Wind loads on a curved roof over a football stadium

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Abstract:

Roofing is becoming a common practice in big sport stadiums. One of the main loads roof have to face is wind loads. The uniqueness of these constructions makes it difficult to directly use the construction codes to calculate the wind loads. Because of that, wind tunnel tests are advisable. In this case, the proposed roof over one of the bleachers of the Balaídos stadium in Vigo, Spain has been studied. The roof consists in 11 curved segments, which have been independently studied.

Wind tunnel tests are very useful to correctly understand not only the global loads but also the distribution of loads in the structure. This way, sizing of structures can be optimized, and rehabilitation works can be performed more adequately. In addition, in case of fails of a structure, they can help to understand the reasons of the failure.

The surroundings of the stadium may play an important role in the wind loads, especially when they are upstream. A model of the stadium with the roof and the surrounding buildings has been manufactured and the wind loads have been calculated for 36 different wind directions (steps of 10°). The roof has been instrumented with pressure taps both in the intrados and the extrados. As expected, high suction loads have been found in the extreme of the roof.

Highlights: wind loads, wind tunnel, roofing

1. Introduction

The roofing of big buildings faces many problems. Loads on such structures are usually big, and one of the main loads that roofs suffer is wind load. The determination of such loads is not straightforward. Lately, coding has been developed to ease the calculation. But constructions are becoming more and more complex, and the normalization of the wind loads is difficult for complex geometries. Some authors have tried to perform parametric studies of several grandstand roofs (Killen and Letchford 2001). Besides, coding is usually (and comprehensively) conservative, and it could lead to oversized structures. Wind tunnel tests have, with all their uncertainties, more bounded values of the wind loads.

Therefore, wind tunnel tests arise as a powerful tool to understand the wind loads. They are versatile and very useful in the first stages of design, since testing is relatively cheap and making changes in an already built structure can be very complex and expensive. In addition, many configurations can be tested to have a deeper view on the phenomenon, and it is fast to perform small modifications and to test them on the wind tunnel.

The validity of the wind tunnel results are guaranteed if geometric, dynamic and kinematic similarity is ensured. Many parameters influence this similarity, being the most relevant the Reynolds number, a non-dimensional parameter which compares the inertial and the friction forces. In streamlined objects, the conservation of the Reynolds number is key to ensure the validity of the tests. However, aerodynamics of bluff bodies do not have this problem once a critical value of the Reynolds number has been reached. The reason for this is that, in bluff bodies, the boundary layer created around the objects detaches when arriving at sharp edges (also in curved edges with small radius). This behavior remains for increasing velocities, so the conservation of the Reynolds number is not a requirement for non-streamlined objects. More information about validity of wind tunnel tests can be seen elsewhere (Meseguer Ruiz et al. 2013; Simiu and Scanlan 1996).

In addition, numerical aerodynamics, which have made a huge progress in last years, do not still reproduce correctly the aerodynamics of bluff bodies (the detachment and reattachment of the shear layers and vortexes are not easy to model), and therefore they cannot substitute the results obtained in a wind tunnel.

2. Experimental setup

A model of the Balaídos football stadium has been built to study the wind loads in the proposed new roofing. The selected scale is 1:200. The reason for this scale is that it allows reproducing a significant amount of the surrounding buildings and the most relevant aerodynamically relevant details. A bigger model would have been able to reproduce more details, but the model would have been too big for the wind tunnel and the surroundings of the stadium could not have been reproduced. It could have also lead to blockage of the test chamber. With the selected scale, front area of the model is smaller to 10 % of the section of the wind tunnel, so no blockage corrections were needed.

Three dimensional printing has been used to manufacture the roofing, for the ease of the pressure tap installation. The rest of the model of the stadium has been manufactured with wood. In addition, since surrounding buildings can influence upcoming wind and create wakes or whirls, they have also been reproduced with expanded polystyrene. The set with the model and the buildings has been place in a wood plate, which is mounted in a positioner, which can rotate the whole set. All this set has been placed in the wind tunnel floor. The whole model in the wind tunnel can be seen in Figure 1.

The new roof covers one of the tiers. The cover is divided in 11 different segments. Each of the parts has been instrumented with 20 pressure taps, located in the center line of each segment. 11 of the pressure taps are in the extrados of the cover and 9 in the intrados. 9 of the taps of each sides are opposed to each other, but in the part of the cover closer to the tier, the intrados cannot be instrumented, and only two taps on the extrados are left. More taps could have been installed, but the tubes that connect the taps with the pressure measurement system would have been too much and the thickness of the cover, which is already not totally in scale, would have increased.

