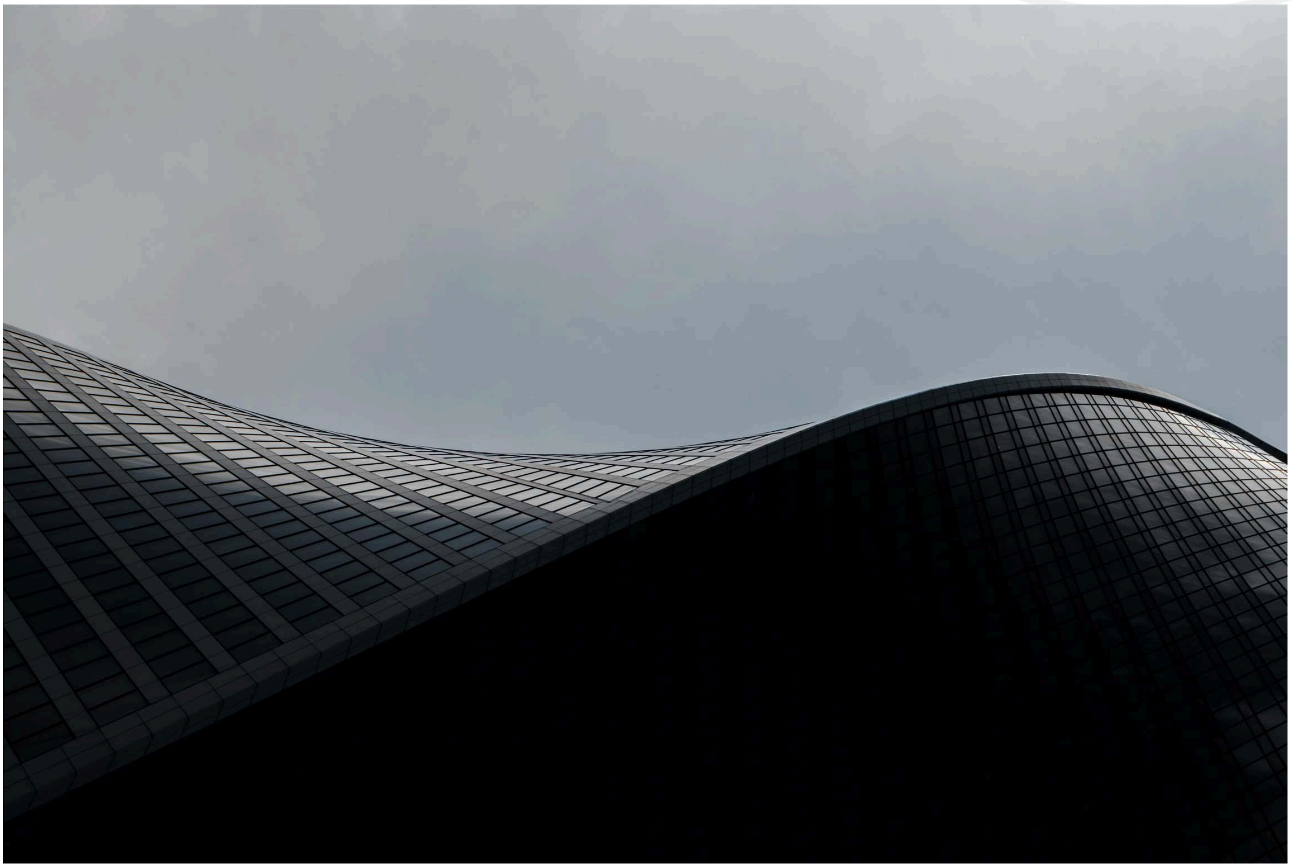
Wind Loads on Buildings

CFD versus Codes: a discussion



Purpose of this document

The evaluation of the forces exerted by the wind on buildings as well as on other civil engineering structures, is mandatory for structural engineers.

To this end, they have long been relying on the many formulas provided by the regulations, also called Codes. In recent years however, the use of Computational Fluid Dynamics (CFD) software has begun to spread. The Eurocode explicitly mentions the possibility to supplement the load evaluations with wind tunnel tests and/or by using proven numerical methods. Particularly when the shape of the structure deviates excessively from those considered in the Codes.

Unlike mechanical and aeronautical engineers, who started using CFD more than 30 years ago and now make routinely use of CFD in their design process, many civil structural engineers do not yet feel at ease using the numerical tool.

