stathopoulos, 1988; Kind, 1988; Stathopoulos et al, 1999; Koop et al, 2005). The purpose of such devices is to detach the vortex from the roof's surface in order to reduce the suction on it, taking into account that the suction is mainly caused by the core of the vortex, see in Figure 3 sketches reproducing the interaction between the solid, porous and cantilever parapets and the wind flow on a flat roof. These solid parapets have been shown to be efficient in reducing the suction on a roof, but only if they are higher than a certain value (Pindado, 2003).

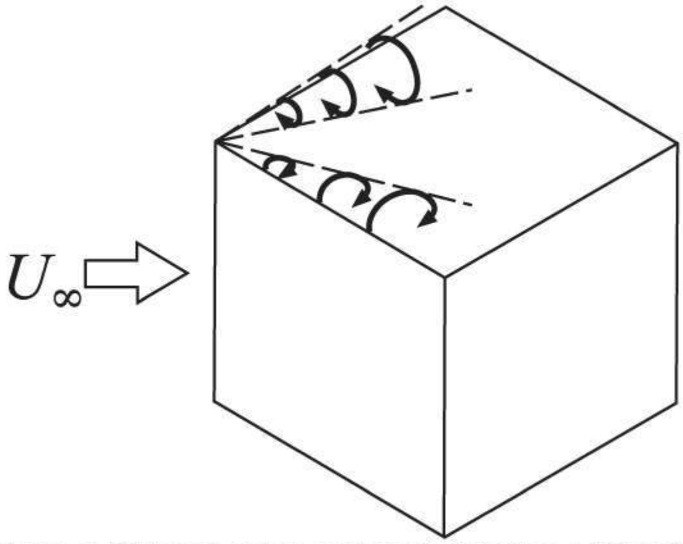


Figure 1. Sketch of conical vortices developed on a flat roof under an oblique air-flow.

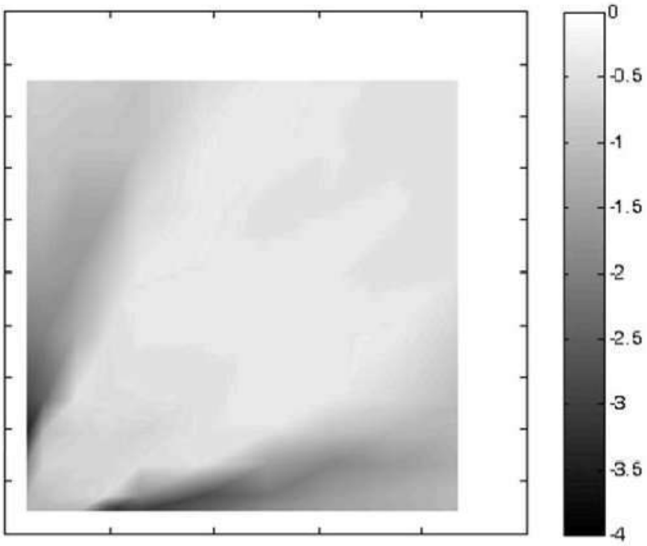


Figure 2. Pressure coefficient distribution, contours of c_p, on a low-building flat roof with 45°-oblique wind flow. Data from wind tunnel testing (Pindado, 2003). The black contour indicates the edges of the model's roof, the shaded area represents the area where the pressure taps were distributed. The post-processing of this data was done using Matlab.

Porous parapets and discontinuous or slotted parapets have also been studied, as a way to introduce small scale turbulence in the flow over the roof which could interact with the conical vortex and reduce the suction on the roof (Pindado, 2003; Baskaran & Stathopoulos, 1988; Pindado & Meseguer, 2003; Koop et al, 2005), see Figure 3. Research done in the past shows a great reduction on the suction produced by the conical vortices (see Fig. 4 and compare to Fig. 2).

Cantilever parapets, also called perimetric spoilers in the literature (Koop et al, 2005), have shown themselves to reduce greatly the suction on roofs (Pindado, 2003), as they force the existence of a jet-flow, which sweeps the surface of the roof (see Fig. 3). The use of cantilever parapets has been studied in some specific cases such as curved roofs. In this case the curvature of the surface can interact with the conical vortex, accelerating the swirl and stretching the core of the vortex, and as a result the high suction zone on the roof can be larger than the one corresponding to a flat roof, and the highest suction point can be higher and detached from the corner (Pindado, 2003, Pindado et al, 2004; Franchini et al, 2005; Cook, 2002), see Figures 5-6.

