Obtaining the Wind Force Coefficients on Non-conventional Buildings

Miguel Ortega Cornejo, M.Sc., Civil Eng., Project Manager, IDEAM, Madrid, Spain and **Francisco Millanes Mato,** PhD, Civil Eng., President, IDEAM, Madrid, Spain. Contact: miguel.ortega@ideam.es

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Abstract

The progress in construction techniques, together with the present command of structural behaviour and the architectural advances in the design of outstanding buildings, have made it possible to erect increasingly complex buildings with unusual geometry. Eurocode 1, part 1-4 (EN 1991-1-4:2005[1]) defines the equivalent static wind force as the product of the basic wind velocity pressure, the square of the risk factor, the exposure factor, the force coefficient and the area exposed to the wind. Determining accurately the force coefficient is the most difficult task when the geometry of the building is not directly covered by the most common geometrical shapes tabulated by the different codes or standards. This article focuses on the different methods to obtain the force coefficients for a case study, the Hotel Vela in Barcelona, applying the simplified parameters tabulated in the standards, with a scale-model wind tunnel test, and with wind action computer modelling based on particle models, a very recently developed alternative approach that delivers highly accurate force coefficients as well as maximum pressure and suction on structures.

Keywords: wind actions; force coefficient; Eurocode; wind tunnel test; computer particle models.

Fig. 1: Two views of the Tower and the Atrium buildings

Introduction

"Eurocode 1: Actions on Structures. Part 1-4: General Actions–Wind Actions" EN 1991-1-4:2005[1] defines the wind force action acting on a structure as the product of the structural factor $c_s \cdot c_d$, the force coefficient c_f, the peak velocity pressure $q_p(z_e)$ and the reference area of the structure A_{ref}.

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

Equation (1) can be developed into a more compact formulation (Eq. (2)) according to Ref. [2]. The new expression for the resultant wind force acting on a structure F_w, could be expressed, in normal cases where $c_s \cdot c_d = 1{,}0$ as the product of the basic velocity pressure, the square of the probability coefficient, the exposure coefficient, the force coefficient and the exposed area:

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

Then, the main problem for obtaining the equivalent wind force acting on the structure is obtaining the force coefficient, as the other factors of the product are easy to obtain. The rest of the article will focus on the different ways of obtaining accurately the force coefficients, applied to a case study: the Hotel Vela in Barcelona.

Hotel Vela's Structure

The main structure of Hotel Vela in Barcelona[3] is composed of two principal buildings, the Tower and the Atrium. The Tower has the shape of a huge "sail" (called "Vela" in Spanish, giving the name to the hotel) and it has 26 storeys 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 is seven storeys above the ground level (*Fig. 1a and b*).

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 storey grows from level 1 to level 10, while from level 10 to the top it decreases following the shape of the sail (*Fig. 1*).

The maximum length of level 10 is 57,90 m, while the transverse dimension keeps constant with 23,15 m width. *Figure 2* shows a typical plan view of the Tower and the Atrium.

The building is located in front of the sea in the port of Barcelona in an area very exposed to wind forces. The wind force acting transversely on the Tower induces the worst bending moment hypothesis for the structure and foundations.

With the building location very exposed to the wind forces, placed on a piece of ground reclaimed from the sea, the complex foundation conditions of the main buildings made necessary the use of pre-cast profound concrete piles. The Tower is supported on 398 profound piles of 45 m length and 0,40 × 0,40 m cross section, while the Atrium building is supported on 120 piles. It can be easily understood that the steep cost of the deep foundation made it necessary to optimize the wind force hypothesis, analyzing accurately the wind force coefficients.