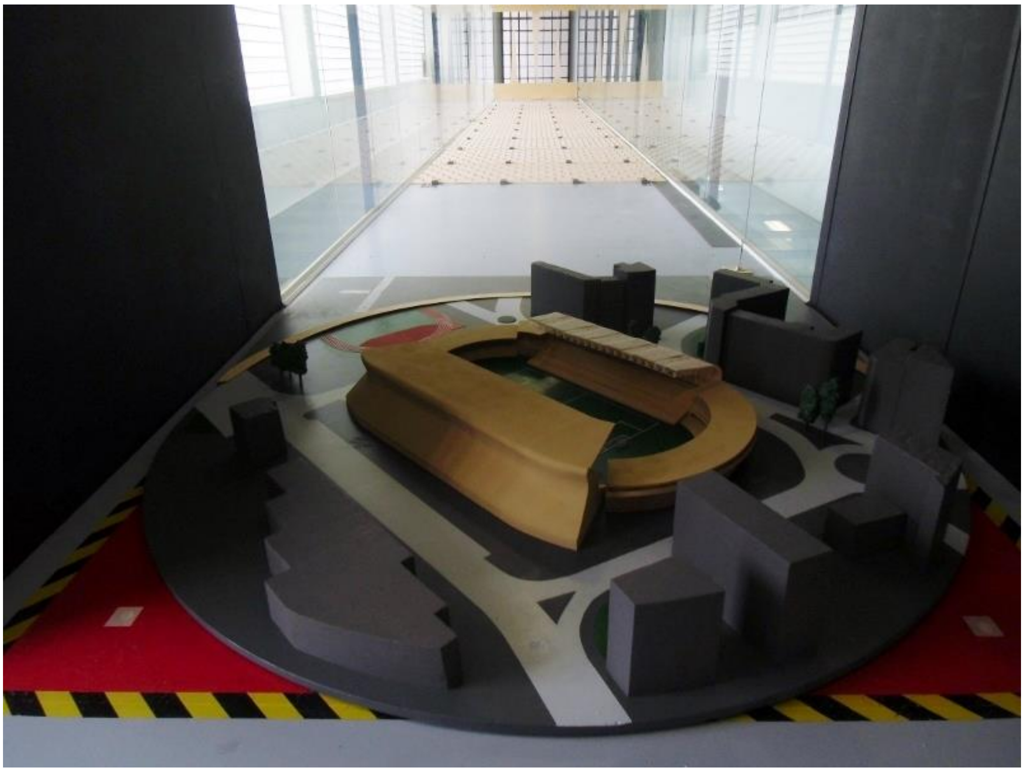

Figure 1 – Picture of the model placed in the wind tunnel. Upstream, roughness elements reproducing atmospheric boundary layer can be seen

The position of the taps depends on the segment (each one of them has a different geometry), but all of them are close to the positions presented in Figure 2. In the same Figure, it can be seen that the roof has a small but not negligible angle of attack. This study allows having the distribution of loads for each segment and each pair of taps, not only the overall wind load can be calculated but also the individual wind loads are known. This way, the lattice that supports the loads can be optimized.

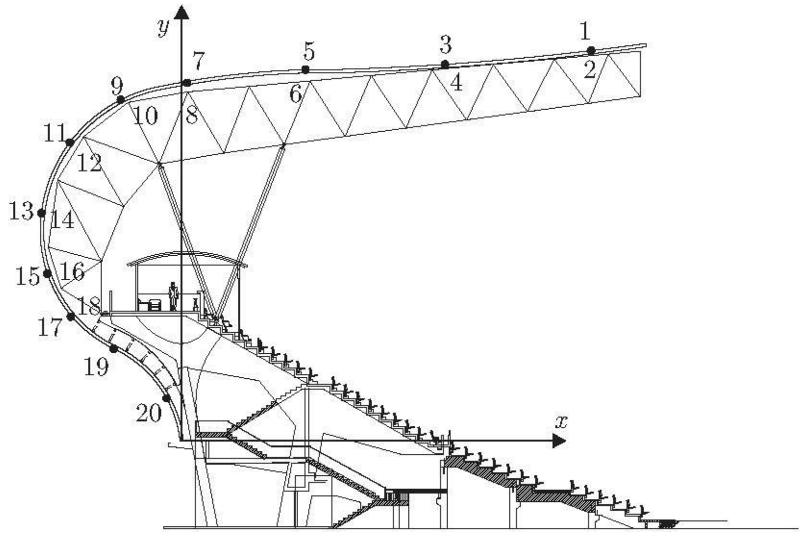

Figure 2 – Position of the pressure taps on a segment. Taps 1-18 are placed in pairs (odd taps in the extrados, even taps in the intrados), and taps 19 and 20 are placed without their counterpart in the intrados

The segments have been named A-K, as can be seen in Figure 3. Segments are in a mirrored position: segments A-K, B-J, C-I, D-H, and E-G are equal to each other, whilst the central one, segment F is unique. Overall, 220 pressure taps have been installed in the model.

