

WIND-TUNNEL TESTS AND DESIGN LOADS OF THE ROOF OF THE NEW KARAIKAKI OLYMPIC STADIUM IN PIRAEUS

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Abstract

The paper presents the experimental tests carried out in the Boundary-Layer Wind Tunnel (BLWT) for the design of the roof of the new Olympic soccer stadium in Piraeus, Greece, and some results of the Finite Element (F.E.) analyses performed. The roof covers all the stands of the stadium and is supported by 14 cantilevered steel lattice structures with a span of about 33 m. Due to the vicinity of the site to the sea, the wind loading has an important influence on the design of the roof, whose peculiar shape let arise some doubts about the actual distribution of the wind loads, i.e. on the pattern of pressure coefficients (c_p) over the entire roof. For every wind direction investigated, the following quantities have been evaluated: mean values of the aerodynamic coefficients c_p , standard deviation of c_p , maximum and minimum values of c_p . Finally, the recorded data have been used for the numerical simulation of the dynamic response of the structure in Time Domain, whose aim is the definition of the design loads of the steel lattice structures.

1 Introduction

Experimental tests have been performed in the Boundary-Layer Wind Tunnel (BLWT) of the CRIACIV in Prato, close to Florence [AUG95], on the rigid model of the new Olympic soccer stadium in Piraeus, Greece. The BLWT model (Figures 1 and 2) (in scale of 1:250) includes also the neighbouring buildings within a distance of 250 m from the centre of the football field (Figure 3). The roof of the model has been equipped with 252 taps: 126 taps at the extrados of the roof surface and 126 taps at the intrados, in order to measure the net pressure at each point. In the model the roof of the stadium has a box structure in order to allow for the settlement of the pressure taps inside. The distribution of the pressure taps on the whole roof and their influence areas are shown in Fig. 4.

The tests have been performed for 20 wind directions in three sets of measures; in each set, only half of the pressure taps were connected (in the first set only the North side and in the second one those in the South side, instead in the last test crisscross measurements have been carried out).

Data refer to the measured net pressures at the 126 couples of taps. The time histories of the recorded pressures have been divided by the dynamic pressure at the mean height of the roof (103 mm in the model scale, about 25 m at full scale) to obtain the pressure coefficients. Subsequently the data have been filtered using a low pass filter up to 40 Hz in order to clean up the processes from the noise due to the wind tunnel disturbances (engine, fan, own resonance, etc.).

The model has been built in a geometric scale of 1:250 and includes: the roof, the stands, all the structures of the stadium, and other private and public buildings not far more than 250 m (at full scale) from the centre of the stadium. The geometric scale has been chosen in order to fulfil the similitude laws for tests in the BLWT. In turn the extension of the model around the stadium was dictated by the chosen scale and by the diameter (2 m) of the rotating platform over which the model has been placed in the wind tunnel.

A box structure with a minimum thickness of about 7 mm has been required for the roof structure to allow for the insertion of the pneumatic connections. The location of the pressure taps has been chosen

¹ CRIACIV: Inter-University Research Centre in Building Aerodynamics and Wind Engineering, grouping the Universities of Florence, Rome "La Sapienza", Perugia and Trieste.

to cover the whole roof surface; Figure 2 shows the position of the pressure taps and the influence area of each pressure tap. Each position identifies a couple of taps, the one at the intrados and the other at the extrados, which lay on the same vertical and are spaced out by the thickness of the box structure of the roof.



Figure 1. Top view of the stadium's model.



Figure 2. View of the BLWT model.



Figure 3. Circle which identifies the location of the buildings included in the BLWT model.

The influence areas have been obtained performing a triangulation among the pressure taps and linking the centre of mass of the identified triangles.