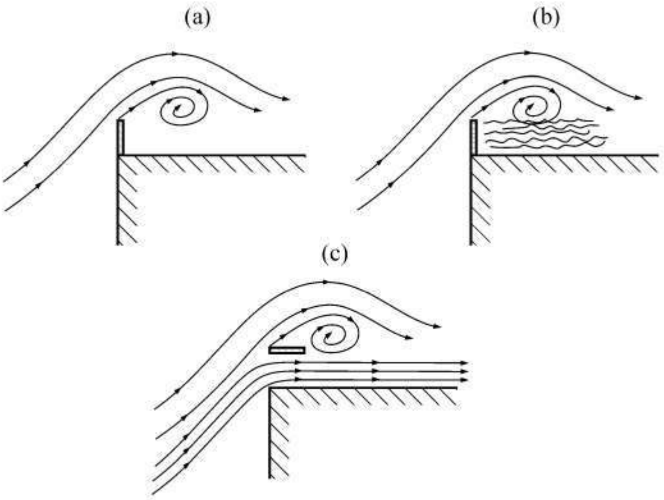


Figure 3. Sketch of a conical vortex over a roof in three different situations: roof with (a) solid, (b) porous and (c) cantilever parapets located at the roof border.

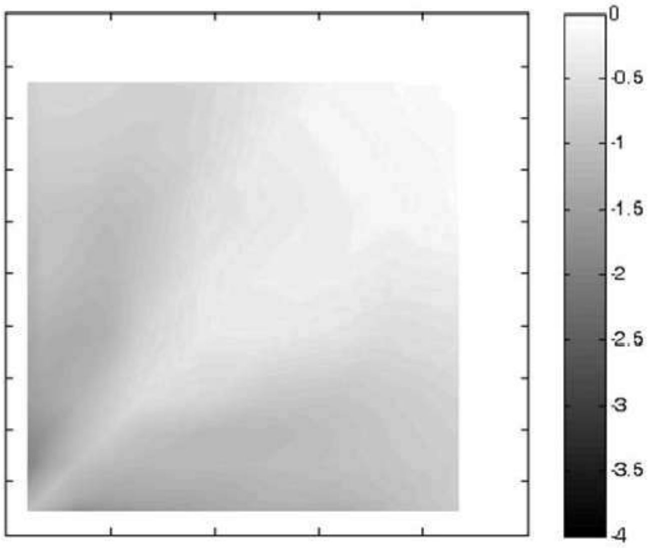


Figure 4. Pressure coefficient distribution, contours of c_p, on a low-building flat roof with vertical porous parapets located at the edges of the roof, and with 45°-oblique wind flow. The parapets height is $h/H = 0.063$, h and H being the height of the parapet and the height of the building respectively. The porosity of the parapet is $\phi = 0.28$. Data acquisition and post-processing was done in the same way as the distribution of Figure 2.

The aim of the present paper is to give some examples of the benefits (from the wind-loading point of view) of using cantilever parapets in two different construction projects: the R.C.D Espanyol de Barcelona football team stadium and the new terminal at Santiago de Compostela's airport, both in Spain. The wind-tunnel research corresponding to these projects was carried out in 2005 and 2006 respectively at the IDR/UPM institute of the *Universidad Politécnica de Madrid* (Polytechnic University of Madrid). A description of the wind-tunnel and other facilities used to carry out the results, that is, the wind action on each construction, is included in the following sections.

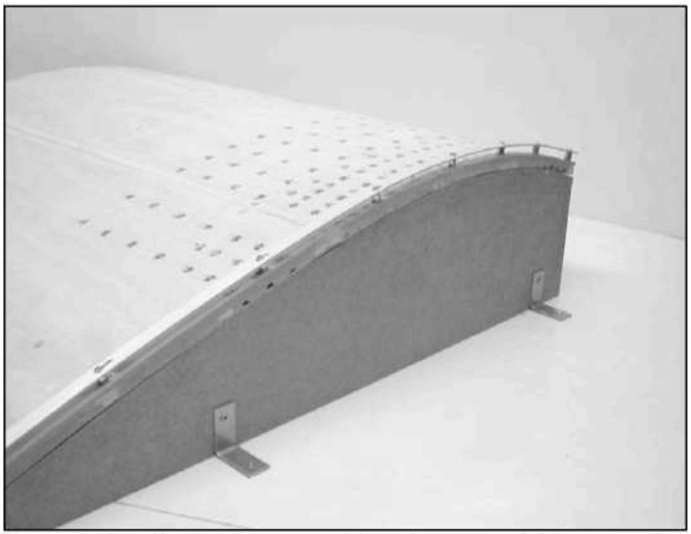
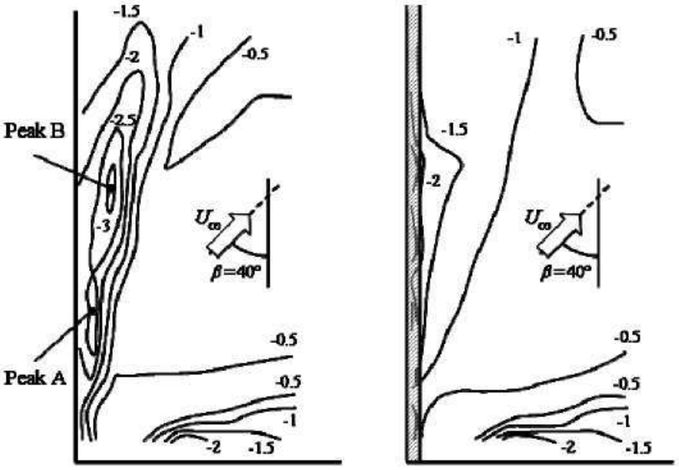