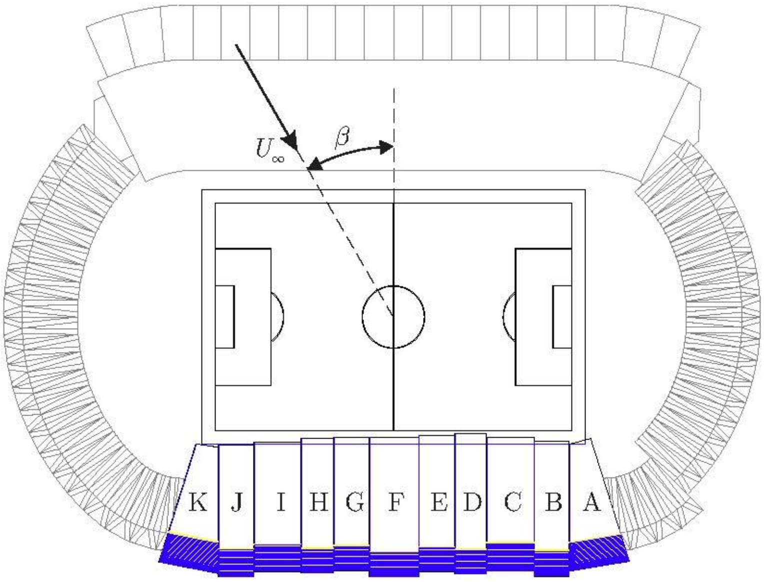

Figure 3 – Naming of the eleven segments and definition of the yaw angle, β

The measurement procedure is simple. The pressure measurement has been acquired with a sampling frequency of 100 Hz for 60 seconds. After measuring, the yaw angle (see its definition in Figure 3) has been adjusted to a new one, and process has been repeated. The yaw angle has been varied in steps of 10°, from 0° to 360°.

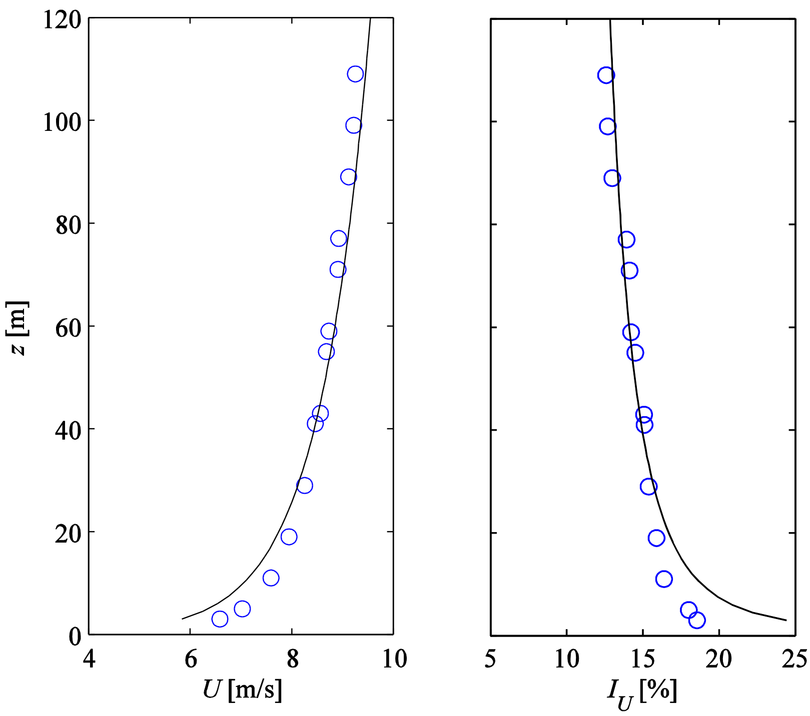

Figure 4 – Vertical profile of wind velocity (left) and turbulence intensity (right) in the wind tunnel (blue circles) and in the Eurocode model (black line)

Upstream the model, in the wind tunnel, roughness elements have been placed in order to reproduce the boundary layer to the appropriate scale. In this case, a type II boundary layer has been placed, according to Eurocode (European Committee for Standarization 2004). Figure 4 presents the obtained results of the measured boundary layer (blue circles) and the objective type II terrain (black line). On the left, velocity profile is displayed, and on the right, turbulence intensity profile. These measurements have been done with a 2 component hot wire anemometer.

In addition to this, a pitot tube has been placed upstream, set to a height of 10 meters in the prototype scale. The pitot allows to measure the dynamic pressure and to calculate the wind velocity.

