Historical evolution of shape and aerodynamics

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1. Introduction

While airplanes, boats, cars, trains and windmills were born through a process of optimization of the shape, buildings will remain for a long time anchored in a different reality: first, an architect conceives a shape based on his stylistic taste and just later an engineer makes structurally secure an already defined and untouchable shape. This conception will change at the end of the 20th century, when were born various researches aimed to optimize the form of skyscrapers on the basis of aerodynamics. This is the prelude of a new vision, where the architect and the engineer find a meeting point and work in team to achieve stylistic requirements and structural optimization.

2. Historical evolution aerodynamic shape

The concept of aerodynamic shape has remote origins. In fact, ancient Egyptians, Greeks used sailing boats that exploited the principle of portance and in Persia curious wind mills were born exploiting the principle of acceleration due to canalization of the wind’s flow to set into motion the blades. But the first who studied aerodynamic problems in a more rational way was Leonardo da Vinci that observed the shape of fishes and birds. In the 18th century Smeaton determines the shape of windmill’s blades that maximize energy production and it’s the first time that the shape has been studied rationally to achieve a target. Strouhal in the 19th century demonstrates that frequency depends from the diameter of the element and the velocity of the element in the wind. Afterwards, studies led by Von Karman define the properties of the vortex street that it’s created behind a body in the wind. In the 20th century are constructed the first wind tunnels and a lot of new studies in the field of aerodynamics were born. This innovation affects the aviation, vehicles, and trains. Studies to optimize their shape were held in wind tunnels by measuring the aerodynamic coefficients of various shapes and choosing the shape that gave a better performance.

Along with the construction of more complex structures and the consequent observation of their behaviour in wind tunnels, at the end of the 20th centuries were born various studies on the optimization of the shape of skyscrapers. The idea was that the shape of the building doesn’t have a purely aesthetic purpose but can also be used to mitigate the aerodynamic actions of the wind. In regard to this statement were considered the following points:

a) planimetric shape
b) form of the edges
c) shape of the top
d) variation of the section in elevation
e) introduction of porosity and openings
f) application of ribs
g) Coupled buildings side by side.

I will analyse all these aspects one by one later, but first I will briefly analyse some basic concepts of aerodynamics of buildings.
3. Aerodynamics of buildings

If we consider a construction in the wind, the surface of the construction undergo an aerodynamic action due to a variation of pressure on its surface $p = P - P_0$.

![Figure 1. Bidimensional body in the wind.](image)

On the surface of the construction exposed to the wind’s flow is created a thin boundary layer that can be laminar or turbulent on the basis of Reynold’s number $Re$ and roughness of the body.

![Figure 2. Laminar boundary layer.](image)

![Figure 3. Turbulent boundary layer.](image)

When the boundary layer undergoes a negative pressure gradient in the direction of the wind (the flow is accelerating) the thickness of the boundary layer is becoming smaller and the vorticity is pushed down to the surface.

The opposite phenomenon is realized when the boundary layer undergo a positive gradient of pressure. In this case the thickness of the boundary layer is growing and the vorticity is carried from the surface to outwards. The vorticity it’s no longer adherent to the surface, but occupies a wide area of flow. This area of flow it’s called Vortex Street and plays an essential role in the behaviour of construction that undergoes the wind’s effect.
The arousal of a positive gradient of pressure presents different aspects depending on the edges of the surface. Let’s analyse a first case, where the edges of the body are rounded and the phenomenon depends from the shape, Reynold’s number and roughness of surface.

The figure below shows the classic case of a smooth cylinder of infinite length and circular section which has been placed in a laminar wind field (without turbulence). For $Re < 1$ the boundary layer is laminar and remains attached to the cylinder along the perimeter (figure 4a).

For $1 < Re < 30$ the boundary layer is still laminar, but it’s separated from the cylinder generating two symmetrical stationary vortices with a laminar structure (figure 4b).

For $30 < Re < 10000$ the boundary layer is still laminar, the vortices are shed alternatively from the cylinder generating a Von Karman street (is a repeating pattern of swirling vortices). (Figure 4c).

For $10000 < Re < 200000$ the boundary layer is still laminar, but vortices have in prevalence a turbulent structure (figure 4d).

