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Wind Effects on Permeable Tall Building Envelopes: Issues and Potentialities

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Andrea Giachetti received his PhD in 2017 with a thesis titled "Wind effects on permeable building envelopes: A two-dimensional exploratory study". In the same year, he won the 2017 CTBUH Student Research Competition. He is a research fellow with the Civil and Environmental Engineering Department (DICEA) of the University of Florence, mainly working in the Interuniversity Research Centre in Building Aerodynamics and Wind Engineering (CRIACIV) wind tunnel, and is a member of the CTBUH Academic and Teaching Committee. He focuses his activities on studies of wind loads on permeable double-skin façades, urban resilience and existing tall buildings.

Gianni Bartoli, structural engineer, PhD, is Associate Professor of Theory of Structures at DICEA, University of Florence, Director of CRIACIV, and Vice-President of the Italian Association for Wind Engineering (ANIV). He is the Regional Coordinator for the European-African section of International Association for Wind Engineering (IAWE). He is author or co-author of more than 250 technical papers.

Claudio Mannini received his PhD in 2006. His main research interests are wind engineering, flow-induced vibrations, bluff-body aerodynamics and structural dynamics. He received junior research awards from ANIV (2008), the IAWE (2011) and the European Association for Structural Dynamics (2014). Presently, he oversees courses of Wind Engineering and Steel Structures at the University of Florence.

Abstract

A comprehensive conclusion about the effects of wind on permeable building envelopes (PBEs) remains elusive. The external layer permeability, the gap width, and the internal compartmentations are only a few of the many potential influencing parameters that complicate the study of the fluid-dynamic system that results from creating internal cavities connected to the building exterior. This project sheds light on the aerodynamic behavior of permeable envelopes of tall buildings, focusing on the possible external/internal flow interaction that may strongly influence the overall system. Results from experiments show that a remarkable aerodynamic interaction can occur. This stresses the importance of an iterative dialogue between the experts involved in the design process of such permeable façades and, at the same time, it offers new possibilities related to the control of the complex aerodynamic effects that a PBE can create.

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Keywords: Permeable Building Envelope (PBE), Double-Skin Façades, Wind Tunnel Tests

Introduction

The envelope is one of the crucial elements in the design of high-profile buildings. The requirement to achieve high aesthetic and energy-conservation levels makes the building envelope one of the most expensive and risky parts of the building: a façade can constitute up to 25% of the total building cost, and the consequences of windstorms tend to comprise the highest proportion of total insured losses (Overend and Zammit, 2006). Indeed, for such envelopes, the main load is often represented by wind action.

Given the impact of the façade on the overall worth of a tall building project, it seems logical to require that it carry out more than one function. For this reason, permeable building envelopes (PBEs) are widely used. Indeed, a PBE acts as a special layer that protects the building occupants from the external environment in terms of heat, noise and pollution (see Figure 1). Its permeability is the key means to achieve energy efficiency, where internal cavities can be ventilated, so as to dissipate heat and exhaust air. At the same time, the cavities between the external skin and the building face (on which the façade is fixed) must not present a conduit for fire propagation. Moreover, many funding initiatives are focused on energy saving and generation from renewable power sources (e.g., the European Community research and innovation program "Horizon 2020"), pushing the boundaries of façade-technology development. The concept of "smart city" is also becoming popular, requiring increasingly complex features from future buildings. From this perspective, PBEs can be designed not only for energy saving, but also to take advantage of building characteristics to generate energy. Photovoltaic ventilated façades (e.g., Sick and Erge, 1996, Yun et al., 2007) and building-integrated energy harvesting systems (e.g., Sharpe and Proven, 2010, Hassanli et al., 2017) are only few of the many applications that show great potential.