3. Results

In this section, the results obtained are explained. With the pressure measurements, the pressure coefficients have been computed. These coefficients are defined for the i^{th} tap in the usual way:

$$c_{pi} = \frac{p_i - p_\infty}{q_\infty} \tag{1}$$

where p_i is the pressure measured in the i^{th} tap, p_∞ the static pressure, and q_∞ the dynamic pressure. With this definition, negative value of c_{pi} means suction and positive value of c_{pi} means overpressure. For the taps that appear in pairs (one on the extrados, one on the intrados), the net pressure coefficient has been computed as:

$$c_{p,net} = c_{p,E} - c_{p,I} \tag{2}$$

The time series of the pressure coefficients have been calculated. With these time series, the average and the standard deviation have been calculated.

For each pair of taps (or single tap for taps 19 and 20 of each segment), a graph can be obtained presenting the value of the net pressures coefficient against the yaw angle of the wind. An example of this can be seen in Figure 5. In that Figure, the mean value of the net pressure coefficient is displayed. The positive peaks at 150° and 250° may be created by vortexes shed by buildings that at those yaw angles, are upwind the roof of the stadium

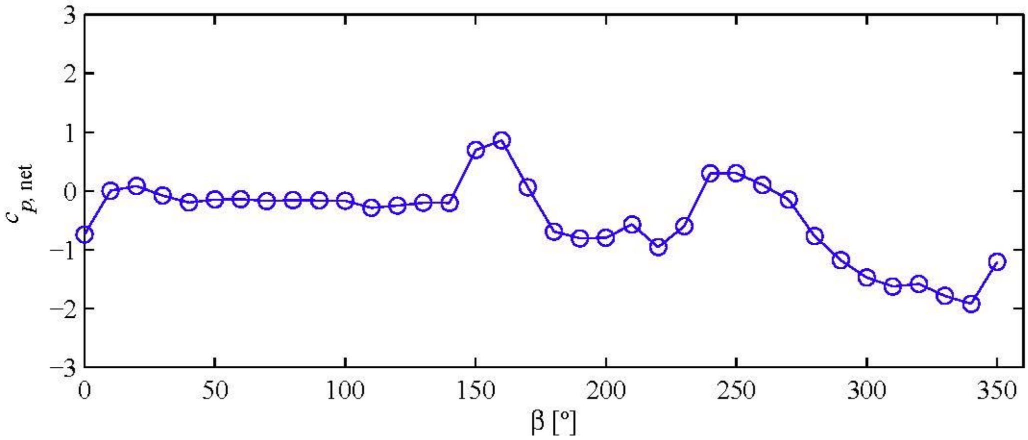

Figure 5 – Net pressure coefficient for pair of taps 9-10 of segment A against the yaw angle of the wind

Designers and builders are usually concerned about the extreme values more than about the mean values. Statistics show that for a time series with a normal distribution, Extreme values can be calculated as

$$c_{p,ext} = \bar{c}_p \pm k\sigma_{c_p} \tag{3}$$

where $\bar{c_p}$ is the mean value of the pressure coefficient, σ_{c_p} the standard deviation of the pressure coefficient and k a coefficient that depends on the confidence interval desired. The positive or negative sign of this equation is selected depending the mean value: if it is negative, the $k\sigma_{c_p}$ term should be subtracted from the mean value, otherwise it should be added. For a time series with a normal distribution, the values of k and its corresponding confidence intervals can be seen in Table 1 (Navidi 2011). In this study, a value of $k = 2$ has been selected, covering a confidence interval of 97.7%.

Table 1 – Values of k and its corresponding confidence intervals

$\boldsymbol{k}$	$\boldsymbol{P}(\%)$
1	84.13
2	97.72
2.5	99.38
3	99.87

Therefore, the extreme values of each pair of taps can be calculated for each yaw angle. Each pair will have a maximum and minimum value of the extreme values of the pressure coefficients, probably located at different yaw angles. For example, in Figure 5, for taps 9-10 of segment A, the maximum is located at 160°, whilst the minimum is located at 340°. Putting together all this maximums and minimums, the envelope of the loads can be obtained.

Figures 6 to 16 present the envelope of the pressure coefficients for each sector. In red, the maximums are displayed, and in blue, the minimums. Negative values represent suction and positive values represent overpressure. It is important to remark that pressure coefficients in taps 19 and 20 are not net pressure coefficients, since they do not have a counterpart in the intrados.

Results show that for most segments, pair of taps 1-2 have the most negative pressure coefficient. This is not unexpected, since the wind probably creates a vortex from a shear layer detached from the leading edge of the roof, which is a low pressure area, that generates suction in the extrados. In the intrados, the air is enclosed (stagnation zone), and strengthens this phenomenon. For the minimum value (blue circles), pair 1-2 seems to have a different behavior to the others, which have an almost equal value. The pressure coefficient in pair 1-2 can be even two times bigger than the rest of pairs (see Figure 14, corresponding to segment I).

In most sectors, in taps 1-8 approximately, the negative loads are, in absolute value, bigger than the positive loads. This means that overall, the area that cover those taps is more likely to suffer suction (force in positive axis y according to Figure 2) than overpressure.

