WIND ACTION ANALYSIS ON OUTSTANDING BUILDINGS. DIFFERENT ACCURATE WAYS OF OBTAINING THE FORCE COEFFICIENTS

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Abstract: *Architectural advances in the design of outstanding buildings, together with the present command of structural behaviour and progress in construction techniques, have made it possible to erect increasingly complex buildings with unusual sections and shapes whose response to wind action must be analyzed in detail. Modern codes on the subject define wind action as an equivalent static load whose force is determined by the product of the basic wind pressure, the square of the risk factor, the exposure factor, the force coefficient and the area exposed to the wind.*

The article focuses on the methods to obtain the force coefficients for a case study: the Hotel Vela in Barcelona, an outstanding building designed by Ricardo Bofill's Taller de Arquitectura, with structural engineering by IDEAM.

Determining the force coefficient by applying the parameters tabulated in the codes and standards is the quickest and easiest way to calculate wind action. In light of the uncertainty around the assessment of the building's force coefficients and the risk of over- or under-engineering their values, a scale-model wind tunnel test was commissioned from the Polytechnic University of Madrid's School of Aeronautical Engineering. The results obtained were verified with wind action computer modelling based on particle models, a very recently developed alternative approach that delivers highly accurate force coefficients as well as the maximum pressure and suction on structures.

1. WIND ACTIONS ON BUILDINGS ACCORDING TO EN 1991-1-4.

"Eurocode 1: Actions on Structures. Part 1-4: General Actions- Wind Actions" EN 1991-1-4 April 2005 [1], defines the wind force actions on a structure as:

$$F_w = c_s \cdot c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref} \tag{1}$$

Where:

Fw	is the resultant wind force acting on a structure
$c_s \cdot c_d$	The structural factor $c_s \cdot c_d$ takes into account the effect on wind actions from the non-simultaneous occurrence of peak pressures on the surface (c_s) together with the effect of the vibration of the structure due to the turbulence (c_d). Section 6.1 of EN 1991-1-4 [1], defines the criteria for the calculation of these parameters. For normal buildings $c_s \cdot c_d=1$.
$q_p(z_e)$	is the peak velocity pressure at a height z_e.
c_f	is the force coefficient.
A_{ref}	is the reference area of the structure.

The peak velocity pressure $q_p(z)$ at a height z, which includes mean and short term fluctuations, should be define as:

$$q_p(z) = \left[1 + 7 \cdot l_v(z)\right] \cdot \left(\frac{1}{2} \cdot \rho \cdot v^2{}_m(z)\right) = c_e(z) \cdot q_b \tag{2}$$

Where:

q_b	is the basic velocity pressure: $q_b = \frac{1}{2} \cdot \rho \cdot v^2{}_b$ (3)
v_m	is the mean wind velocity: $v_m = c_r(z) \cdot c_o(z) \cdot v_b$ (4)
$c_0(z)$	is the orography coefficient. Usually taken 1 unless otherwise specified. Annex A3 of Eurocode [1] proposes the method of obtaining $c_0(z)$.
$c_r(z)$	is the roughness factor: $c_r(z) = k_r \cdot \ln(z / z_0)$ (5)
k_r	is the terrain factor, and depends on the roughness length z_0.

$$k_r = 0{,}19 \cdot \left(\frac{z_0}{0{,}05}\right)^{0{,}07} \tag{6}$$

The different categories of the terrain (0 to IV), and the parameters z_0, and z_{min}, are defined on table 4.1 of EN 1991-1-4 [1].

v_b	is the basic wind velocity $v_b = c_{dir} \cdot c_{season} \cdot v_{b,0}$ (7)

Where:

c_{dir}	is the directional factor. Normally taken 1,0.
c_{season}	is the season factor. Normally taken 1,0
$v_{b,0}$	is the fundamental value of the basic wind velocity, defined in the National Annex.

Where:

K	is a shape coefficient equal to 0,20
n	is equal to 0,50
$l_v(z)$	is the turbulence intensity at a height z: $l_v(z)=\frac{k_l}{c_0(z)\cdot\ln\left(\frac{z}{z_0}\right)}$ (8)
k_l	is the turbulence factor, usually taken 1.
$c_e(z)$	is the exposition coefficient. If we develop ec. 11 considering that $c_0(z)$, c_{dir}, c_{season}, and k_l are equal to 1,0 we will obtain a reduced expression:

$$c_e(z)=\frac{q_p(z)}{q_b}=\frac{[1+7\cdot l_v(z)]\cdot\left(\frac{1}{2}\cdot\rho\cdot v^2{}_m(z)\right)}{\frac{1}{2}\cdot\rho\cdot v^2{}_b}=\left(k^2{}_r\cdot\left[\ln^2\left(\frac{z}{z_0}\right)+7\cdot\ln\left(\frac{z}{z_0}\right)\right]\right) \qquad (9)$$