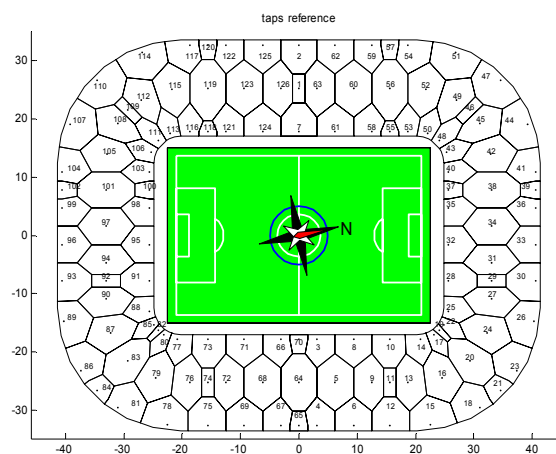


Figure 4. Position of the pressure taps (each position corresponds to a couple of pressure taps, one at the extrados and the other at the intrados of the roof).

The pressure measurements have been performed using piezoelectric transducers linked to the pressure taps through Teflon pipes, properly optimised to get a good dynamic response in the frequency range of interest.

2 Experimental tests

Tests have been performed in two phases: the first phase consisted in the characterization of the most appropriate wind profile in the BLWT, and the second one in the identification of the pressure coefficients on the roof of the stadium. Because of the great number of pressure taps (252), the second phase required three distinct measurement sets.

It is well known that the pressure coefficients are substantially independent from the wind speed adopted in the tests, as one can easily verify performing the same tests with two or more different mean wind velocities, at least for all those phenomena which are not highly Reynold's number dependent. So, the essential parameters for a meaningful reproduction of the real/actual wind conditions of the site are the mean wind profile (variation law of the mean velocity over the height) and the turbulence characteristics, i.e. the (longitudinal) integral length scale.

2.1 Wind Profile

As the stadium is located near to the sea (Figure 5), a "sea wind profile" has been simulated in the BLWT. The target profile parameters at full scale are listed below and have been taken from literature and laboratory expertise, as they seem to be a good approximation of the wind profile in the area:

profile exponent	$\alpha = 0.15 \div 0.18,$
roughness length	$z_0 = 50 \div 150 \text{ mm},$
integral length scale	$L_U = 50 \div 100 \text{ m}.$



Figure 5. Geographic location of the stadium.

The final configuration of the BLWT has been chosen after a series of preliminary tests with different roughness conditions and devices at the inlet of the tunnel (such as Couhnan devices and "spires"). The floor roughness has been created using plywood panels placed in the BLWT zone 8 m long from the inlet. The dimensions of each panel were 220 cm x 80 cm and each panel was equipped with wood cubes, whose dimensions were 10x10x10 mm, 15x20x20 mm and 20x20x20 mm. In the test section the height of the generated boundary layer was equal to about 70 cm.

Measurements of the wind velocity have been performed through a hot-wire anemometer, positioned in 19 points along the vertical passing through the centre of the test section. For each point, a sample of 40 s has been recorded, at a sampling frequency of 2000 Hz, for a total amount of 80000 data for each position.

On the whole the wind velocity has been measured in 19 points at different levels (from 50 to 853.5 mm), in order to cover the entire height of the boundary layer. The mean wind speed at the mean level of the stadium's roof was equal to 17.95 m/s \cong 18 m/s.

The exponential approximation of the measured wind velocities gives (considering only the first 14 points, that is for heights lower than 60 cm) the value $\alpha=0.171$, while the logarithmic approximation gives the value $z_0=0.560$ mm. The roughness length corresponds, at full scale, to a value $z_{0,real} =$

$z_{0,windtunnel} \times 250 = 140$ mm, in agreement with the hypothesis of wind profile over a flat terrain or over the sea. The same values, obtained through the exponential approximation of the whole profile (19 points), are respectively equal to $\alpha=0.17$ and $z_0=0.55$ mm. Table 1 summarizes the characteristics of the wind profile obtained in the BLWT.

Height of the boundary layer	$\delta > 60$ cm
Profile exponent	$\alpha \approx 0.17$
Roughness length	$z_0 \approx 0.55$ mm
Integral length scale	$L_{ux} \approx 25-35$ cm

Table 1 – Characteristics of the BLWT wind profile.

2.2 Pressure measurements

Three measurement sessions have been performed. The first two sessions have been required to acquire all the 126 couple of pressure taps (63 couples for each session, that is 126 pressure taps at the same time), while third session has been performed to evaluate the correlations among roof portions located approximately at the centre of the four sides of the roof. In the first session only the pressure taps located in the North side have been linked to the pressure transducers, while in the second session only those on the South side have been instrumented. This subdivision was suggested by the quasi-symmetry of the stadium with respect to its transversal axis.