Some of the pairs reach positive values of the pressure coefficient over 3. This means a big overpressure, which is usually located in the pair of taps located approximately in the part of the segment with more curvature (pairs 11-12 and 13-14).

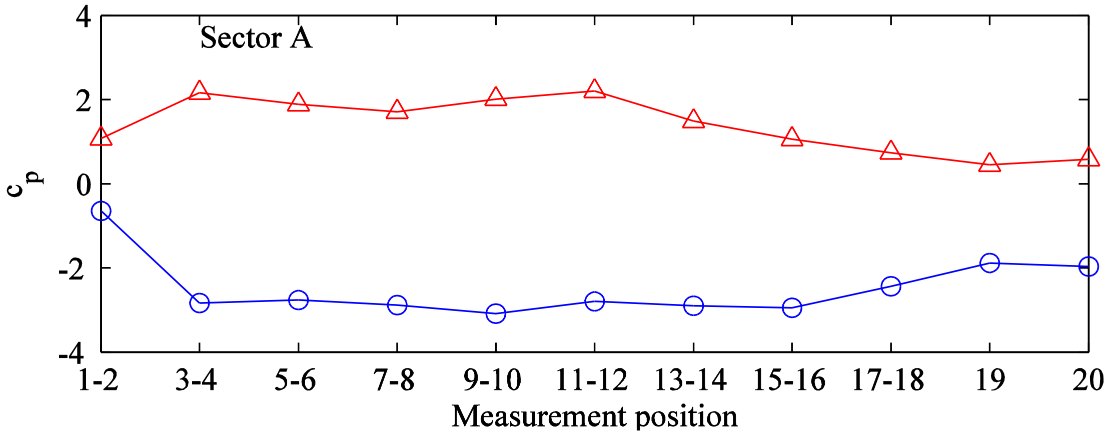

Figure 6 – Envelope of extreme wind loads on sector A

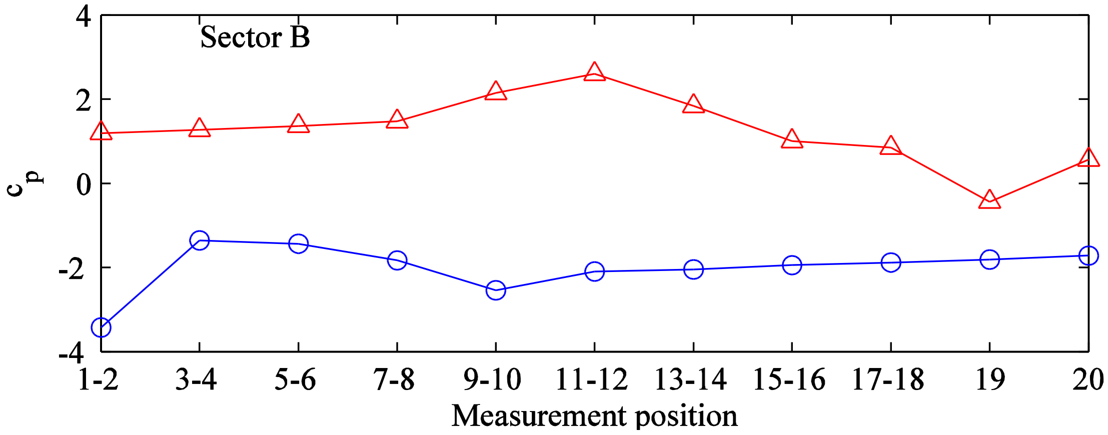

Figure 7 – Envelope of extreme wind loads on sector B

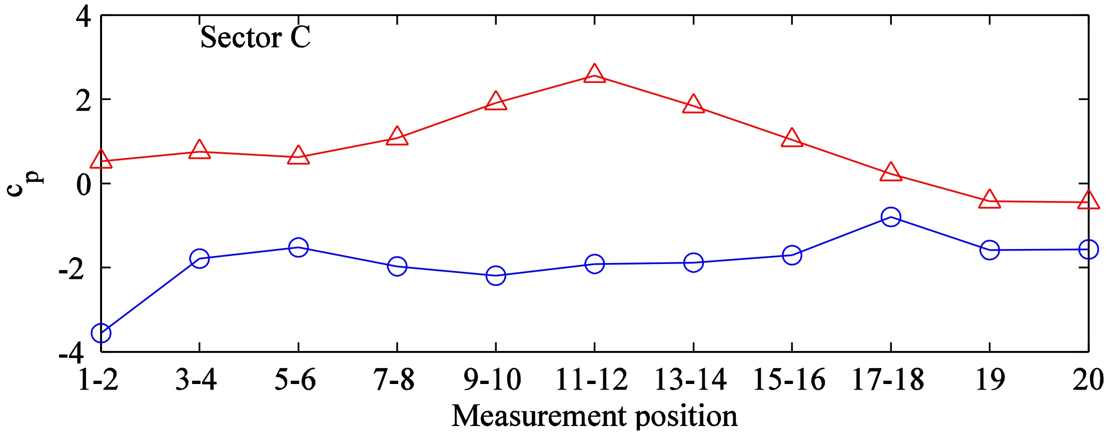