For $Re > 200000$ the boundary layer is turbulent, separation point move at the valley’s wake, still turbulent, becomes more narrow (figure 4e).

The increase of superficial roughness makes the transition regimen to be realized for smaller Reynolds numbers.

![Figure 4](image_url)

*Figure 4.* Smooth cylinder of infinite length and circular section placed in a laminar wind field.

The situation changes completely in bodies with sharp edges. Here, the separation of the wake takes place in the edges of the front side, so the configuration of the flow is independent from Reynolds number and roughness of the surface.
Figure 5. Flow separation from a building with sharp edges.

Elongate bodies in the flow’s direction usually, after the separation from the frontal edges, generate separation bubbles. After the generation of the bubbles, the flow tends to attach again on the surface and then separates when finds on its path the edges in the back of the body.

Figure 6. Separation of the flow from elongate building with sharp edges.

A wide wake generates an intense aerodynamic action due to the fact that the resistance offered from the body to the wind is big. A small wake on the contrary generates a small aerodynamic action. On the basis of these principles, the aerodynamic action of the wind is quantified by aerodynamic coefficients. So with the knowledge of atmospheric parameters $\rho e V$, the characteristic dimension of the body $l$ and aerodynamic coefficients we determine the aerodynamic actions.

4. Optimization of structural shape

As discussed before, the shape of buildings don’t have a purely aesthetic purpose but can also be used to mitigate the aerodynamic actions of the wind. The points below describe the different researches that have been made.

a) Planimetric shape

If we consider a building, the displacements can be esteemed by applying on it aerodynamic actions outlined trough a longitudinal force $f_D (D = drag, \text{ in } x \text{ direction}), a \text{ transversal force } f_L (L = lift, \text{ in } y \text{ direction}) \text{ and a twisting moment } (m, \text{ around } z \text{ axis}).$

As an effect of these actions the building has three types of responses: longitudinal, transversal and twisting.
For an ordinary building the prevalent response is the longitudinal, while the transversal and twisting are less important. But this it’s not the case of tall very tall buildings such as skyscrapers, towers or very long elements such as bridges, cables, where the transversal and twisting responses are crucial.

In fact, in the early 90s it has become evident that the aerodynamic load prevailing on high buildings is the force induced by the vortex street orthogonally to the wind direction. In other words, the shedding of vortices from the structure that is formed in the area of separation of the flow causes a transversal force to the wind direction that with a first approximation it can be expressed through the harmonic law whose amplitude and frequency depend on the planimetric shape of the building.

\[ f_{sl}(t) = A_s \cdot \sin(2\pi \cdot n_s \cdot t) \]  

Where:
- \( A_s \) is the amplitude
- \( n_s \) is the dominant frequency of shedding vortices given by the Strouhal law:

\[ n_s = \frac{St \cdot v_m}{b} \]  

\( St \) is a dimensionless number, called Strouhal number which depends principally on the shape and on the Reynolds number.
- \( v_m \) is the mean velocity of the wind
- \( b \) is a characteristic dimension of the section.

The most critic conditions are performed when frequency of shedding vortices is equal to the first frequency associate to a form of vibration perpendicular to the direction of the wind.

Tests in wind tunnels show a complex correlation between the shape parameters and the mechanical parameters. It is observed for example, that structures with high stiffness (almost static response) with a square-shape undergo greater effects than those of buildings with circular shape. The situation tends to be the opposite in the field of flexible structures, due the resonant component of the response. Such considerations are not sufficient to address the choice of architectural form but they help to understand the structural behaviour of the action of the wind on the basis of the chosen form.
b) Form of the edges

By noticing that the prevailing aerodynamic action on tall buildings is the one induced by vortex street perpendicular to the direction of the wind, and that the separation of the street takes place at the corners of the building, it is immediate to understand that any alteration of the shape of the edges is able to modify the aerodynamic behaviour of the buildings. On the basis of this principle, many experiments are held in wind tunnels aimed to define the shapes of the edges that can mitigate the aerodynamic actions. The results have shown that smooth, round, or more generally shaped edge can lead to a high decrease of base reaction forces and acceleration of the highest floors.