Figure 5. Cantilever parapet positioned on one of the eaves of a wind tunnel model's roof. The purpose of this research was to study the wind load on a curved roof and the effect of a cantilever parapet in order to alleviate it. See also Figure 6.



No parapet
Cantilever parapet

Figure 6. Contours of the pressure coefficient distribution, cp, measured on the roof model at wind direction β = 40°. See in the sketch that as a result of the roof's curvature a suction peak (Peak B) is developed far from the point where the conical vortex is originated. See also that the use of a cantilever parapet (shaded in the right side sketch) can greatly reduce the wind load on the roof.

2 WIND LOADS ON THE GRANDSTAND ROOFS OF R.C.D. ESPANYOL FOOTBALL STADIUM

In this section, the results of the wind-tunnel testing concerning the wind action on the grandstand roofs of the R.C.D. Espanyol football team new stadium are shown. This work was ordered by the Spanish construction company *Fomento de Construcciones y Contratas* (FCC).

2.1 *Construction of the testing model and testing campaign preparation*

To carry out the testing campaign a 1:200 scale model of the stadium was made at the workshop of the IDR/UPM. Three criteria were followed to select said scale. First of all, in all wind-tunnel experiments the cross-section of the model must not block the stream at the testing chamber of the wind tunnel (the front area of the model should never exceed 8% of the testing chamber's cross area, although there are ways of compensating the blockage effects in case of greater values). This fact represents the upper limit for the model's scale. Secondly, the model must be as big as possible to increase the Reynolds number, in order to guarantee the equivalence between wind tunnel results and full-scale loads. Thirdly, even if very small models can be designed and made, the pressure taps installation and the pneumatic connections used to measure the wind loads impose a human limit on the reduction of the scale, this limit consisting of the skill of the specialist who makes the model. The model was constructed in MDF (Medium Density Fiberboard) and 1.2 mm plywood. The pressure taps consisting of holes in the upper and lower sides of the grandstand roofs that are connected to a cavity in pairs, that is, the grandstand of the model was thick enough to have small cavities inside connected to the upper and lower sides. Each cavity was connected through 1 mm inner diameter brass tube and a pneumatic plastic tube to the pressure scanners from Scanivalve Corp.. Pictures of the model under construction are shown in Figures 7-9.

232 pressure taps were installed in the model's grandstands' roofs (116 at the upper side and 116 at the lower side). Each pressure tap was scanned at 100 Hz for 10 seconds, this sampling rate has been shown to be appropriate for scanning the mean pressure coefficients. Pressure measurements have been made dimensionless by using the values of both the static pressure and the dynamic pressure of the incident wind at the model's roof height, the pressure coefficient being defined as usual, $c_p = (p-p_\infty)/q_\infty$, where p is the mean pressure measured on each tap, and p_∞ and q_∞ are the static and dynamic pressures upstream the test model, respectively.