The study of building aerodynamics mainly focuses on the effects caused by wind on the building surfaces. To properly evaluate

Figure 1. Permeable façade of the Post Tower, Bonn. © Left & Right: Murphy/Jahn; Center: Rainer Viertlboeck

these effects on a specific structure, a combination of influencing elements must be considered, starting from the atmospheric boundary layer (ABL) characteristics—namely, the approaching flow—and culminating in the shape and dynamic properties of the building itself. This approach was formalized in the Alan G. Davenport Wind Loading Chain by the International Association for Wind Engineering (IAWE), named in honor of its creator (IAWE General Assembly, 2011) (see Figure 2). The envelope defines the shape of a building, and therefore plays a fundamental role concerning wind-induced actions. In spite of the small scale of the elements that comprise a façade, previous studies have shown how their features can influence overall building aerodynamics (e.g., Dutton and Isyumov, 1990, Kwok and Bailey, 2006).

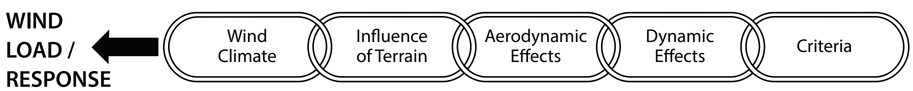

Figure 2. The Alan G. Davenport Wind Loading Chain is used to describe the many factors contributing to wind loads. (International Association for Wind Engineering (IAWE)).

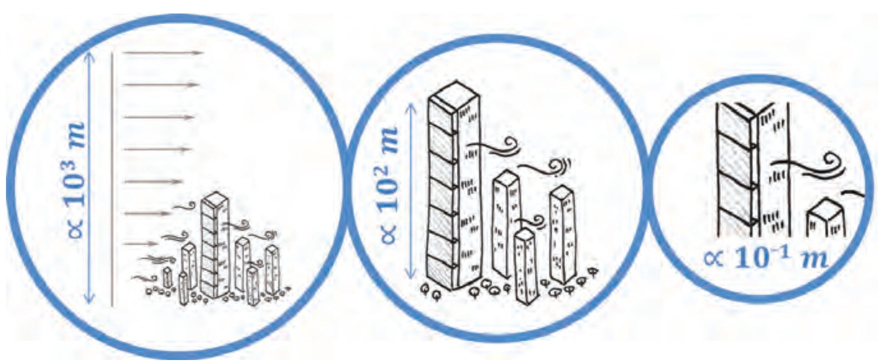

Figure 3. The definition of wind effects on a permeable building envelope (PBE) involves a wide range of scales. In the sketches, the order of magnitude of the dimensions are shown for: the atmospheric boundary layer (ABL) (left), the building (center) and the façade detail (right). © Courtesy of C. Torsoli

The present work considers an additional complication: the fact that a building envelope can create a gap where the air can flow in. In particular, from an aerodynamics point of view, a PBE represents one (or more) additional layer(s) fixed on one (or more) airtight building face(s), at a relatively small distance, which creates one (or more) internal cavity or cavities, which are somehow connected to the exterior. The connection between the internal cavity and the exterior (namely, the permeability of the building envelope) can be represented by openings of a certain size and location, or by porous layers with uniformly diffused openings. The cavities are compartmentalized, depending on the desired internal ventilation and/or fire-safety requirements. However, this work focuses only on the role of external layers and compartmentations with respect to wind effects. Consequently, whether the external additional layer is a glazed skin of a ventilated façade, a rainscreen, a sunshade or a porous metallic layer, the main parameter remains its permeability.

Wind action produces positive or negative pressures on the envelope, which are transferred as forces to the building structure through the supporting systems. The main problem while assessing the wind loads on a PBE is the evaluation of the net pressures—namely, the difference between external and internal pressure distributions. The relatively small dimensions of the cavity compared to the overall building dimensions, and the relation between the size of the building and that of the ABL in which the building is immersed, determine the multi-scale characteristics of the problem (see Figure 3). This feature accounts for the number of

Figure 4. A scale model of a tall building with a complex façade inside the CRIACIV wind tunnel. View is from inside the wind tunnel towards the inlet.