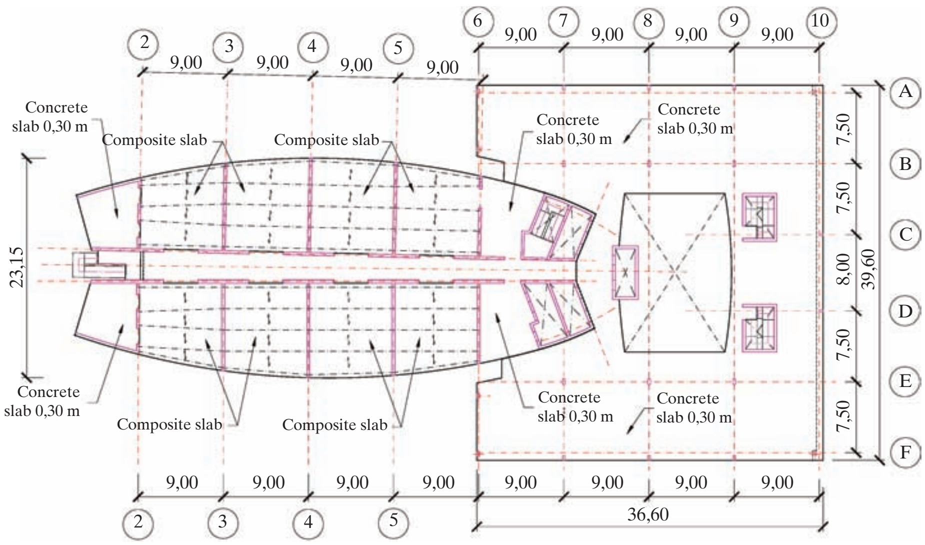

Fig. 2: Typical plan view between level 1 and level 7 of the Tower and the Atrium (Units: m)

	Rectangular cross section		**Elliptical cross section**	
Standard	c_f ($\lambda = \infty$)	c_f ($\lambda = 1{,}72$)	c_f ($\lambda = \infty$)	c_f ($\lambda = 1{,}72$)
EN 1991-1-4[1]	2,225	1,4	—	—
CECM Nº 52[5]	2	1,23	1,5	1

Table 1: Force coefficient assimilating the actual shape to a rectangle or an ellipse

Obtaining the Force Coefficient

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 the wind action, provided the building's geometry can be likened to the simple shapes typified in these tables. Difficulties arise, however, when a building, such as Hotel Vela for instance, has an unusual shape not directly addressed in the standards.[4]

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.

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 Tower's standard storey could be likened either to a rectangle—a conservative hypothesis *a priori*—or to an ellipse—a hypothesis that would probably err on the side of risk. An accurate estimation would therefore appear to lie somewhere in between these two initial hypotheses.

As a first approach, the typical shape of the Tower was assimilated to a rectangular plan cross section with a length of 57,90 m (B) and a depth of 23,15 m (D). In this case, an infinte slenderness was considered, neglecting the influence of the limited height of the building, and the actual slenderness of the Tower (defined as the coefficient between the height of the building and the length exposed to the width $\lambda = H/B$).

In a second try, the shape of the Tower was assimilated to an ellipse with the length of the big axis double the length of the small axis ($a = 2b$), and the wind blowing in the direction of the small axis.

Table 1 resumes the different force coefficients defined in the Eurocode[1] and in the CECM Nº 52,[5] depending on the slenderness of the building, for each case, the shape assimilated to was rectangular or elliptical cross section.

Table 1 shows how the force coefficients for the ellipses are inferior to the ones for the rectangular form, owing to the more aerodynamic shape of the cross section. But these results show a sensible difference in the force coefficients depending on the shape of the plan cross section and the slenderness of the building.

The different results obtained from the simplifications, added to it that the Tower of the building has variable length storeys, will introduce more uncertainty in the actual force coefficients of the building, and unless it is considered on a highly safe side, a high force coefficient value, around 2,25, could err on the side of risk considering an insufficient wind force, underdimensioning the structure, the facade and the foundation.

As the wind forces were one of the main actions for the dimensioning of this particular building, it was necessary to verify by more accurate methods the actual force coefficient of the building.

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 Polytechnic University of Madrid's School of Aeronautical Engineering.[6] The Tower and the Atrium were modelled on a scale of 1/125 (*Fig. 3a, b and c*).