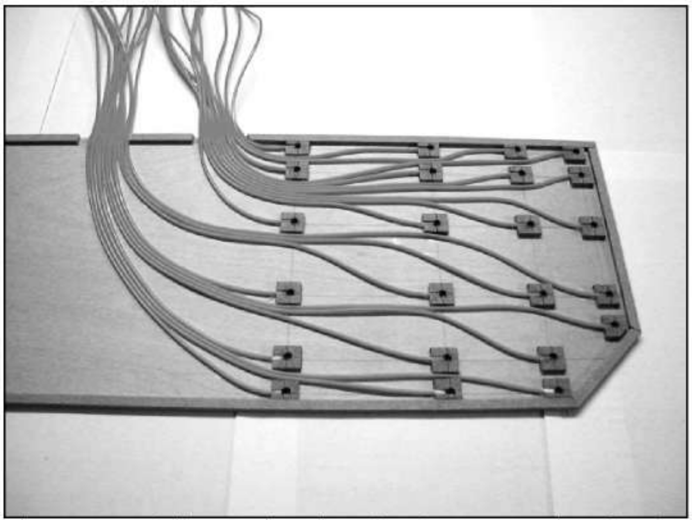


Figure 7. Model's grandstand roof under construction. See the cavities built on MDF used to connect the upper side and lower side taps with the pneumatic connexion that drives the pressure signal to the scanners. View from the lower side (that is, in the image the MDF blocks where the cavities are built are glued to the plywood surface that forms the upper side of the grandstand's roof).

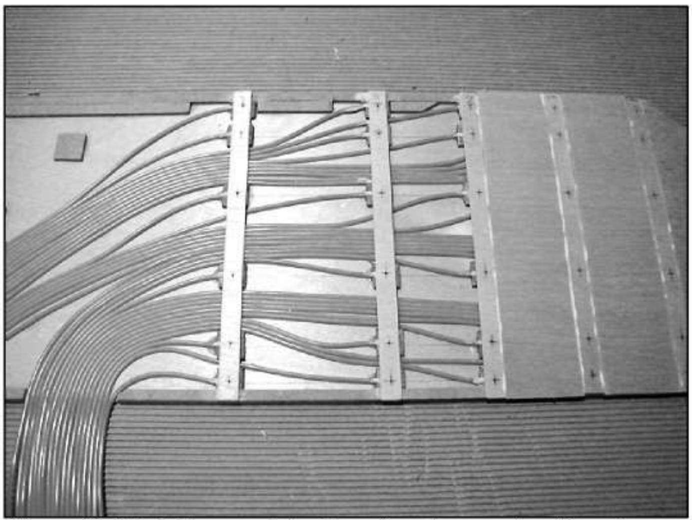


Figure 8. Model's grandstand roof under construction. Lower side of the grandstand's roof in process of being covered with 1.2 mm thick plywood.

Measurements have been carried out in the A9 low velocity wind tunnel of the IDR/UPM (see in Fig. 10 a picture of the model placed at one of the A9 wind tunnel's testing platforms). The test section of the A9 wind tunnel is 1.5 m wide and 1.8 m high. The wind velocity of the stream at the test section of the wind tunnel, at model roof height, was 22 $m \cdot s^{-1}$. No atmospheric boundary layer was simulated. Additional details on the measurement conditions are available on request from the authors.

The positions of the pressure taps are indicated in Figure 11. See that a higher density of pressure taps was set next to the corners, as conical vortices were foreseen to be formed there. From here on the four grandstand roofs of the model will be named A, B, C and D (indicated in Fig. 11). As already mentioned, the position of each pressure tap in Figure 11 indicates the position of both the tap installed on the upper surface of the grandstands' roofs and the one on the lower side. As a result of this design of the experiments, the testing campaign was carried out in two parts, one to measure the pressure coefficients of the grandstands' roofs upper surface with the lower-side taps covered with adhesive tape, and the second one to measure the pressure coefficients of the grandstands' roofs lower surface with the upper-side taps covered with the adhesive tape.

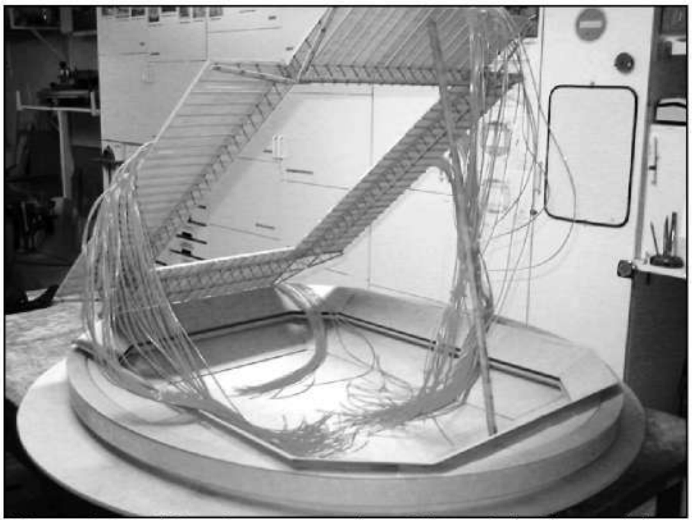


Figure 9. Model under construction. View of the lower side of the grandstands' roofs once finished.