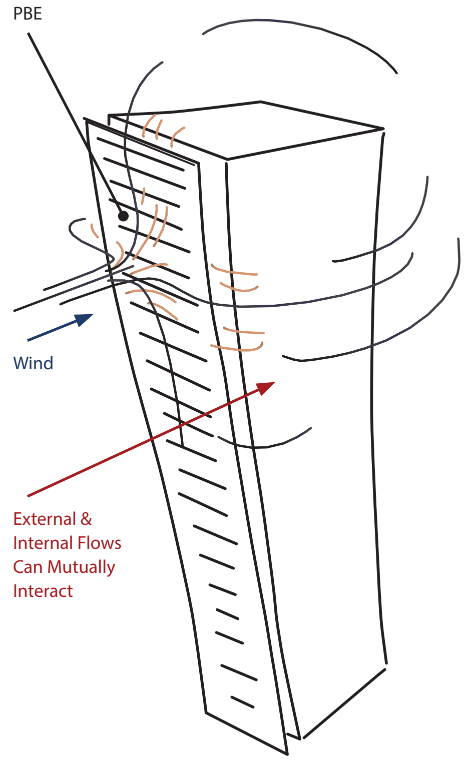

Figure 5. A sketch of possible flow streamlines expected around a tall building with a generic PBE.

open issues surrounding this topic, especially those related to the standard tools adopted in wind engineering used to evaluate wind effects, such as wind tunnel tests and numerical simulations.

In the first case, scale models are used (see Figure 4), and the dimensions of the internal cavities may become too small to be reproduced. In the second case, to model accurately the flow in the cavities, the computational cost of the grids may become unaffordable. Nevertheless, sometimes it is possible to simplify the problem. If the presence of the PBE only produces negligible aerodynamic effects, and the building equipped with the PBE behaves both locally and globally as a similar building without a connection between internal and external flows—that is, as if the openings or the porous layers of the façade were sealed—it is possible to uncouple the study of external and internal pressures. In this case, the external pressures can be evaluated on the building model without reproducing the internal cavities; the internal pressures can be estimated from the pressures obtained on the building surfaces in correspondence to the sealed openings. By contrast, the simplification of the problem is not possible when the aerodynamic behavior of the building with or without PBE is significantly different. In such instances, as sketched in Figure 5, the presence of the PBE creates a new fluid-dynamic system, where the mutual interaction between external and internal flows makes it impossible to uncouple the problem as described above. Unfortunately, in most of the cases, it is not possible to know *a priori* if a simplification is allowed for the evaluation of wind effects on the considered PBE.

This research project, the recipient of the 2017 CTBUH Student Research Award, kindly sponsored by Underwriters Laboratories, aims at investigating a basic tall building equipped with different PBEs at a relatively small distance from the structure, by means of wind tunnel tests. The study is inspired by the main findings achieved by Giachetti (2018) through two-dimensional experimental and numerical exploratory studies on the aerodynamic effects of a screen attached to rectangular cylinders (see Figure 6).

Investigation Methodology

Today, wind tunnel tests on scale models are the main tool of investigation in the field of wind engineering. Although the facilities have become larger and more sophisticated over the years (e.g., Letchford et al., 2002, Butler et al., 2010), the use of a scale model always leads to a critical choice: at which scale should the building's geometry be reproduced? The importance of this topic is underscored by the number of investigations into the effect of balconies on the building aerodynamics performed to date (e.g., Stathopoulos and

Zhu, 1988, Chand et al., 1998, Maruta et al., 1998). On the other hand, even if computational grids are capable of reproducing almost any geometry, and the use of computational fluid dynamics (CFD) in wind engineering has become popular, the obstacles to implementing it in a way that is useful for standard wind engineering applications, mean that it will be some time before the potential replacement of wind tunnels by CFD becomes a reality (Irwin, 2009). The ongoing development of this subject, called computational wind engineering (CWE), reveals that both wind tunnel and CFD studies show their limits and strong points, suggesting that contemporaneous use of both, when possible, is complementary (Blocken, 2014).