Figure 8 – Envelope of extreme wind loads on sector C

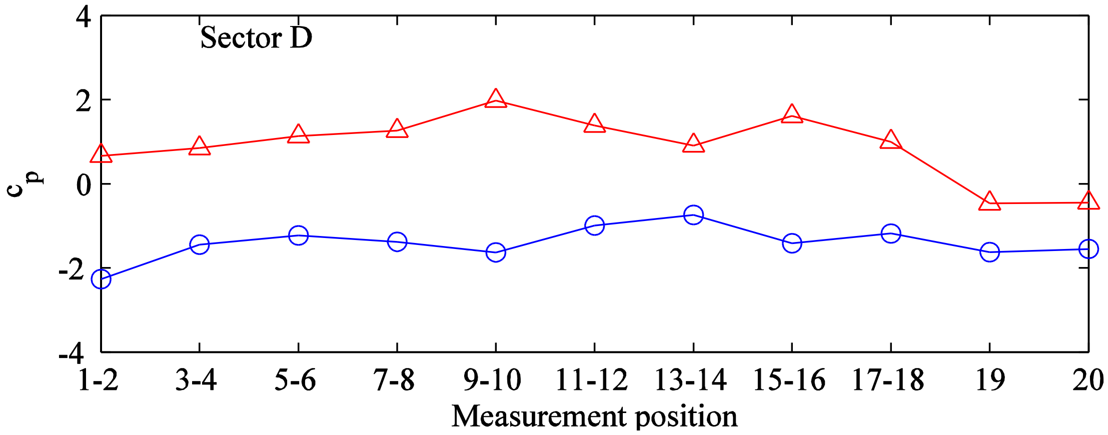

Figure 9 – Envelope of extreme wind loads on sector D

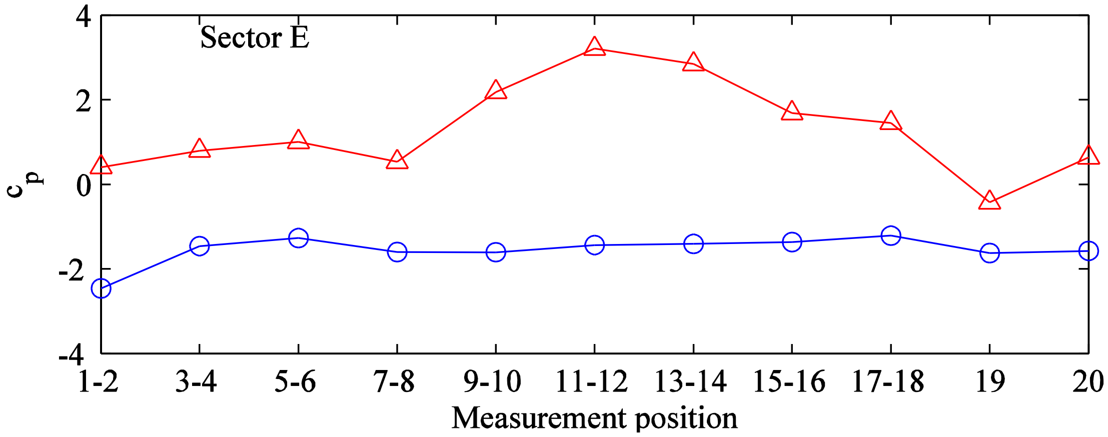

Figure 10 – Envelope of extreme wind loads on sector E

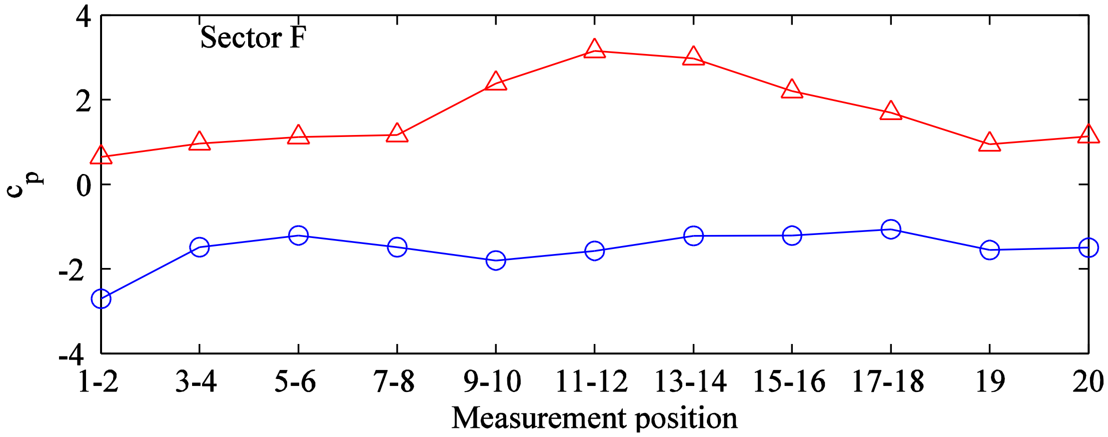

Figure 11 – Envelope of extreme wind loads on sector F

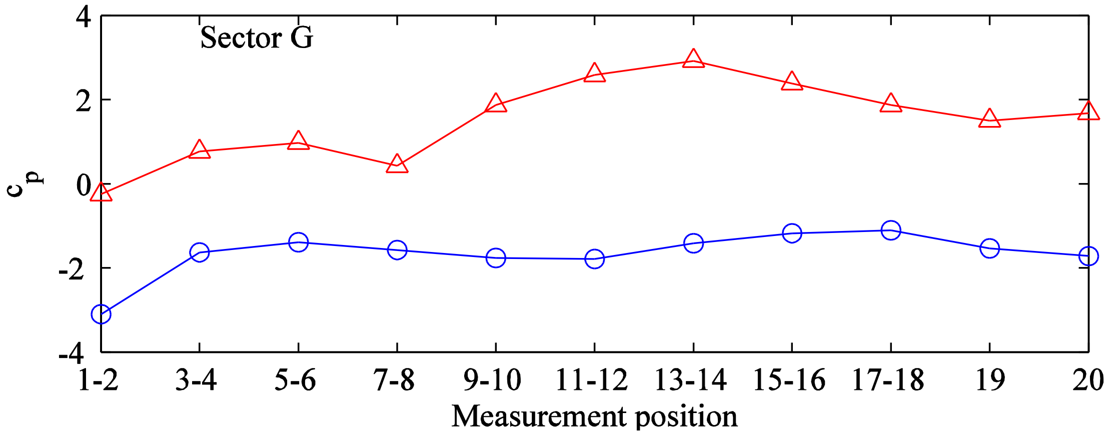

Figure 12 – Envelope of extreme wind loads on sector G

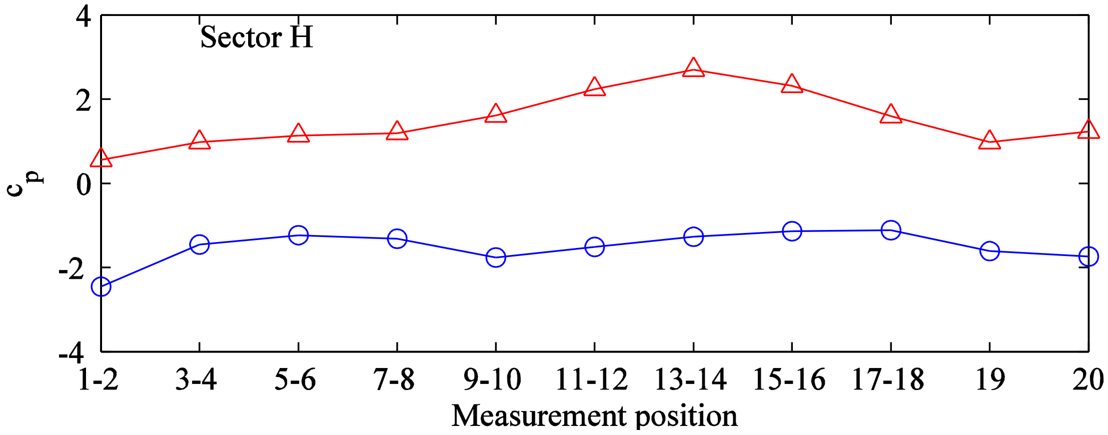