Figure 10. Testing model of the R.C.D. Espanyol football team's new stadium placed at the testing chamber of the A9 wind tunnel.

The wind direction with respect to the model is also indicated in Figure 11. The model was tested at twenty-four different wind angles, from $\beta = 0°$ to $\beta = 345°$ at 15° steps. After this first group of experiments (first testing round), some more wind angles were tested, in order to measure the highest possible loads on the grandstands' roofs. And finally, more testing was carried out in order to see the possible influence of a cantilever parapet on the wind load on one of the grandstands' roofs.

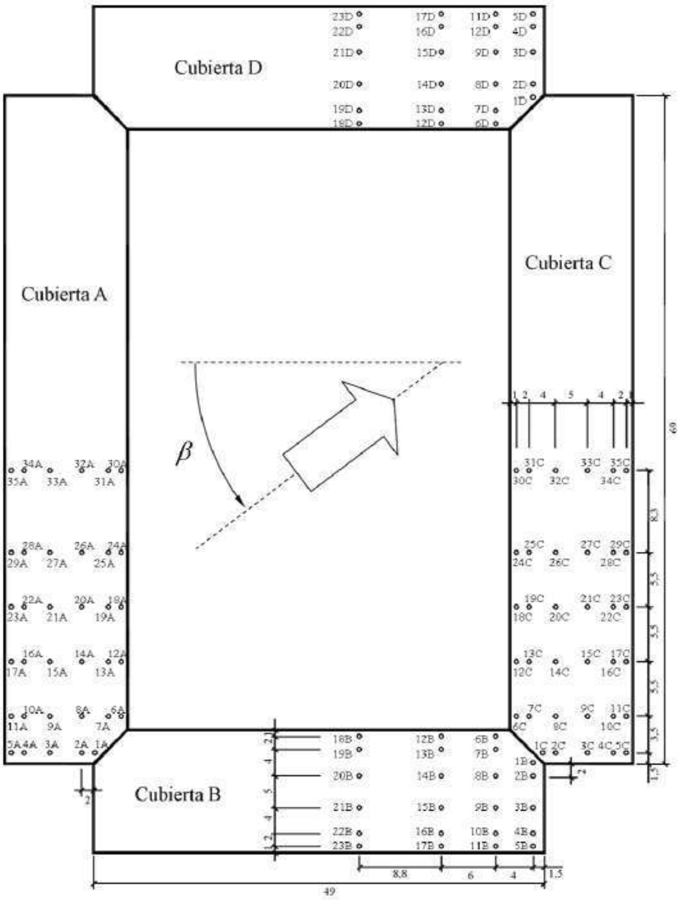


Figure 11. Position of the pressure taps on the four grandstands' roofs (A, B, C and D) of the testing model. Dimensions in mm.

2.2 *Results*

The highest suctions, $-c_{p\ \min}$, measured on each grandstand roof's upper side are shown as a function of the wind angle in Figure 12. The maximum value of these highest suctions, and the corresponding pressure tap number and wind angle, β, are included for each grandstand's roof in Table 1. The suctions included in Table 1 were measured close to the corners, as expected, but not exactly for oblique wind directions. However, high suctions were also measured on each grandstand's roof upper side for exact oblique wind angles (that is, for $\beta = 45°$ $-c_{p\ \min} = 2.35$ on grandstand's roof A, for 125° $-c_{p\ \min} = 2.2$ on grandstand's roof B, for 130° $-c_{p\ \min} = 2.32$ on grandstand's roof C, and for 240° $-c_{p\ \min} = 2.07$ on grandstand's roof D), see Figure 12.

As mentioned in the introduction, a cantilever parapet was tested in order to alleviate the suction on the grandstands' roofs upper side, see Figure 13. The results are shown in Figure 14. With the cantilever parapet installed, the maximum highest suction on grandstand roof B is reduced by 30 %.

Concerning the lower side of the grandstand's roofs, the pressure coefficient measured was in the range from −0.3 to 0.38. No differences were observed in terms of pressure coefficient on the lower side of the grandstands' roofs with the cantilever parapet installed.

In order to estimate the load on the grandstand roofs, a lift coefficient was defined as $c_l = c_{p\ \mathrm{low}} - c_{p\ \mathrm{upp}}$, where $c_{p\ \mathrm{low}}$ stands for the pressure coefficient measured on the lower side of the grandstand roof and $c_{p\ \mathrm{upp}}$ for the one measured on the upper side and at the same location. Four different zones (Z1, Z2, Z3 and Z4) were defined on each grandstand's roof to study the lift distribution (see Fig. 15).