Given the exploratory approach of the current research project, it was based only on experimental mock-ups. The experimental campaign was carried out in the Inter-University Research Center on Building Aerodynamics and Wind Engineering (CRIACIV) ABL wind tunnel.

The facility is an open-circuit wind tunnel installed inside the wind engineering laboratory of the Department of Civil and Environmental Engineering of the University of Florence. Figure 7 shows the CRIACIV wind tunnel. It is worth noting that the laboratory, active since 1994, was the first ABL wind tunnel in Italy.

In order to study the wind effects on a scaled building model, it is fundamental to properly reproduce the approaching ABL in terms of mean wind profile, turbulence intensity and integral length scales. Therefore, a wind flow with characteristics similar to those expected in a suburban environment was reproduced at model scale by means of opportune roughness elements, barriers and other devices, as shown in Figure 8.

The tall building model was a rigid square prism with side ratios 1:1:5. The shape was decided at the early stage of the project, after a wide literature review concerning the rectangular-prism tall-building models

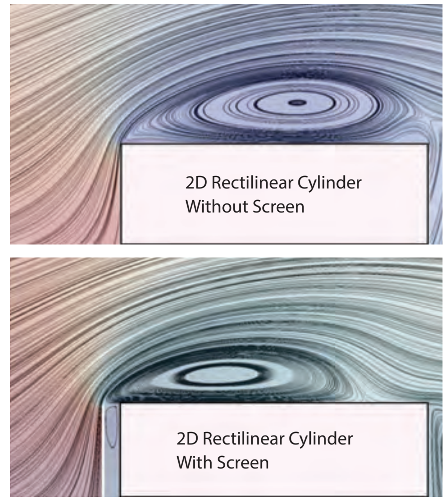

Figure 6. Two-dimensional numerical results from Giachetti (2018). Mean flow streamlines for the case of the rectangular cross-section (top); and for the system with an airtight, laterally opened, screen at 1/20th of the body cross-flow dimension (bottom).

Figure 7. A view of the CRIACIV Atmospheric Boundary Layer Wind Tunnel from the inlet.

Figure 8. A picture inside the CRIACIV wind tunnel, facing from the working section to the inlet, showing the set-up needed to reproduce the Atmospheric Boundary Layer (ABL).