The scale model of the building was finally instrumented with 179 pressure sensors (*Fig. 3a*), distributed between the lateral facades of the Tower and the back facade of the Atrium (*Fig. 3b*). Note that the Atrium's lateral facades do not have any sensor (*Fig. 3a*), and this will influence the obtaining of the force coefficients of the building's lower part.

For the wind tests, the scale model of the building was fixed to a lateral turning platform (*Fig. 3c*), located inside the wind tunnel, such that the normal pressure in the different sensors can be measured, varying the incising angle of the direction of the wind.

Figure 4 shows the results obtained in 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 building. As it can be seen in *Fig. 5*, the mean value of the force coefficient in the Tower, where there are enough sensors around the perimeter, is between 1,60 and 1,70.

The force coefficients in the inferior part of the building were not so accurately measured, as it will be seen later, because the limited number of pressure sensors obliged to reduce the

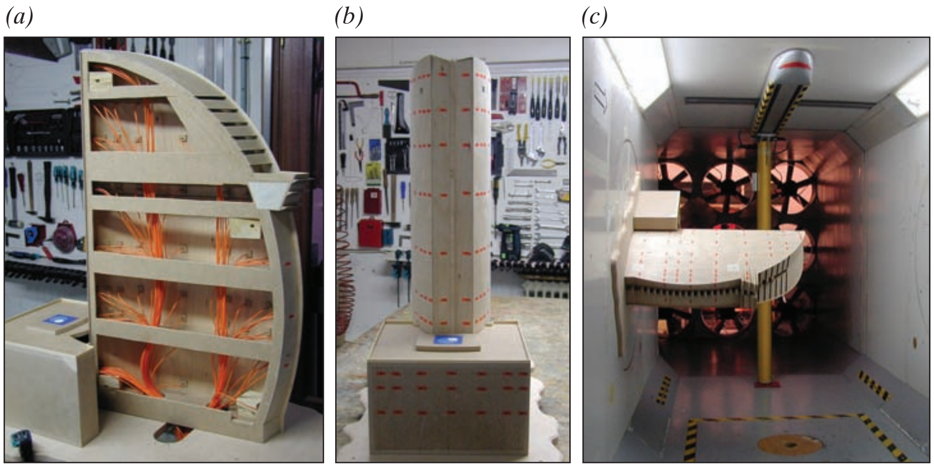

Fig. 3: (a, b and c) Views of the model in the interior of the wind tunnel

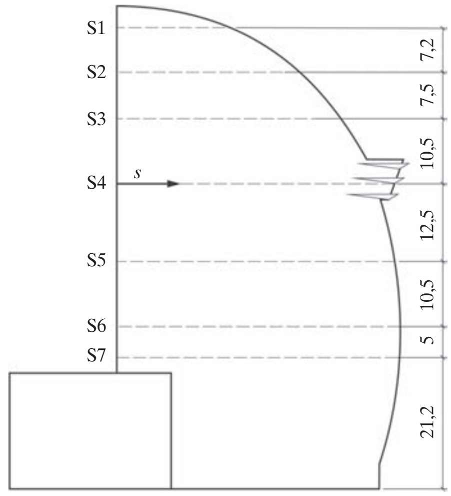

Fig. 6: Instrumented cross sections, S is the horizontal distance of each cross section S1 to S7