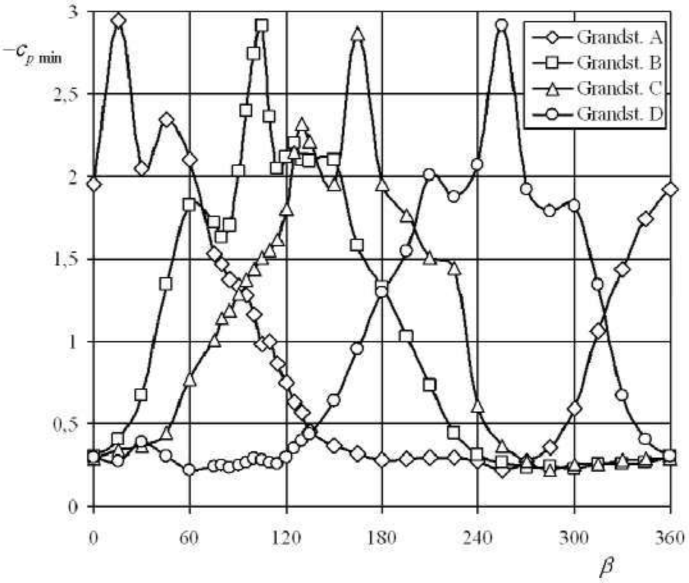


Figure 12. Maximum highest suctions, $-c_{p\ \min}$, measured on the upper surface of each grandstand's roof.

Table 1. Highest suction, $-c_{p\ \min}$, measured in each part of the model's grandstand's roof in the first testing round. The tap number and the wind direction, β, corresponding to those suction values are also included.

Grandstand roof	$-c_{p\ \min}$	Tap number	β
A	2.944	5A	15°
B	2.911	5B	105°
C	2.864	5C	165°
D	2.918	5D	255°

In Figure 16 the maximum lift coefficients, $c_{l\ \max}$, measured in zones Z1-Z4 of grandstand roof B are shown as a function of the wind angle, β. As expected, a reduction of the lift was observed when a cantilever parapet was installed on the grandstands' roof's eaves. This reduction was up to 26 % in zone Z1, which is the most loaded area.

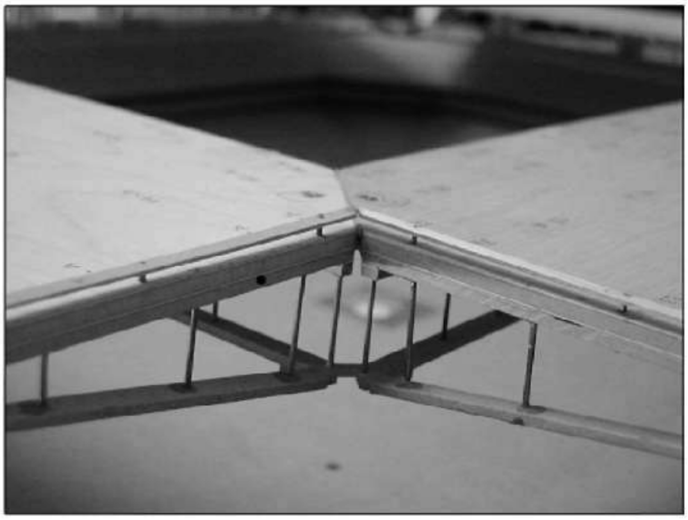


Figure 13. Cantilever parapet set on the eaves of the model's grandstands' roofs.

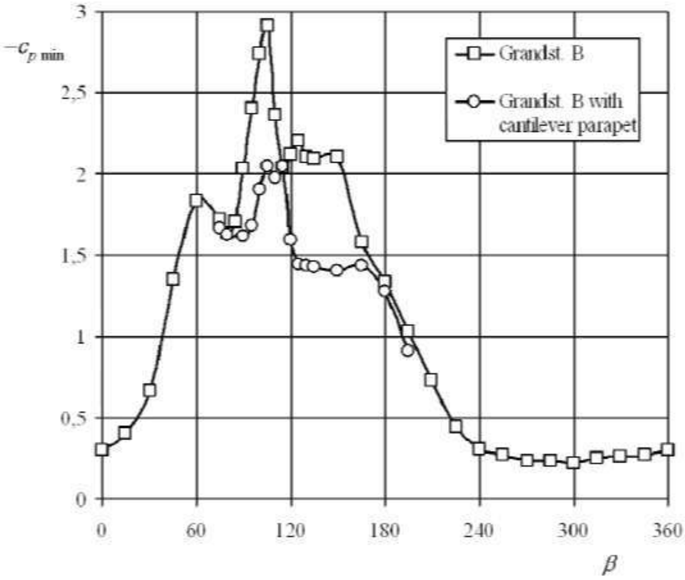


Figure 14. Maximum highest suctions, $-c_{p\ \mathrm{min}}$, measured on grandstand roof B upper surface, with and without cantilever parapet.