Twenty different wind directions (Table 2) have been investigated in the first two sessions and only four directions in the third session of crisscross measurements. Considering a reference system coincident with the geographical axes, the position corresponding to 0° coincides with the North direction, which is offset of 11.7° with respect to the longitudinal axis of the stadium in the counter clockwise sense (see Figure 6).

0°	22.5°	45°	67.5°	78.3°	90°	112.5°	135°	157.5°	168.3°
North		N/E		Stadium East axis	East		S/E		Stadium South axis
180°	202.5°	225°	247.5°	258.3°	270°	292.5°	315°	337.5°	348.3°
South		S/O		Stadium West axis	West		N/O		Stadium North axis

Table 2. List of the wind directions investigated (bold character highlights the directions of the axes of the stadium).

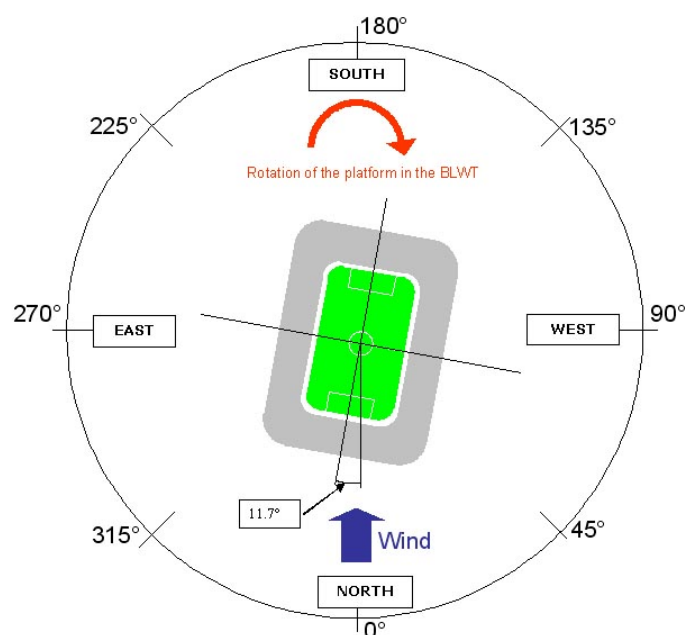


Figure 6. Reference system for the wind direction.

2.3 Maximum, mean and minimum pressure coefficients

For each wind direction, the dynamic pressures at all the instrumented pressure taps have been logged, registering time histories 30 seconds long at a sampling frequency of 250 Hz. The measured time histories have been normalized by the kinetic pressure at the reference level to obtain the time histories of the pressure coefficients:

$$c_p(t) = \frac{p(t) - p_0}{\frac{1}{2} \cdot \rho \cdot \bar{U}_{ref}^2}, \quad (1)$$

where the reference level is the mean height of the roof (103 mm in the model scale). For each couple of pressure taps, the time history of the net pressure has been obtained: e.g., given the position no. i , denoting the time history of the pressure tap at the intrados by SP_i^{in} and that of the tap at the extrados with SP_i^{ex} , the time history of the net pressure is equal to: $SP_i^{net} = SP_i^{ex} - SP_i^{in}$. Figure 7 shows the distribution of the mean values and standard deviation of the net pressures for the wind direction of 0° (North).