Structural engineers are in fact somewhat stunned to observe that CFD-calculated loads are lower than those determined by using Codes. However, they are more likely to trust wind tunnel measurements, even though the measured loads in wind tunnels are also lower than Code-based loads[1], similarly to the CFD results.

It is in fact well known that, in all industrial sectors and primarily in the automotive and aerospace industries, the CFD have demonstrated over the past decades that its results do match the wind tunnel measurements. Todays, the most skilled and demanding users of CFD simulations, the Formula1 aerodynamics engineers, have in fact great confidence in the CFD results[2].

Until a few years ago, when experimental and numerical practices were developing, there used to be a saying among the experimental and numerical engineers:

"*nobody trusts the results of a simulation but the engineers who developed the software; everybody trusts the results of the wind tunnel experiments but the engineers who carried out the measurements*"

This was clearly a joke, but there is some truth to that, which persists to this day.

The purpose of the present White Paper is to compare the two approaches, highlighting the differences between them as well as the common points, and to broaden the comparison to wind tunnel testing as well. We will try to pursue this purpose based exclusively on the formulas and on the equations, and not on opinions.

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[1] interesting web article of a renowned world top engineering firm
[2] the CFD simulations in designing Formula1 cars

Applying Codes

The Codes provide a guide for determining the wind actions on buildings as well as on other civil engineering works. They are useful for the evaluation of the wind loads on the entire structure and its individual parts. We will refer to the Eurocode in the present document.

The main input parameter that allows the evaluation of the wind load is the so-called terrain category (described in the table 4.1 below) which is identified by the parameter z_0, the roughness length, also called aerodynamic roughness:

Table 4.1 — Terrain categories and terrain parameters

Terrain category		z_0 m	z_{min} m
0	Sea or coastal area exposed to the open sea	0,003	1
I	Lakes or flat and horizontal area with negligible vegetation and without obstacles	0,01	1
II	Area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights	0,05	2
III	Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest)	0,3	5
IV	Area in which at least 15 % of the surface is covered with buildings and their average height exceeds 15 m	1,0	10
NOTE: The terrain categories are illustrated in A.1.			

The Eurocode, as well as other codes used in other countries, prescribes the value of the basic wind velocity v_b that must be used: it is the average wind speed in 10 minutes, regardless of the wind direction and the time of the year, at 10 m above the ground level in an open country with low vegetation and isolated obstacles (corresponding to category II). Often the measurement stations are located at airports.

The vertical profiles of the mean wind velocity $v_m(z)$ and the peak pressure $q_p(z)$ depend on z_0 and are determined by these relations:

$$v_m(z) = k_r \, ln(\frac{z}{z_0}) \, v_b$$

$$q_p(z) = [1 + 7 \, I_v(z)] \frac{1}{2} \rho v_m^2(z)$$

where:

- ➢ $k_r = 0,19\,(\frac{z_0}{z_{0,II}})^{0,07}$ (with $z_{0,II}$= 0,05m, terrain category II),
- ➢ $I_v(z)$, called turbulence intensity, is proportional to $1/ln(z/z_0)$

It is not the purpose of the present paper to report all the formulas and definitions of the Eurocode, all civil engineers know them very well.

The purpose is instead to illustrate the logic of the formulas and the dependence of the resultant pressures and forces, both quantitatively and qualitatively, from the terrain category.

The figure 1 shows the wind profiles for v_b=28 m/s, and for all terrain categories:

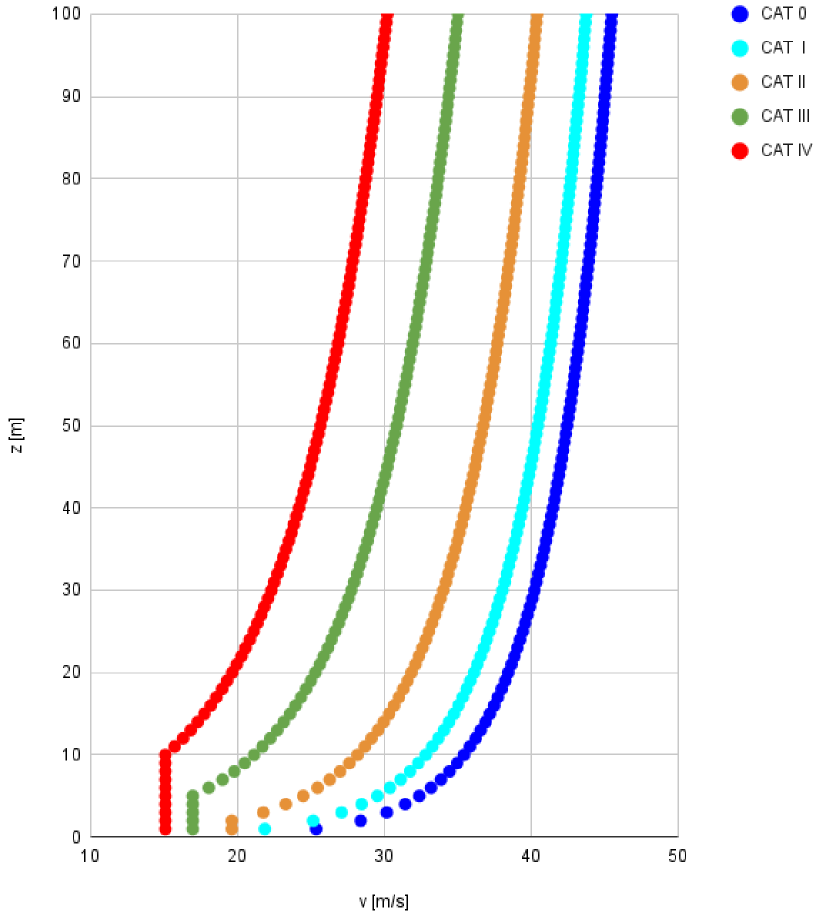

Figure 1: $v_m(z)$ with v_b=28 m/s (Eurocode wind profiles)

The figure 2 shows the factor $[1 + 7\,I_v(z)]$ which multiplies the dynamic pressure in order to provide the load (peak pressure) profile:

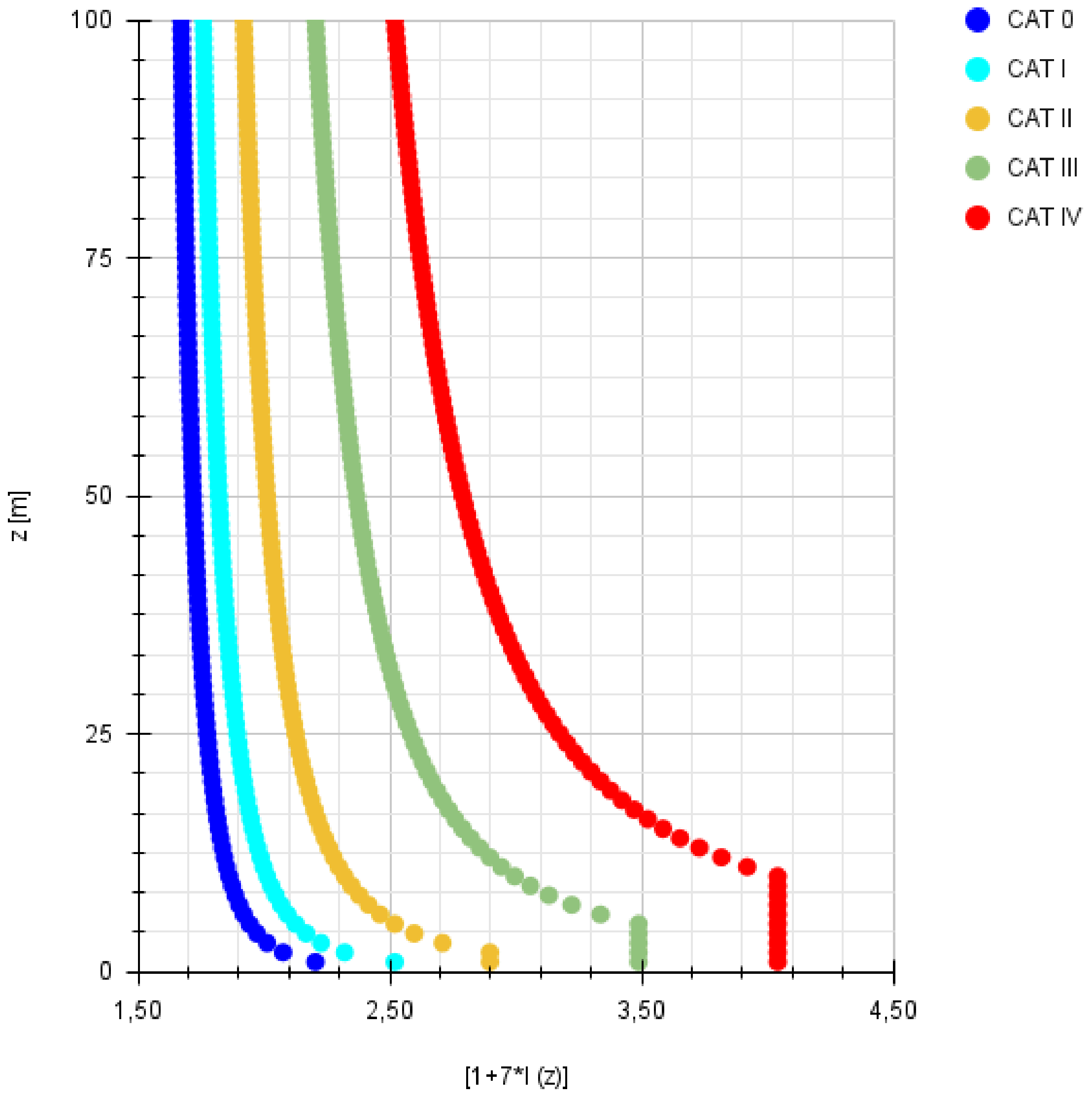

Figure 2: turbulent factor$[1 + 7\,I_v(z)]$

This multiplication factor, which takes care of the turbulence created near the ground by vegetation and/or buildings:

- is higher for urban environments (categories III and IV),
- and it is maximum near the ground, remaining well above unity even at higher altitudes.

Finally, figure 3 shows the load profile, the so-called peak pressure profile, which is based on the previous two profiles.