![Changes of the edges of buildings](image)

**Figure 6.** Changes of the edges of buildings.

![Central Plaza, Hong Kong, 1992](image)

**Figure 7.** Central Plaza, Hong Kong, 1992.

c) Shape of the top

The most relevant aerodynamic actions for the base reactions and the accelerations on the top are those applied by the wind in the higher part of the building. For this reason were conducted various test in wind tunnels to define shapes of the top that were best able to mitigate the aerodynamic actions. The results demonstrate that taper or sculpt the top can lead to a decrease of actions and effects of the wind.
d) Variation of the section in elevation

It seems clear that any intervention aimed to change the building’s section in elevation is very effective to mitigate the actions and effects of the wind. This type of intervention in fact destroys the regularity of shedding vortices, makes chaotic the vortex street and delivers the excitation over a wide band of harmonic components. Were born four different operative strategies:

- the tapering or the retraction of the section
- the variation of the size of the section
- the variation of the shape of the section
- the rotation of the section

![Figure 10. Sears Tower, Chicago, 1974.](image)

The tapering and the retraction of the section appears for example in Sears Tower, but the structure was not conceived on the basis of aerodynamic concepts, the shape was just an architectural choice. The effectiveness of the solution was demonstrated afterwards.

![Figure 11. Millenium Tower.](image)

The situation is different for some of the projects developed in the 90s with the aim of achieving the highest construction in the world. Millenium Tower (800 m) is a clear example of skyscraper that was designed by a team of engineers, architects and aerodynamics experts that perhaps for the first time
worked together from the designing phase. This building won’t be built, but the conception of attempting to find a shape capable of mitigating the aerodynamic actions will be revolutionary.

Figure 12. Endless column, Targu Jiù Romania, 1938.

The variation of the size of the section has a distinguished ancestor: the endless column made by Constantin Brancusi Targu Jiu, in Romania, in 1938 that is still one of the most important examples of aerodynamically efficient construction.

Figure 13. Republic Plaza, Singapore, 1995.

The variation of the shape of the section can be found for the first time in Republic Plaza in 1995. The tests made upon the model in wind tunnel highlight, once more, the reduction of wind actions and effects.
The rotation of the section is undoubtedly the most spectacular but also an especially good aerodynamic solution. In fact, the edges are no longer straight and the vortex street is highly irregular. To this is added that the aerodynamic actions of the wind vary with continuity along the axis of the tower as a result of rotation of the section. Consequently, whatever the wind direction is, the highest actions do not occur simultaneously at the same height. These two effects drastically reduce wind effects.

e) Introduction of porosity and openings

The idea was to provide the construction with openings, in which the wind would be canalized giving place to a high damping of aerodynamic nature. The introduction of this idea in the body structure has been tested in wind tunnels that showed that it can lead to a high natural aerodynamic damping.
f) Application of ribs

The application of ribs appropriately placed, contrast the regular separation of vortices, mitigating transversal wind actions but enhancing longitudinal actions.

Figure 15. Twisted shaft, Harry Weese.

g) Coupled buildings side by side

The construction of coupled buildings one aside another gives birth to a large literature aimed to study the aerodynamic interference effects. The aerodynamic phenomenon of interference occurs when two or more close bodies give rise to significant changes in the local flow and of the aerodynamic actions that compete to isolated bodies. This phenomenon is particularly important, for example, in the case of tall buildings of similar shape and type.

The figure below shows the case of two cylinders, highlighting the different flow regimes, which are realized in function of the mutual position of the bodies invested by the wind. To each configuration corresponds a very different aerodynamic action. Studies have showed that, varying the position of two bodies in respect to the wind direction, can have as consequence screening effects but also the amplification of loads.
Amplification of loads occurs, for instance, when a building produces a vortex trail that invests another similar building placed on the wake of the first building. If the frequency of shedding vortices from the upwind body is equal to the frequency of the body leeward, this body will undergo a resonant action caused by the interference.

The mitigation of the problem can be achieved by two alternative criteria. The first, consists in placing bodies of different shapes and the second, involves the connection of the bodies side by side with the purpose of eliminating or reducing certain degrees of freedom of the buildings and increase the dissipation energy.
5. Conclusion

With the new Millenium, the points quoted above will be used in a renewed vision of design where the architect and the engineer find a meeting point and work in team to achieve stylistic requirements and structural optimization.

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