The result of the development of equation (1) is the new expression (10) for the resultant wind force acting on a structure F_w.

$$F_w=(\frac{1}{2}\cdot\rho\cdot v^2{}_{b,0})\cdot(c^2{}_{prob})\cdot\left(k^2{}_r\cdot\left[\ln^2\left(\frac{z}{z_0}\right)+7\cdot\ln\left(\frac{z}{z_0}\right)\right]\right)\cdot c_f\cdot A_{ref} \qquad (10)$$

2. HOTEL VELA’S STRUCTURE.

The main structure of Hotel Vela in Barcelona [2] is composed by two principal buildings, the Tower and the Atrium. The Tower has the shape of a huge sail and is the highest building with 26 floors and a total height of 100 m. The Atrium is a smaller building placed at the rear part of the Tower. It has a rectangular plan view and raises 7 floors above the ground level (Figs. 1a &1b).

Figures 1a & 1b: Two views of the Tower and Atrium buildings.

The plan view of the Tower has the shape of an eye with the ends cut by two inclined flat planes (Fig. 2). The length of each floor grows from level 1 to level 10, while from level 10 to the top it decreases following the shape of the sail (Fig. 1c).
The maximum length of level 10 is 57,90 m, while the transverse dimension keeps constant with a length equal to 23,15 m. Figure 2 shows a typical the plan view of the Tower and the Atrium.

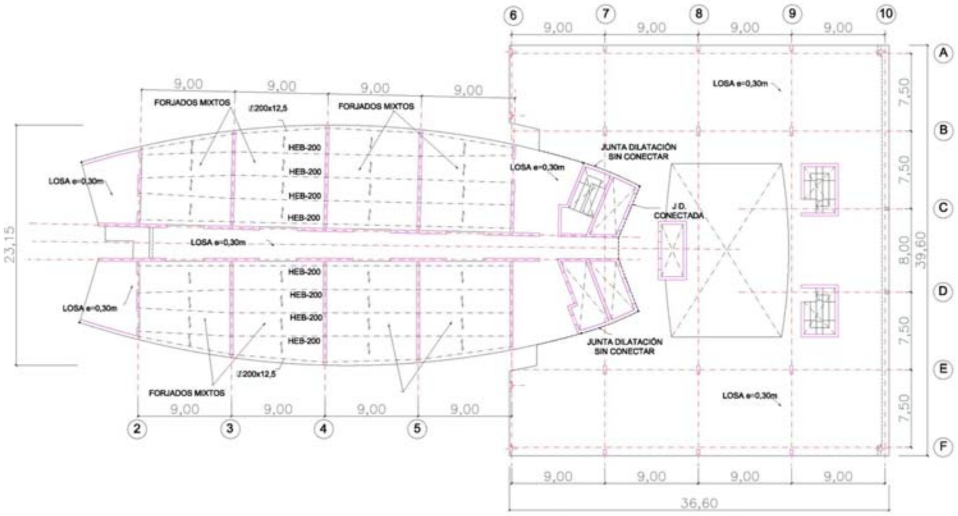


Figure 2: Typical plan view between level 1 and level 7 of the Tower and the Atrium

3. OBTAINING THE FORCE COEFFICIENT.

3.1. Obtaining the force coefficient by applying codes of actions.

Determining the force coefficient by applying the parameters tabulated in the codes and standards is the quickest and easiest way to calculate wind action, providing the building’s geometry can be likened to the simple shapes typified in these tables. Difficulties arise, however, when a building, such as the Hotel Vela for instance, has an unusual shape not directly addressed in the standards.
The simplifications involved in likening a complex shape to simple typified forms may yield values higher than the actual force coefficients, which, while erring on the side of safety, would raise structural and foundation costs unnecessarily. But they may also result in force coefficients lower than the real values, erring on the side of risk, in which case the structure and facade may well be insufficiently dimensioned to resist wind action [3].
With a plan view whose area varies with elevation and whose shape resembles an eye blunted at the two ends by slanted planes (Fig. 2), the hotel’s standard storey could be likened either to a rectangle (Table 1), a conservative hypothesis a priori, or to an ellipse (Table 2), a hypothesis that would probably err on the side of risk (Fig. 3). An accurate estimation would therefore appear to lie somewhere in between these two initial hypotheses.