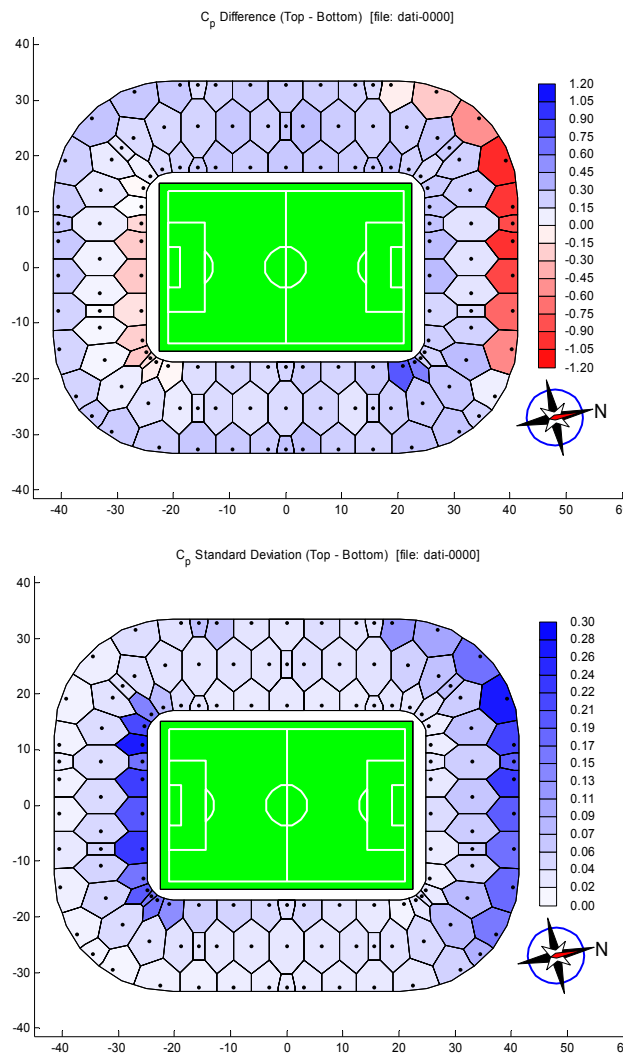


Figure 7. Mean values and standard deviations of net pressure coefficients (wind direction: 0° = North).

Then the maximum and minimum values of all the time histories of the net pressures have been calculated using the Gumbel method. Firstly each time history has been subdivided into n time windows of equal duration and the maximum and minimum values of each time window have been determined.

Secondly the n values obtained for the maxima (and the n values obtained for the minima) have been put in the ascending order and reported on a Gumbel chart. Through the BLUE correction (Best Linear Unbiased Estimators), the values of the parameters which characterize the distribution of the extreme values of each pressure coefficient have been obtained. The design value, maximum or minimum, has been finally obtained as the value which, in the distribution of the extreme values, has a probability of 22 % to be overcome, according to the instructions given by Cook and Mayne [COO80], and according to the procedure which has been utilized also in the drafting of the Eurocode 1. Before applying this procedure, a 40 Hz low-pass filter has been applied to the registered time histories. The filter has been used to eliminate the noise due mainly to the BLWT motor. This technique does not change the mean values of the pressure coefficients c_p , but reduces the maximum and minimum values.

3. The numerical model

The results of the wind tunnel tests have been used to perform numerical simulations in Time Domain of the whole structure of the stadium. Thus, a complete numerical model of the structure (Figure 8) at full-scale has been created using the well known FEM software SAP 2000 [SAP03].

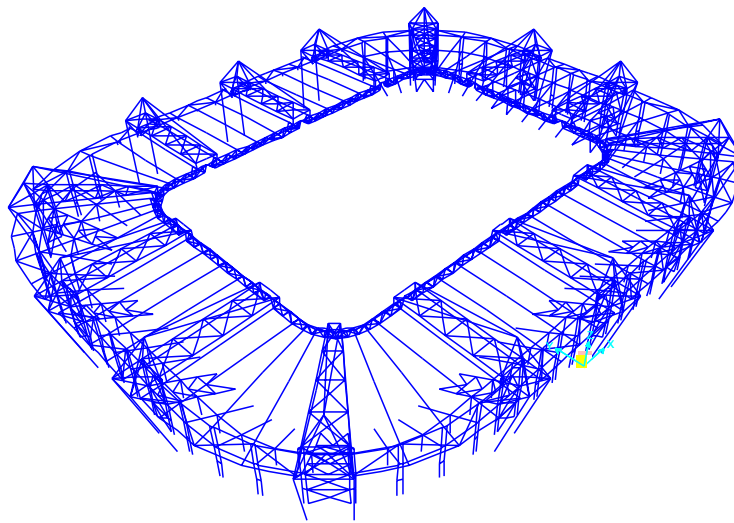


Figure 8. View of the numerical model of the stadium.