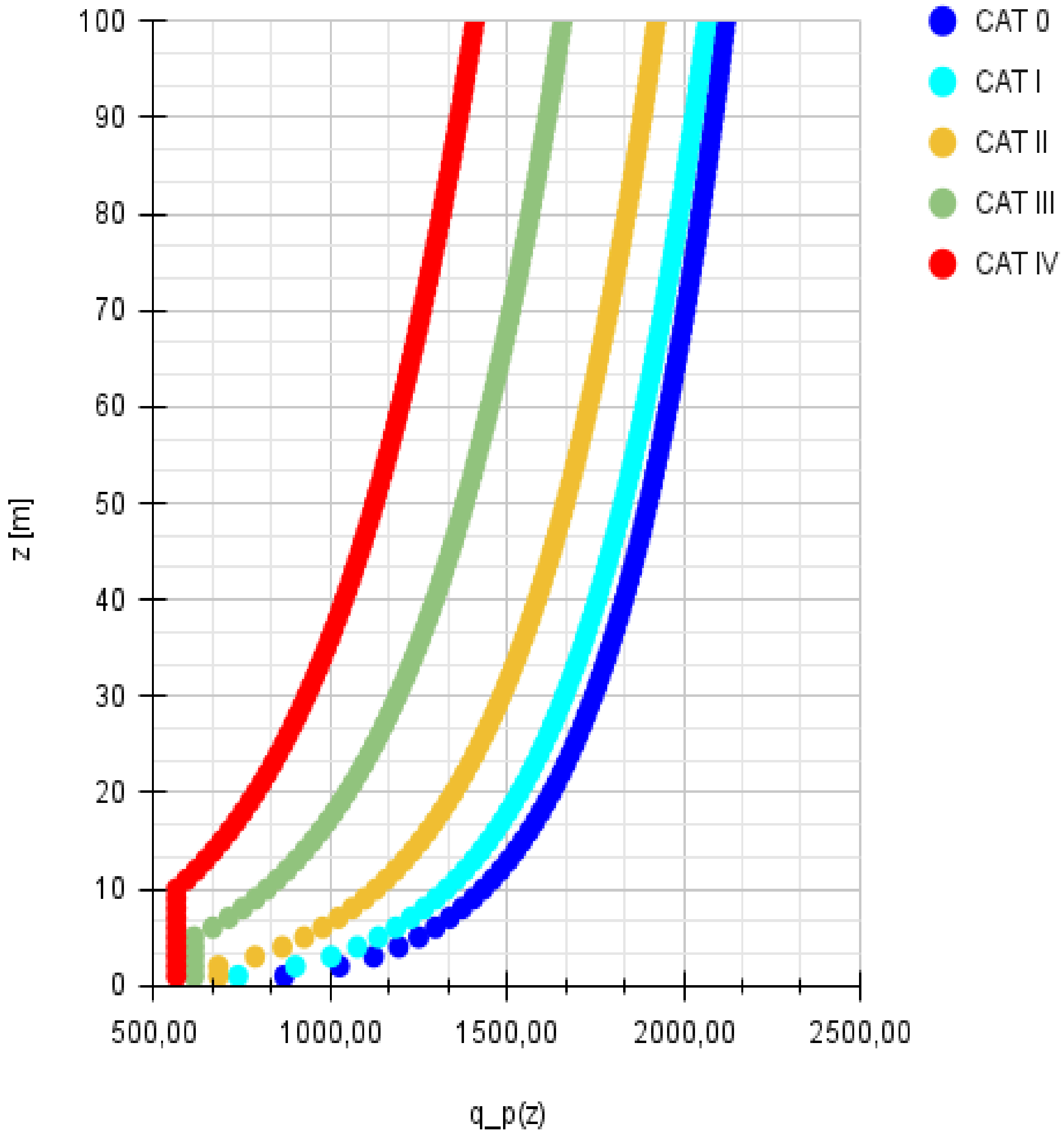

Figure 3: peak pressure profiles $q_p(z)$ [Pa]

It is important to highlight some concepts underlying the application of the regulations:

- ➔ the formulas and equations in the Eurocode, as well as in all of the other codes used outside Europe, are a set of zero-dimensional semi-empirical formulas where the context which surrounds the building under consideration are taken into account by the single parameter called aerodynamic roughness;
- ➔ the velocity wind profiles (figure 1) do not represent the incoming wind at some distance, they represent instead the wind profiles that hit the building under examination. All the obstacles encountered before reaching the building are accounted for by the roughness z_0;
- ➔ only the wind profile for Category II mantains the prescribed value of 28 m/s at 10 metres from the ground. The value of the wind intensity at 10m increases for the lower categories (0 and I) and decreases for higher categories (III and IV), generating somewhat unrealistic values of the wind speed at higher distances from the ground;
- ➔ when considering a building in Category IV (urban), the value of the wind intensity from the ground till the height of 10 metres is kept constant at 15 m/s (this is the effect of z_{min} in table 4.1). N.B. *this is somewhat contrary to the daily experience that near the ground, in heavily populated urban contexts, the wind is greatly attenuated by the obstacles, and it is locally changed in its direction by the multitude of vortices that the obstacles created.*

VENTO
NON CONFORMAL THINKING

Simulating by means of CFD

The CFD simulation, and also the experimental measurements in a wind tunnel facility, represent two alternatives for evaluating the wind load which are provided for by the regulations (codes).

CFD is a branch of the computational sciences. The system of the Navier-Stokes equations which governs the mechanics of all fluids (a coupled system of 5 partial differential equations together with the equations for turbulence), is solved by a computer code which implements the methods of the Numerical Analysis. The mathematical and numerical solution is sought in a 3D domain where a digital 3D geometrical representation of the buildings is provided, usually as a STL, CAD or IFC file.

At the domain boundaries, which are placed at a certain distance from the buildings under analysis (can be a few kilometres away), the profile of the incoming wind is provided as a boundary condition. The most common wind profile is given by the following expression:

$$u_z = \frac{u_*}{\mathrm{k}} [ln(\frac{z+d}{z_0})]$$

where u_* is the friction or shear velocity in (m/s), k is the Von Kármán constant (~0.41), and z_0 is the aerodynamic roughness (m), introduced to account for the effect of the elements present in the ground upstream of the domain boundary. It is exactly the same parameter used by the Eurocode to define the 5 terrain categories. The wind profiles that are obtained with the above log relation are reported in the following Figure 4, for the same base speed 28 m/s.

The effect of the aerodynamic roughness z_0 is easily understood by looking at the Figure 4: the higher the value of z_0, the more obstacles (vegetation and/or buildings) are present upstream, which cause the wind to slow down near the ground but also to increase the intensity at the higher altitudes. This is due to the fact that all profiles are constructed in order to return the base speed at the height of 10 metres.