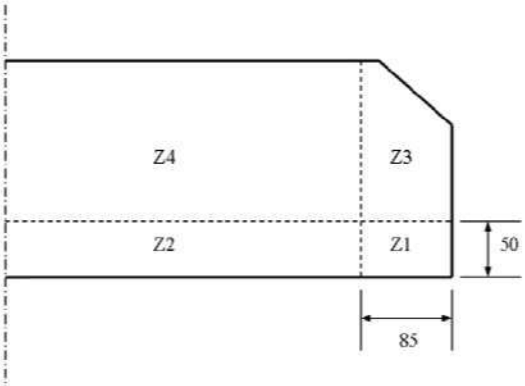


Figure 15. Different zones, Z1, Z2, Z3 and Z4, defined on the grandstand roofs of the model to study the lift distribution. Dimensions in mm.

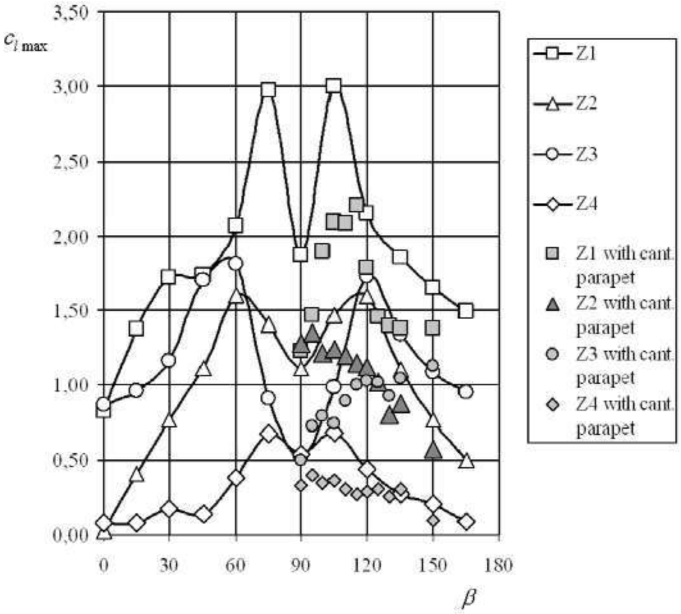


Figure 16. Maximum load measured in the zones Z1-Z4 of grandstand roof B (see Fig. 14).

3 WIND LOADS ON THE NEW TERMINAL OF SANTIAGO DE COMPOSTELA'S AIRPORT

In this section, the results of the wind-tunnel testing concerning the wind action on Santiago de Compostela airport roofs are shown. This work was ordered by the Spanish construction company INITEC.

In order to carry out the testing campaign a 1:250 scale model was made (see Fig. 17). The construction of this model followed the procedure explained in the previous section concerning the R.C.D. Espanyol football team's stadium. The terminal consists of two buildings, A and B, see Figure 18. In this case, 231 pressure taps were installed in the model as follows: 186 pressure taps on building A's roof (120 on the upper side and 66 on the lower side), 35 pressure taps on building B's roof and 10 on building B's façade. Pressure taps were more densely concentrated close to the roof corners.

The testing procedure was as explained in section 2. The model was tested at twelve different wind angles (see Fig. 18), from β = 0° to β = 330° at 30° steps. Some more wind angles, β = 105° and β = 125°, were tested in order to measure the highest loads on the roofs. Once the first group of measurements were completed, some more angles were tested again in order to evaluate the advantages of installing a cantilever parapet on one of the eaves of building A's roof (see Fig. 19). The results concerning the highest suction, $-c_{p\ \mathrm{min}}$, measured on building A's roof are shown in Figure 20. As expected, the results showed a great wind-load reduction if a cantilever parapet is installed.