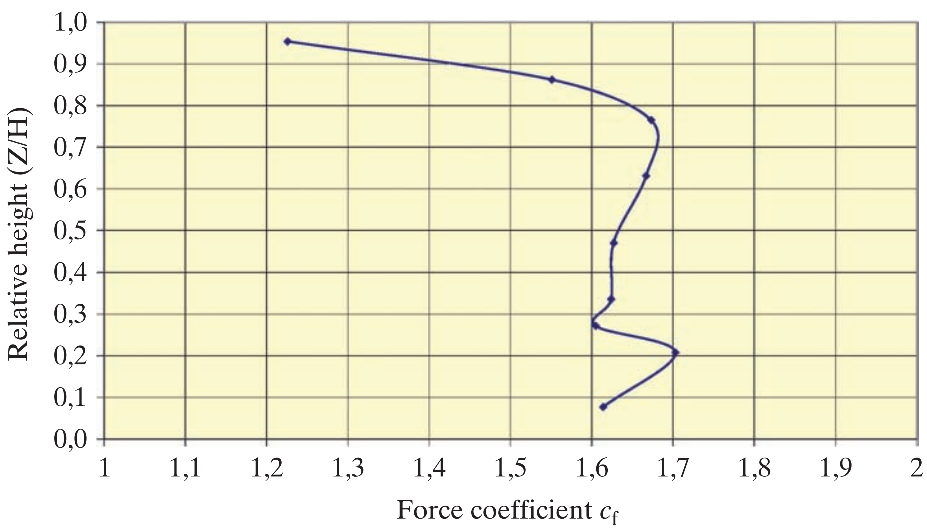

Fig. 4: Force coefficient with transverse wind

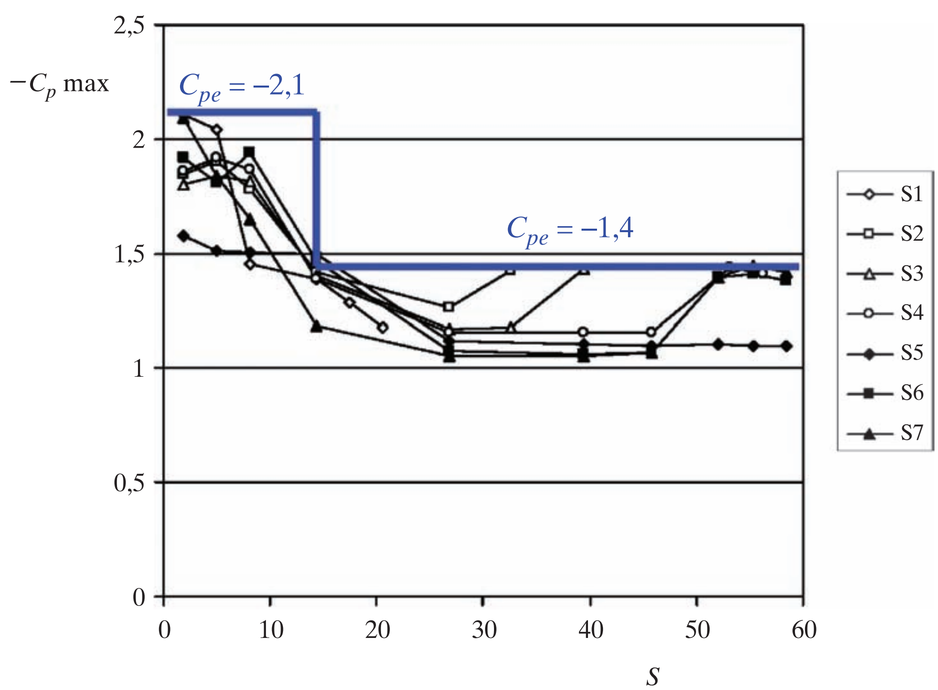

Fig. 5: Maximum suction pressure in the facade, Horizontal axis: ***s*** *is the distance according to Fig. 6. Vertical axis: -**$C_p$max** is maximun (negative) external pressure coefficient (suction).*

instrumented zones, and the lateral facades of the Atrium were finally not instrumented (*Fig. 3a*).

The wind tunnel test also gives another useful information about the maximum local pressure (c_{pe} positive) or suction (c_{pe} negative) for the dimensioning of the facade panels.

The results of the maximum (negative) external pressure coefficients (suction) in the Tower obtained in the wind tunnel test depending on the direction of the wind are shown in *Fig. 5*, for the main seven cross sections instrumented (*Fig. 6*).

The results of the tests demonstrate very high pressure suction coefficients in determined areas of the facade, higher than two times the peak velocity pressure. Therefore, the wind tunnel test have made possible to know with precision the actual values of the pressure and suction on the facades, permitting a correct dimensioning not only for the structure but also for the facade panels. Without the results of the wind tunnel test, the facade panels probably would have been under-dimensioned.