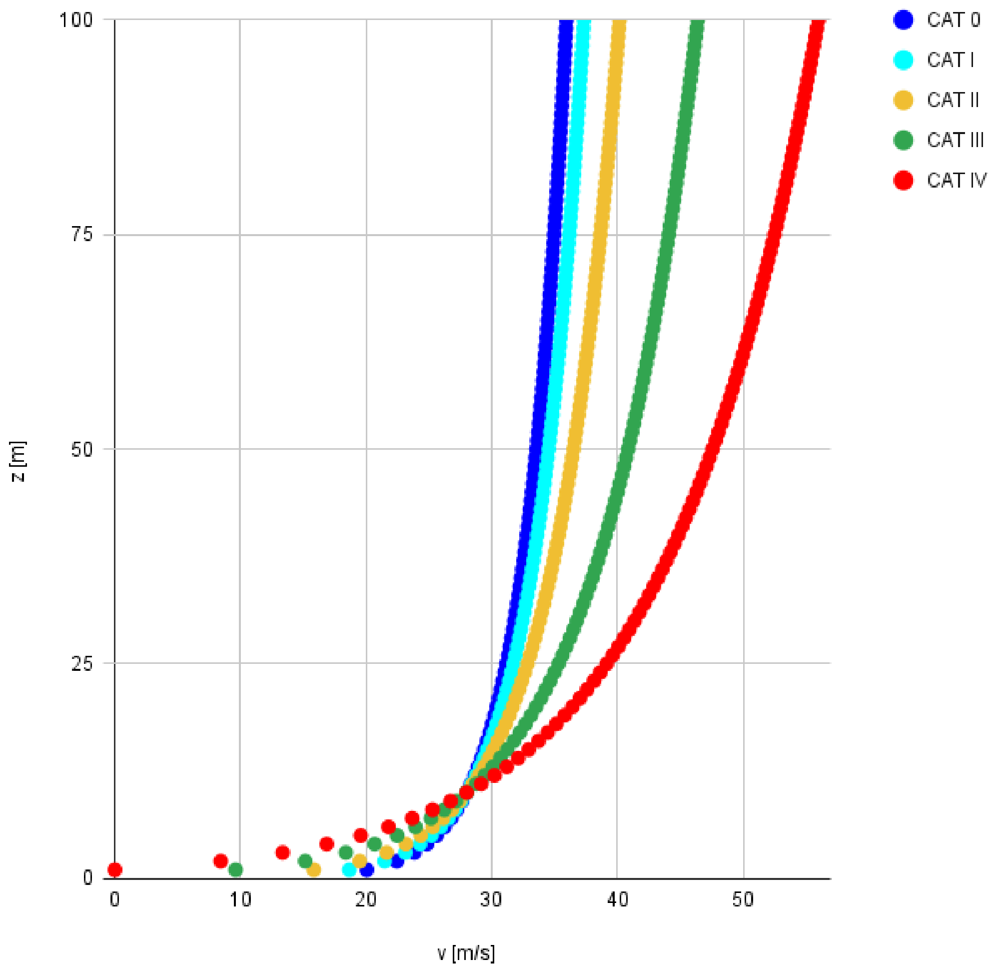

Figure 4: “CFD” logarithm wind speed profiles for v_b=28 m/s

An alternative to the logarithmic profile is given by a power law profile, which can easily be found in the net. In the present document the discussion is limited to the use of a logarithmic profile only.

Comparing Codes and CFD procedures

At first glance, when comparing the wind profiles for the different terrain categories, shown in the fig.1 (Codes) and in the fig.4 (CFD), the two approaches seem at odds.

As was previously noted, the wind profiles in the fig.1, despite the fact that they all refer to a nominal wind speed of 28 m/s at 10 meters from the ground, show a value of velocity at that height different from the "nominal" value. Higher values for the categories 0 and I, and lower values for the categories III and IV. Only the terrain category II shows exactly the value of 28 m/s at 10 meters above ground.

However, if the values of the velocities at 10 meters that result from the Eurocode semi empirical formulas, are inserted in the log CFD profile for the corresponding value of z_0, the two approaches yields a near-perfect match, as shown in the fig.5.