The model includes the roof structure and the stands; it consists of 3779 linear elements and has 9708 DOFs. The roof is subdivided into portions, being each portion included between two successive cantilever structures. All the portions of the inner lattice beam of the roof are simply suspended to the lattice cantilevers, so that each portion behaves independently from the others.

Firstly a modal analysis has been run to evaluate the main eigenfrequencies of the structure. The mode shapes associated with the first 35 eigenfrequencies are similar to those shown in Figure 9, while after the 35th mode shape one can observe only local mode shapes.

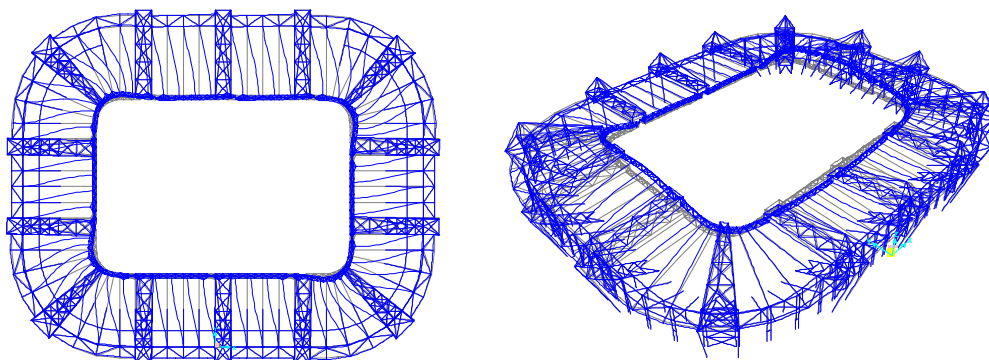


Figure 9. First (0.82 Hz) and third mode (0.96 Hz) shape of the structure.

Once determined the dynamic properties of the structure, the registered time series referring to the wind direction of 78.3° have been used to apply the wind load in the computational model, where additional nodes have been inserted in correspondence of the pressure tap positions.

Taking into consideration the ratio between the quantities at full scale (marked with the symbol “r”) and the corresponding quantities in the model scale (symbol “m”), the relation between the mean velocity, the time and the length is:

$$\frac{\bar{U}_r \cdot T_r}{L_r} = \frac{\bar{U}_m \cdot T_m}{L_m}, \quad (2)$$

so that the ratio between an interval time registered in the BLWT and the same interval at full scale is equal to:

$$\frac{T_m}{T_r} = \frac{\bar{U}_r}{\bar{U}_m} \cdot \frac{L_m}{L_r}. \quad (3)$$

Therefore the frequency scale is given by the ratio between the velocity scale and the geometric one:

$$\lambda_n = \frac{T_m}{T_r} = \frac{\lambda_V}{\lambda_L} \cong 129, \quad (4)$$

where λ_L is the BLWT model scale (1:250) and λ_V ($=18/35=0.514$) is the ratio between the velocity at the roof level in the BLWT model (103 mm) and the velocity at the roof level in the numerical model ($\cong 25$ m). The last velocity has been calculated considering the profile exponent of 0.17 and the recommended wind velocity of 30 m/s at 10 m height suggested by the wind climate report issued by the AG Davenport Lab. [GAL02] (10 min average, 50-years return period).

Using (4) the sampling frequency of 250 Hz in the wind tunnel corresponds to 1.93 Hz at full scale, that is 30 seconds of wind tunnel test duration correspond to a 64 min wind storm sampled at a time step of 0.516 ($=1/1.93$) seconds. As the first eigenfrequency of the structure is equal to 0.82 Hz ($T = 1.22$ s), one can observe that the sampling time is not sufficiently small to excite dynamically the structure, therefore the performed analysis assumes the form of a quasi-static analysis, that is only the background response of the structure has been taken into account, while the resonant response has been neglected.