Standard	c_f ($\lambda=\infty$)	c_f ($\lambda=1,72$)
EN 1991-1-4. 2005 [1]	2,225	1,40
CECM Nº 52 [4]	2,0	1,23

Table 1: Force coefficient. Assimilation of the real shape to a rectangular form.

Standard	c_f ($\lambda=\infty$)	c_f ($\lambda=1,72$)
CECM Nº52 [4]	1,50	1,00

Table 2: Force coefficient. Assimilation of the real shape to an elliptical form.

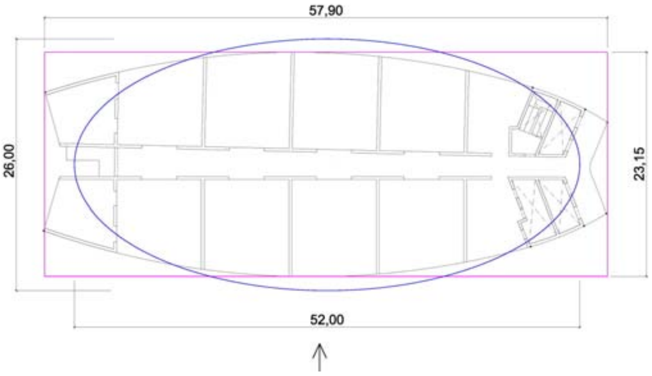


Figure 3: Assimilation of the real shape to a rectangular or an elliptical form.

3.2. Obtaining the force coefficient with a wind tunnel test.

In light of the uncertainty around the assessment of the building's force coefficients and the risk of over- or under-engineering their values, a scale-model wind tunnel test was commissioned from the "Ignacio da Riva University Institute", a centre working out of the Polytechnic University of Madrid's School of Aeronautical Engineering [5]. They modelled the Tower and Atrium in a scale 1/125 (Figs. 4a, 4b &4c).

Figures 4a, 4b & 4c: Views of the model in the interior of the wind tunnel.

Figure 5 shows the results obtained with the wind tunnel test, with the wind blowing perpendicular to the Tower, which is the worst direction for the maximum bending moment at the base of the tower. As it can be seen on figure 4, the mean value of the force coefficient is between 1,70 and 1,60.

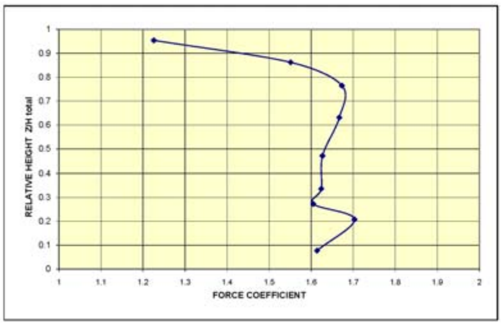


Figure 5: Force coefficient with transverse wind

3.3. Obtaining of the force coefficient with the use of software based on particle models for simulating fluids

NextLimit Technologies has developed Xflow's software for the analysis of multi-physical systems, which is a tool that can model solids and fluids. A short description of the mathematical fundaments of this software can be found on reference [3].

The results obtained with the first assimilation of the real shape to simple shapes typified, and those obtained with the wind tunnel test, were verified with wind action computer modelling using particle models. This recently developed alternative approach delivers highly accurate force coefficients as well as the maximum pressure and suction on structures.

Two different computer models were made. The first one reproducing the actual geometry of the Madrid School of Aeronautics' wind tunnel (fig. 4c), reducing the flow passage cross-section. Figure 6 shows a horizontal cut of the pressure contour and the projection onto the surface of the building.

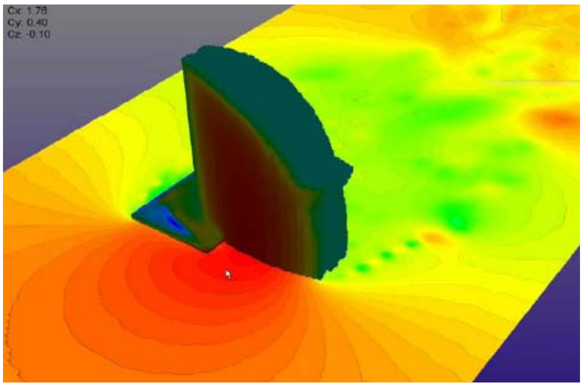
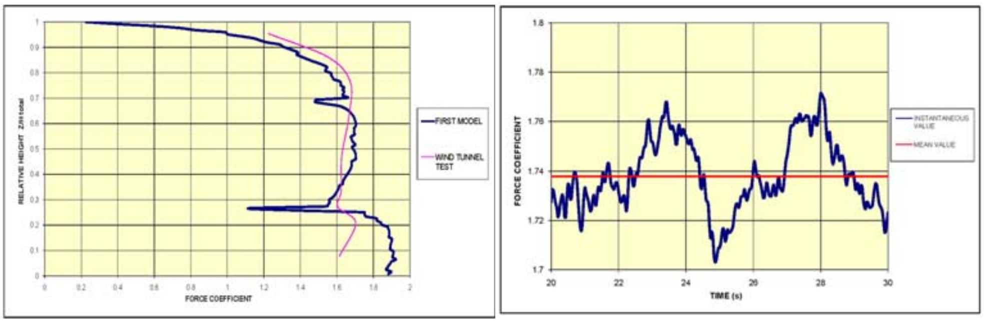