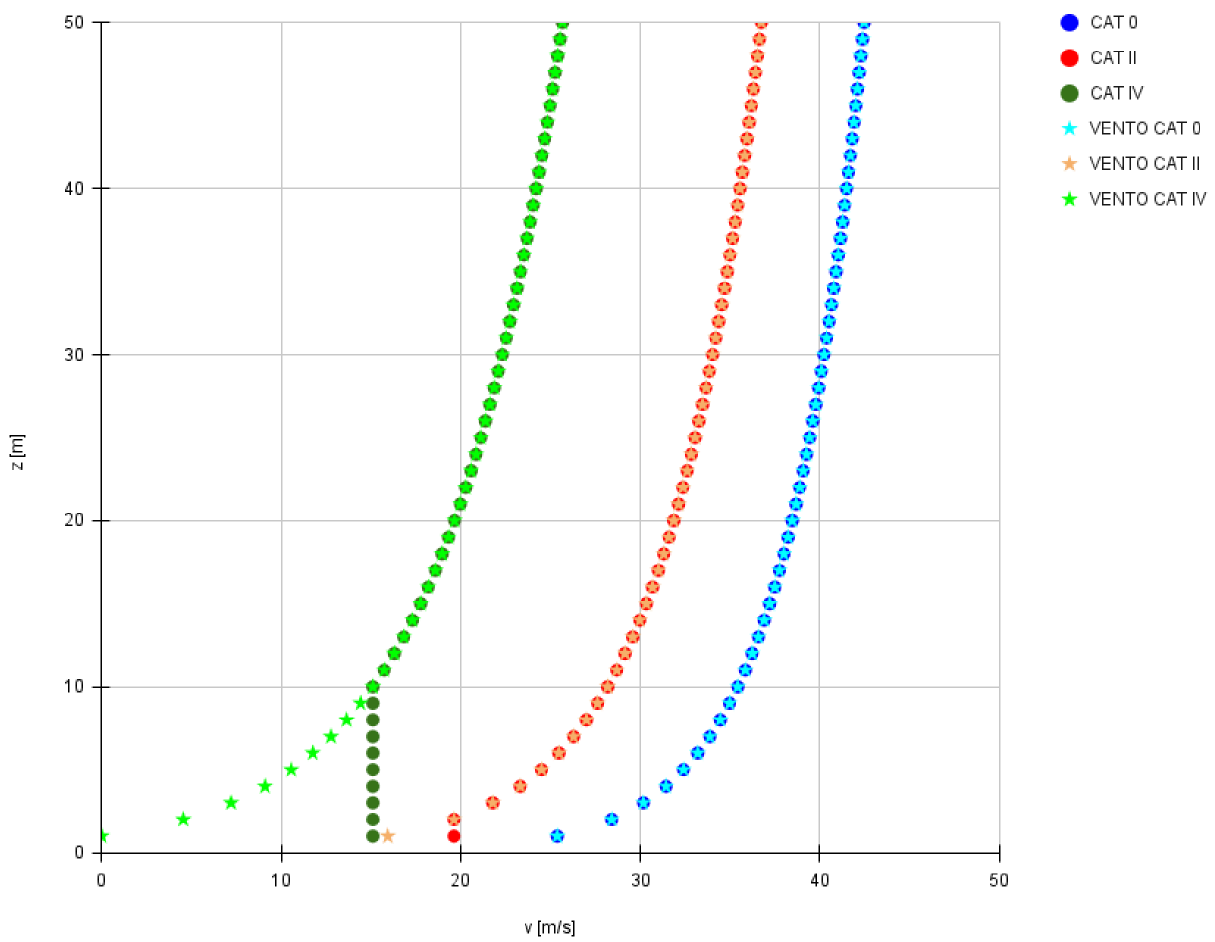

Figure 5: Eurocode and "CFD" wind speed profiles "true" matching, for v_b=28 m/s

Essentially the effect of applying the Codes is that of modifying the wind speed in the CFD simulation. That said, the major common points and differences between the two approaches are:

1- Common points:

- both approaches are based on an analytical definition of a vertical logarithmic profile of the wind;
- in both cases the wind profile depends on the parameter z_0, the aerodynamic roughness, which identifies the terrain category taking into account the density of obstacles (bushes, trees, small and big buildings, or urban environments) that the wind encounters;

2- Differences:

- the first difference between the two approaches is the location of the wind profile. For the Eurocode, this is the profile which actually hits the building. For the CFD, this is the boundary condition at the domain bounding box, in other words it is the profile of the incoming wind, far upstream the building under analysis (typically several kilometers further away);
- the second difference is how the two approaches (Codes and CFD) determine the load based on the wind profile:
    - the Eurocode makes use of the empirical formula for the "turbulent factor" shown in fig.2, which is used to determine the pressure profile that hits the building shown in the fig.3;
    - the CFD determines the pressures on the building by solving the equations of Fluid Dynamics together with the equations for generating and transporting the turbulence, in a computational domain that extends for many kilometers around the building;
- the last difference, not less important, is that, when the site is wavy showing differences in altitudes, the wind pressure, the turbulence and the air velocity that finally get to the building can turn out to be very different. While the CFD is fully capable of simulating the effects of the particular terrain, the Codes are not.