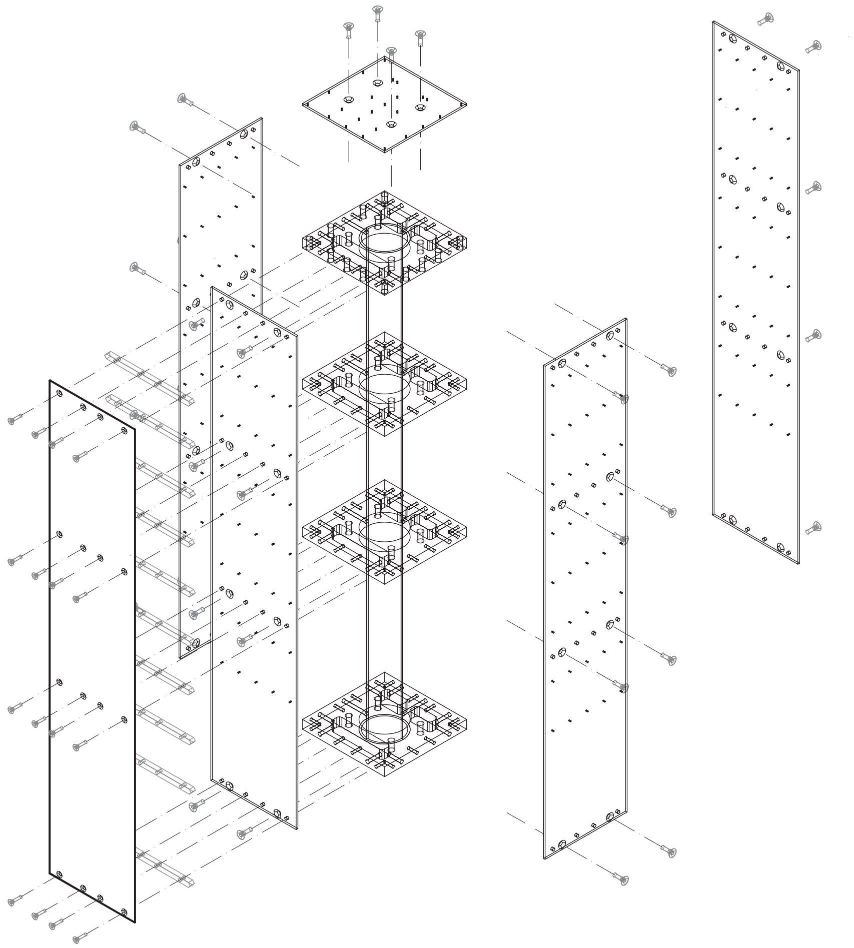

Figure 9. A drawing of the tall building model designed for the purposes of the CTBUH research project, showing an exploded view of the components.

Figure 10. A picture of the tall building model during the assembly phase.

> “The models were equipped with approximately 200 pressure taps, which were distributed mainly across the upper part of the model, in order to investigate the aerodynamic behavior in this portion of the building. The number of measurement points was increased closer to the building edges.”

mostly adopted in wind engineering. The relatively simple shape, characterized by a square cross-section, was selected in order to have a better insight into PBE fluid-dynamic behavior. Different PBEs, with the common feature of an airtight external skin, were tested. The internal cavity was divided into airtight horizontal compartments, arranged in different ways. The cavities were connected to the exterior through lateral openings located at the edges of the building. The models were equipped with approximately 200 pressure taps, which were distributed mainly across the upper part of the model, in order to investigate the aerodynamic behavior in this portion of the building. In particular, the measurement points were increased close to the building edges. In Figure 9, a complete view of the elements composing the model is provided. In addition, Figure 10 shows a picture of the model during the assembly phase, when each element is verified together with its connections.

Numerous tests were carried out by varying potential influencing parameters, such as the PBE gap width (to a maximum of 1/20th of the building's characteristic cross-section's side length), the number of horizontal compartments, the number of building faces equipped with the PBE, wind direction, and mean flow speed.

Results

In order to understand if the overall aerodynamic effects caused by the considered PBE were negligible or not (that is to say, if the study of the wind-induced loads on certain PBEs can be simplified), the tests were conducted by considering global and local aerodynamic quantities of the system "tall building with PBE." The global wind action on a tall building is given by the resultant of all the pressure acting on the surfaces of the building itself, and it can be mainly divided into three contributions: the along-wind, the across-wind and the torsional load. Broadly speaking, these depend on the geometric features of the building and the approaching wind characteristics; but, in the case of very flexible structures, the mechanical properties of the building (aeroelastic effects) also play a role. Additionally, local effects are caused by relatively small portions of the building, including cladding and non-structural components. Since the building envelopes are usually made of panels of different materials, joined together by appropriate structures and fixed to the building through supporting systems, the pressures on their tributary areas are often directly related to their design (Holmes, 2007).

At the end of the experiment, the pressure signals were analyzed in order to understand the aerodynamic behavior of the system, by comparing the case with and without the PBE in different configurations. An example of the possible effects caused by the presence of this additional layer is presented by considering the case of a PBE on the building face directly hit by a perpendicular wind, characterized by a gap width equal to 1/20th of the building cross section. Maps of normalized mean pressures (i.e., the mean pressure coefficients) are shown in Figure 11. The pressures along the lateral sides (labeled side A and side B) and on the leeward face of the building model are different if the model is equipped with this specific PBE. In particular, the pressures are reduced in the upstream portion of the lateral sides close to the edges behind the cavity openings when the permeable envelope is present. The pressure distributions around an alignment of