Figure 6: Pressure contour obtained in the first computer analysis

In this analysis, the results of the force coefficient are represented on figure 7a. Figure 7b shows the temporal evolution of the mean value of the global force coefficient of the building, varying between 1,70 and 1,77, with a mean value of 1,74.

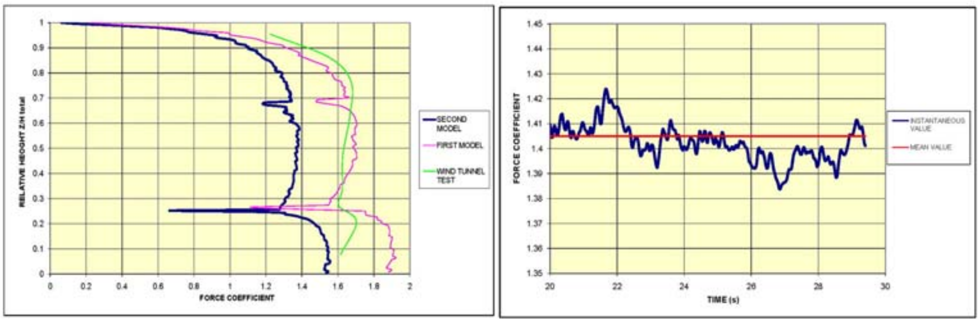


Figures 7a & 7b: Force coefficient of the building reproducing the geometry of the wind tunnel, and temporal oscillation of the mean value.

The force coefficient of the lower part of the building, with Tower and Atrium, has a mean value near 1,90, a little bit higher than that obtained in the upper part of the Tower, which has a more aerodynamic shape, with a mean value of 1,60.

The shape and the results of the mean values of the force coefficients obtained with the computer model (Fig. 7a) are very similar to those obtained experimentally in the wind tunnel test (Fig. 5). The only difference is that the scale model used in the tunnel wind test has a physical limitation in the number of pressure sensors, while the computer model admits a higher number of sensors, which yields higher precision.

For the analysis of the real force coefficient of the building, we made a second computer simulation, which reproduced the real shape of the building but without any lateral restriction for the wind flow. This is equivalent to an open field situation. Figures 8a and 8b show the results of the force coefficient of the building varying with the height and the temporal oscillation of the mean value.



Figures 8a & 8b: Force coefficient of the building in open field without any restriction for the wind, and temporal oscillation of the mean value.

The results of the force coefficient values obtained with this second model, which represents reality more accurately, show a mean value of 1,405, around 20 % smaller than the one obtained when the test was conducted with a reduced cross-section for the wind.

4. CONCLUSIONS

The possibilities that a computer tool like Xflow offers in comparison with the traditional wind tunnel test are significant. While the software works on real shape models, the wind tunnel test does with scale models, which makes it impossible to reproduce simultaneously the Reynolds number and the Mach number that we are interested to study. This problem is not so important, because with a Reynolds number high enough the flow behaviour doesn't experiment big differences.

On the other hand, the computer model has great freedom in modelling the environment, e.g. if we are interested in studying the flow of the air round a building, we can reproduce the real geometry of the terrain and the surrounding buildings.

The wind tunnel has a limited cross section, and that can produce a block effect. A typical value of the block coefficient (ratio between the frontal section of scale model and the section of the wind tunnel) could be 0,10.

The conclusion drawn was that by reproducing the actual geometry of the Madrid School of Aeronautics' wind tunnel but reducing the flow passage cross-section, the force coefficient values obtained were over 20 % higher than when the test was conducted with no constraint on the cross-section.

As described before, the computer model doesn't have the physical limitation of the scale model in the wind tunnel, because it admits hundreds of thousands of pressure sensors on the surface of the building without distorting the wind flow. It also permits the analysis of the wind flow, making possible the study of the wind trail or the analysis of the environmental impact induced by the presence of a new building creating comfort contours according to a specified criterion.

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