The Eurocode and CFD approaches are therefore conceptually different, and it is impossible to introduce elements of the Eurocode (or of other similar codes) inside the CFD algorithms, or to somehow mix the two approaches up.

The Codes, by using a single parameter z_0 and a set of zero-dimensional and semi empirical formulas, try to reproduce the 3-dimensional highly non-uniform distribution of obstacles that the wind encounters. And, similarly, an empirical turbulent factor attempts to reproduce the real turbulence generation.

On the other hand, the CFD allows the use of the realistic three-dimensional surrounding context, as shown in the fig.6, variously distributed in height and density in all directions.

The ultimate wind profile impacting the structure is a result of the wind's progression as it navigates from the upstream boundary toward the building under analysis through the distinct array of obstacles. This dynamic process shapes the wind's characteristics in the whole 3D domain, generates vorticity and turbulence, alters the wind speed and direction due to realistic interactions with all architectural or natural elements that the wind encounters. This is a result of the mathematical solution of the equations governing the fluid dynamics.

Moreover the CFD provides results and values of pressure, velocity and possibly temperature everywhere both on the buildings and on the surroundings.

Similar comments can be made on the Wind Tunnel testing. There might be some control over the incoming wind profile which enters the test section. From then on, however, no control can any longer be exercised. The flow evolves freely, gets to the building, and is finally measured by the probes.

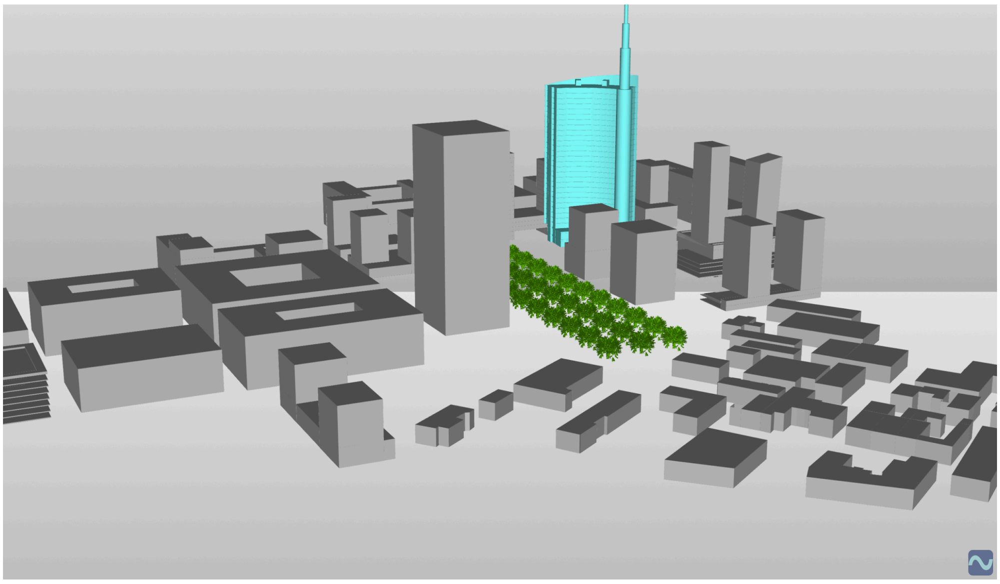

Figure 6: CFD electronic 3D model and nearby urban context

The same conceptual approach is shared by the Wind Tunnel testing (fig. 7).

Figure 7: Wind Tunnel 3D model together with the nearby urban context
(http://www.ccea.zju.edu.cn/cceaenglish/2016/0324/c6034a426975/page.htm)

In conclusion, the two approaches, the use of CFD and the application of Codes, are totally different. They are, however, not necessarily alternative. Each new design will be different from all of the others. Knowing and understanding the results of both approaches help the designer and contribute to build her/his own knowledge and experience as wind engineer, regardless of the choices she/he finally makes.