The time history of the wind load acting on the node corresponding to the pressure tap no. i has been obtained by the following formula:

$$F_i(t) = \frac{1}{2} \rho U_d^2 \cdot c_p(t) \cdot A_i \quad (5)$$

where U_d is the wind velocity at full scale at the mean roof level (25 m), $c_p(t)$ is the time history of the net pressure coefficient and A_i is the influence area of the pressure tap position no. i (see Figure 4). Figure 10 shows the load function for the node 1807.

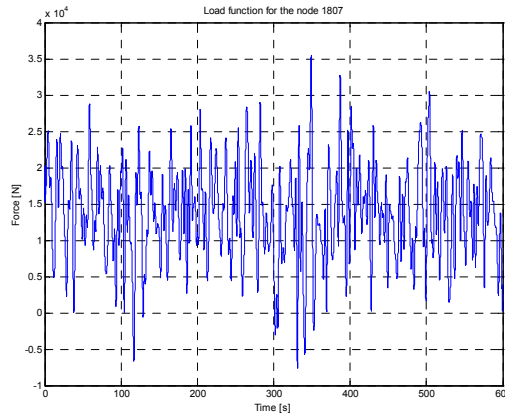


Figure 10. Load function for the node 1807.

The final model has been loaded with all the wind load time histories applied on the roof nodes corresponding to the pressure taps of the BLWT model. At the end of the analysis the time histories of the displacements of two significant nodes (one placed at the free end of the cantilever structure and the other in the midsection of the inner beam between two successive cantilevers) and the axial forces of two main trusses of the cantilever lattice structure have been analyzed. The maximum and minimum values have been evaluated through the same procedure used for the pressure coefficients. Table 3 lists the mean, standard deviation, maximum and minimum values, and the peak response factors for the maximum and minimum value of the selected responses. The peak factor of the maximum displacements is equal to about 3.5 for the node at the free end and 3.75 for the midsection of the inner beam, while the peak factor for the maximum value of the tensile axial force and minimum compressive axial force are equal to about 3.2. This value is only a little bit smaller than the peak response factor of 3.5 commonly used in the wind engineering.

	Mean value	Std	Max	Min	g_{\max}	g_{\min}
Displ. free end of cantilever	25.29 mm	4.07 mm	39.47 mm	8.45 mm	3.48	4.13
Displ. midsection of inner beam	36.2 mm	5.15 mm	55.51 mm	12.19 mm	3.75	4.67
N tension	182090 N	31528 N	283160 N	47581 N	3.21	4.27
N compr.	-196380 N	34782 N	-49387 N	-307820 N	4.23	3.20

Table 3. Mean, standard deviation, maximum and minimum values, peak response factor for maximum and minimum value of the selected responses.

4 Concluding remarks

The experimental tests carried out in the BLWT on the model of the roof of the new Olympic soccer stadium in Piraeus, Greece, have allowed to correctly define the actual distribution of the net pressures over the roof. The net pressure coefficients have been obtained by difference of the measured pressures at the extrados and at the intrados of the roof. The first results of a series of numerical simulations of the behavior of the roof under the turbulent wind have been proposed. Only one direction of the wind has been considered and a quasi static analysis has been performed. New analyses are still in progress to take into account the resonant response of the structure considering all the wind directions investigated.

References

- [AUG95] G. Augusti, P. Spinelli, C. Borri, G. Bartoli, M. Giachi and S. Giordano (1995), "The C.R.I.A.C.I.V. Atmospheric Boundary Layer Wind Tunnel", in *Wind Engineering : retrospect and prospect*, IAWE, International Association for Wind Engineering, vol. 5, Wiley Eastern Limited, New Delhi.
- [COO80] N.J. Cook and J.R. Mayne (1980), "A refined working approach to the assessment of wind loads for equivalent static design", *J. Wind Engrg. & Ind. Aerodyn*, vol. 6, 125-137.
- [GAL02] J. Galsworthy, B.J. Vickery, M. Mikitiuk, L. Kong and D. Surry (2002), "The Athens Olympic stadium roof and velodrome roof Athens, Greece", AG Davenport BLWT Lab., SS50-2002.
- [SAP04] E.L. Wilson and A. Habibullah (2003), SAP2000. Structural Analysis Program. Computers and Structures, Inc. 1995 University Ave. Berkeley, California.