Obtaining the Force Coefficient with the Use of Software Based on Particle Models for Simulating Fluids

Once the first approach was made for obtaining the force coefficients by applying wind action codes,[1,5] assimilating the actual shape of the building to simple typified shapes and carrying out the wind tunnel tests at the same time, it was decided to study and compare both results with the ones

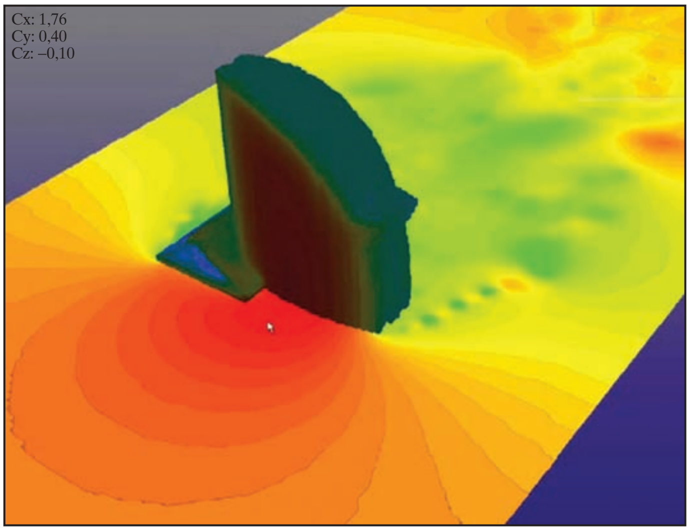

Fig. 7: Pressure contour obtained in the first computer analysis

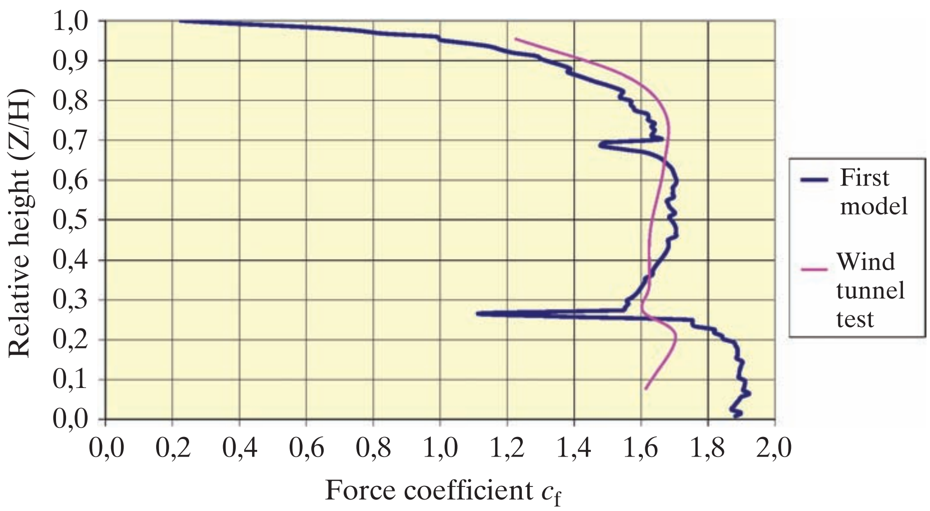

Fig. 8: Force coefficient of the building reproducing the actual geometry of the wind tunnel

obtained through wind action computer modelling using particle models.

Xflow software is a tool that can model solids and fluids for the analysis of multiphysical systems using particle models. A short description of the mathematical fundamentals of this software can be found in Ref. [4].

This recently developed alternative approach delivers highly accurate force coefficients as well as more accurate values of the maximum pressure and suction coefficients on structures.

Two different computer modelling were carried out, the first one reproducing the actual geometry of the Madrid School of Aeronautics' wind tunnel (*Fig. 3c*), reducing the flow passage cross section, and the second computer model without any lateral restriction, reproducing with more fidelity the actual position of the building in the port of Barcelona.