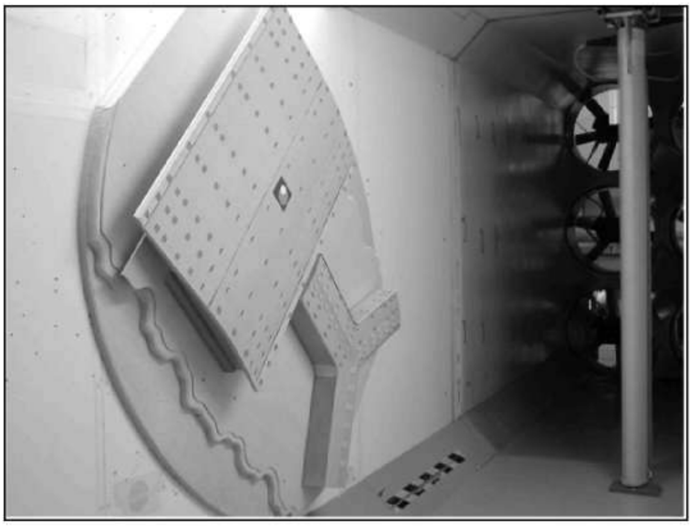


Figure 17. Model of Santiago de Compostela's new airport terminal, ready to be tested in the A9 wind tunnel of IDR/UPM.

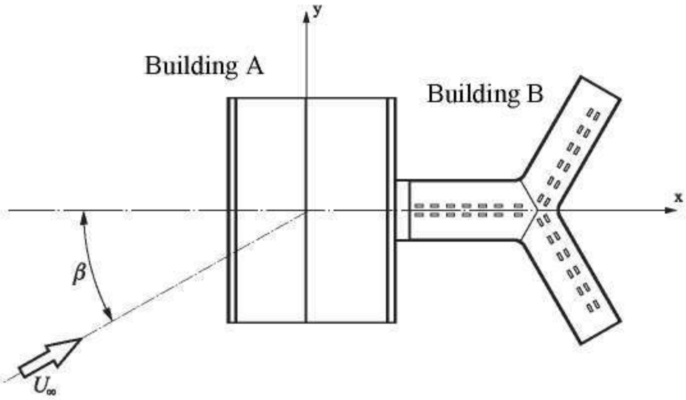


Figure 18. Sketch of Santiago de Compostela's new terminal wind tunnel model.

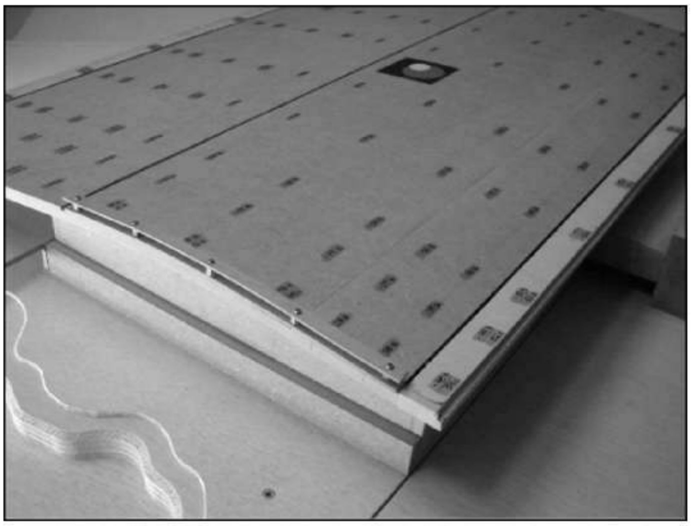


Figure 19. Santiago de Compostela's new terminal wind-tunnel model. Cantilever parapet installed on one of the eaves of building A's roof.

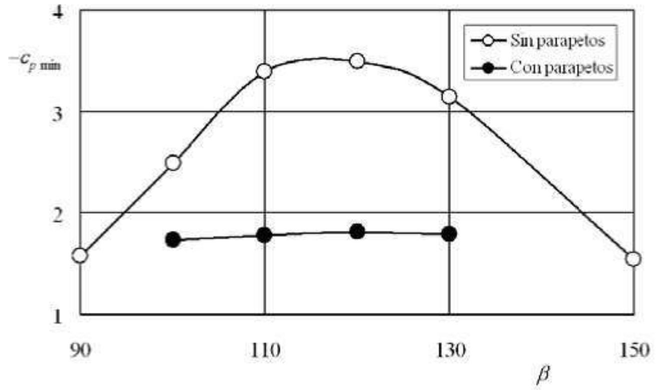


Figure 20. Maximum highest suctions, $-c_{p\ \min}$, measured on building A's roof's upper surface. Circles indicate the highest suction in the first group of measurements, that is, with no cantilever parapet installed. Closed circles indicate the highest suction measured with the cantilever parapet installed (see Fig. 19).

4 CONCLUSIONS

Cantilever parapets (or perimetric spoilers) have been shown to reduce the wind load on buildings' roofs. This device creates an air jet close to the structure's surface that can interact with other aerodynamic effects like wakes or vortices, reducing the wind load on the mentioned roofs. For this reason, the authors suggest this solution as a way of reducing wind loads on buildings and other civil engineering structures.

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