Figure 13 – Envelope of extreme wind loads on sector H

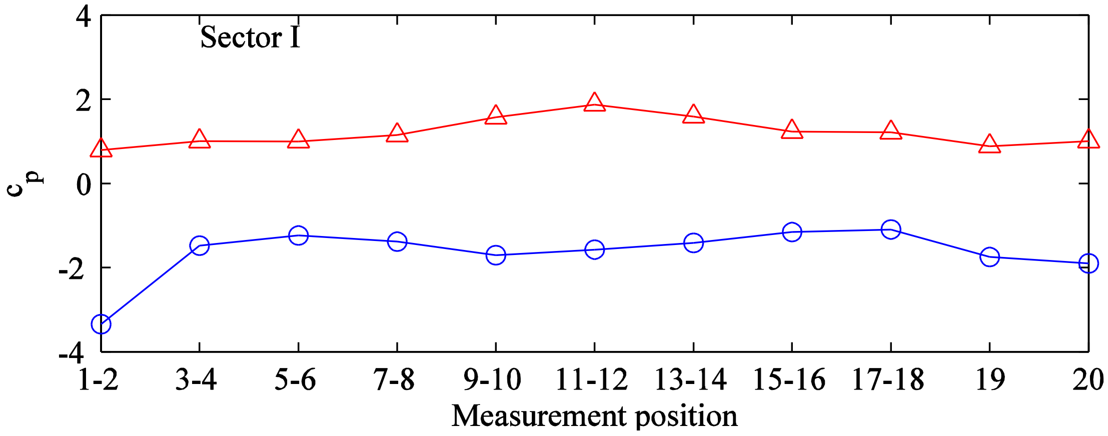

Figure 14 – Envelope of extreme wind loads on sector I

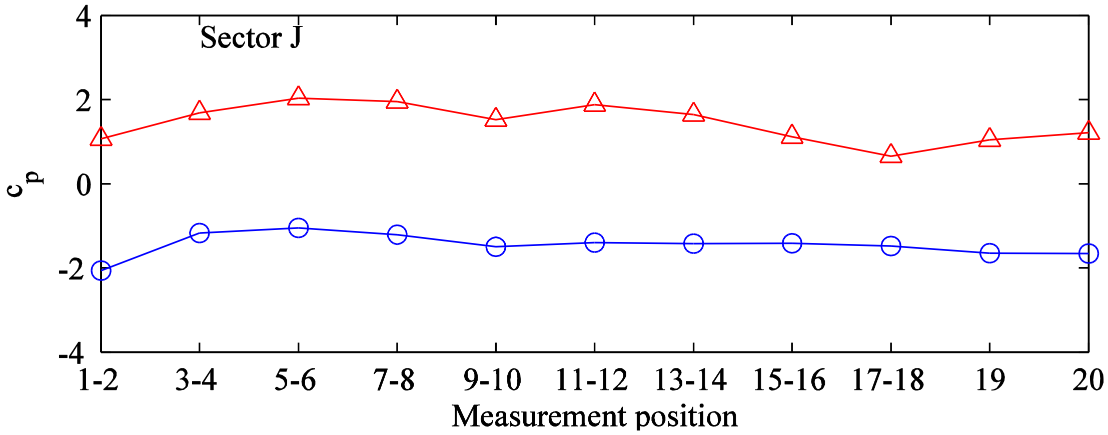

Figure 15 – Envelope of extreme wind loads on sector J

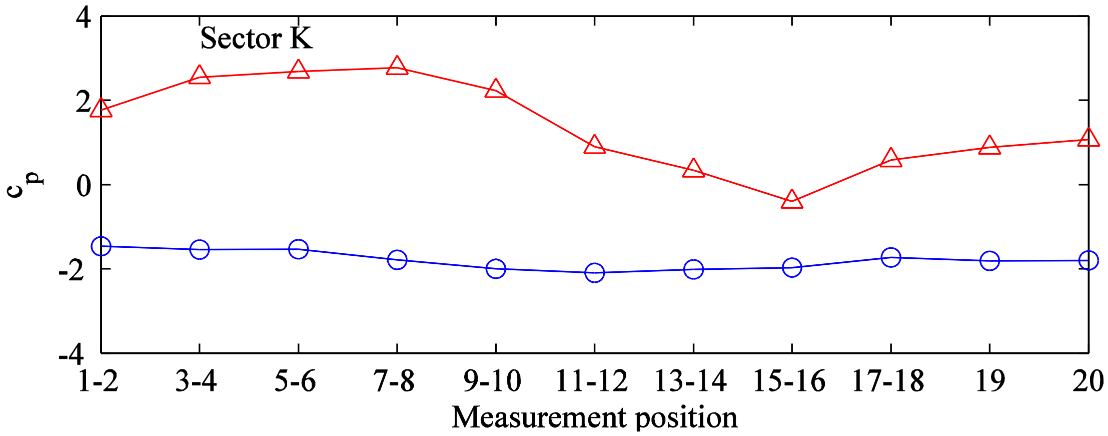

Figure 16 – Envelope of extreme wind loads on sector K

Concluding remarks

Wind loads on a roof are highly dependent on the yaw angle of the wind. Wind tunnel tests are a useful tool to understand the wind distribution in singular structures such as big roofs of stadiums. In comparison with codes, which are conservative, wind tunnel tests let us comprehend more deeply the behavior of the air, and to adjust the design wind loads to more realistic ones (Williams et al. 2003). With the information obtained in wind tunnel tests, structures can be optimized. Therefore, for complex geometries, wind tunnel tests are usually advised.

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