Figure 7 shows an image of the first computer model, and represents a horizontal cut of the pressure contour and the projection onto the surface of the building. Red colour indicates the maximum wind pressure, while green and blue colours represent the maximum suction.

For the first computer model, results of the force coefficient are shown in *Fig. 8*, varying with the height of the building.

The force coefficient of the lower part of the building with the Tower and the Atrium has a mean value near 1,90, a little higher than that obtained in the upper part of the Tower, which has a more aerodynamic shape and a mean value of 1,60 (*Fig. 8*).

The shape and the results of the mean force coefficients obtained by the first computer model (blue line in *Fig. 8*) are very similar to those obtained experimentally in the wind tunnel test (pink line in *Fig. 8*), at least in the Tower. The only difference is that the scale model used in the wind tunnel test had a physical limitation in the number of pressure sensors, and the lack of them in the lateral facades of the Atrium (*Fig. 3a and c*), clearly conditioned the force coefficients obtained in the inferior part of the building. Meanwhile, as the computer model admits a much higher number of sensors, it was possible to obtain more accurately the force coefficients everywhere, including the inferior part, which had to have force coefficients higher than the Tower because of its less aerodynamic shape.

Once verified that the results obtained in the wind tunnel test were similar to those obtained in the first computer model, reproducing the actual geometry of the wind tunnel, the influence of the reduced dimension of the wind tunnel and its probable influence on

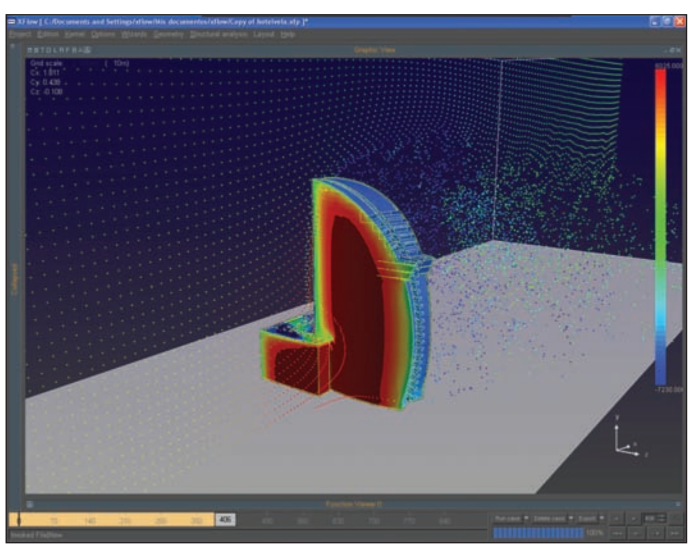

Fig. 9: Pressure field obtained in the second computer analysis

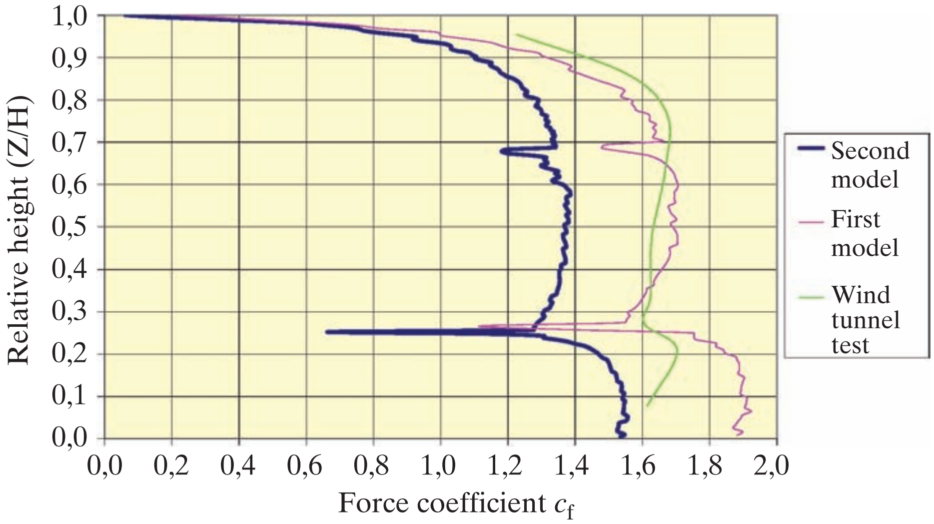

Fig. 10: Force coefficient of the building in open field without any restriction for the wind

the results of the force coefficients were analyzed.

For the analysis of the actual force coefficient of the building, a second computer simulation was carried out, reproducing the shape of the building without any lateral restriction for the wind flow. This is equivalent to an open field situation, representing more reliably the location of the building in front of the sea, without any surrounding buildings.

Figure 9 shows the pressure wind field projected in the facades of the building in the second computer model, without any lateral restriction to the wind.

The blue line in *Fig. 10* represents the results of the new computer model without any lateral restriction to the wind, the pink line represents the results of the first model, and the green line is the results of the wind tunnel test.

The force coefficient of the lower part of the building, has a mean value close to 1,50, instead of that obtained in the first model (around 1,90), while the one obtained in the upper part of the Tower, with more aerodynamic shape, has a mean value below 1,40, in comparison with that obtained in the first computer model, higher than 1,60.

Therefore, how the limited cross section of the wind tunnel has a significant influence on the final results was verified, with global force coefficients higher than those obtained in the computer model without any lateral restriction.

These results obtained for the force coefficient of the Tower, with a mean value around 1,35, are in between those obtained and listed in *Table 1*, for rectangular and elliptical cross sections, confirming the first hypothesis realized when assimilating the actual complex shape of the Tower into simple typified and more common cross sections.

Conclusions

Modern wind codes define the equivalent static wind force acting on a structure as the product of the basic wind velocity pressure, the square of the risk factor, the exposure factor, the force coefficient and the area exposed to the wind.

Accurate determination of the force coefficient is the most difficult task when the geometry of the building is not directly covered by the most common geometrical shapes tabulated by the different codes or standards.

In these cases, it is usual to resort to wind tunnel tests or to a more precise method by analysing the force coefficients 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.

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 so with scale models, which makes it impossible to reproduce simultaneously the Reynolds number and the Mach number that are relevant to the study. This problem is not so significant, because with a Reynolds number high enough the flow behaviour does not experiment big differences.

As described in the article, the normal wind tunnels usually have 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 by 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.

Another advantage of the computer model is that it does not 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.

References

[1] EN 1991-1-4:2005. *Eurocode 1: Actions on Structures. Part 1-4: General Actions–Wind Actions*, April, 2005.

[2] Ortega M, Millanes F. Wind action analysis on outstanding buildings. Different accurate ways of obtaining the force coefficients. In *Proceedings of the Joint IABSE-fib Conference Codes in Structural Engineering Developments and Needs for International Practice*, vol. II. SECON-CSSE: Dubrovnik, 2010; 735–742.

[3] Matute L, Ortega M, Millanes F. *La Estructura del Hotel Vela de Barcelona.* Asociación Científico-técnica de hormigón Estructural (ed.), *IV Congreso de la Asociación Científico técnica del hormigón Estructural. Proc. intern. symp., Valencia, Nov. 208.* Valencia, Spain, 2008.

[4] Ortega M, Lacoma LM, Colman DM. *Wind action analysis in outstanding buildings. Case study of Hotel Vela at Barcelona.* Asociación Científico-técnica del Hormigón Estructural (ed.), *Hormigón y Acero. vol. 60 Nº251.* Madrid, 2009; 37–64.

[5] Recommandations pour le calcul des effects du vent sur les constructions. *European Convention for Constructional Steelwork*. CECM Nº 52, 1987.

[6] Pindado S, Franchini S, Meseguer J. Medida de las cargas de viento en un modelo aerodinámico del Hotel Vela de Barcelona. *Laboratorio de Aerodinámica IDR/UPM ETSI Aeronáuticos de Madrid*, 2007.