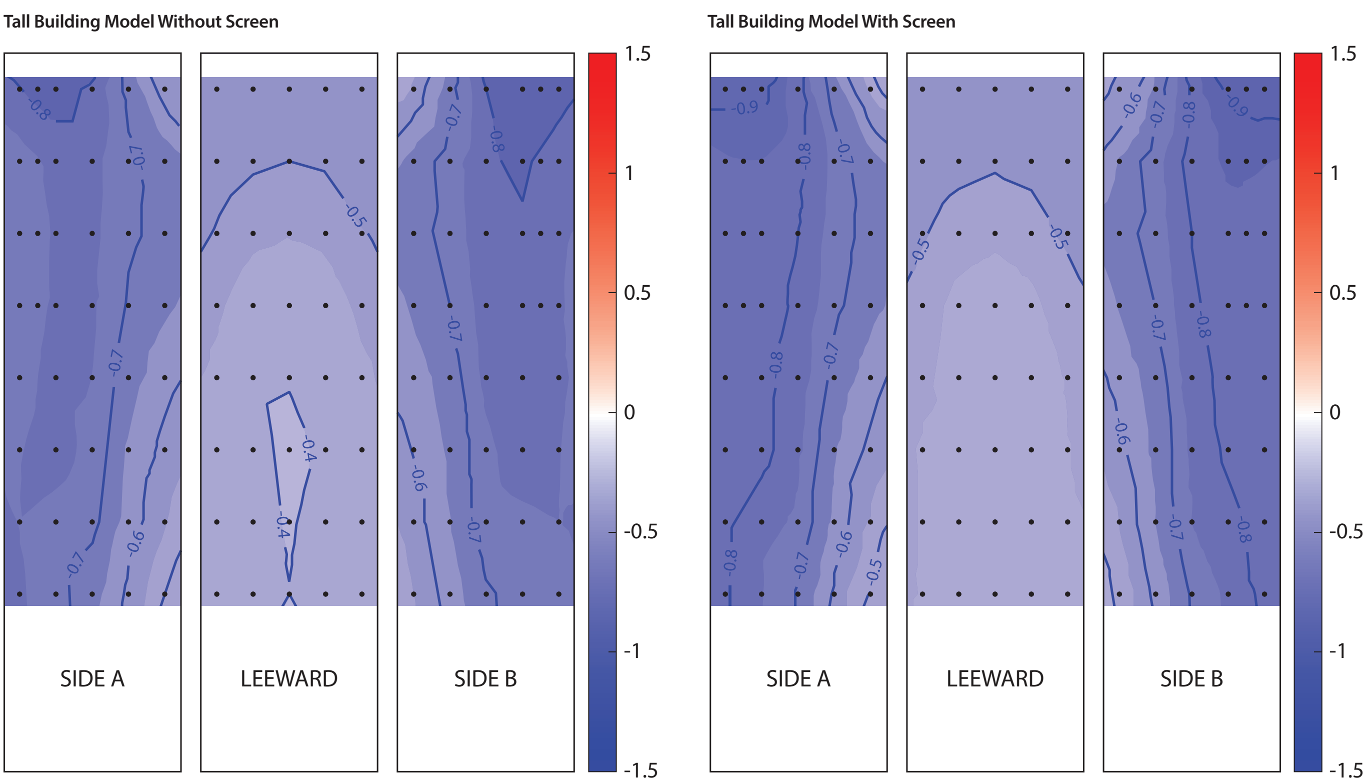

Figure 11. Mean pressure coefficients over the lateral and the leeward sides of the building model. The mean wind direction is perpendicular to the face equipped with the PBE. The case without PBE is on the left; on the right is the case with a laterally-opened airtight screen fixed at a distance equal to 1/20th of the horizontal cross-section side length, with 10 horizontal compartments.

pressure taps at a given height is reported in Figure 12, in order to compare the results obtained with different conditions of horizontal compartmentations, for the same wind direction considered above. The mean pressures in the cavity are lower than those measured on the lateral sides of the model without PBE, close to the edges where PBE openings are located. The difference between the results obtained, with and without the permeable building envelope, gives an idea of the error that can be made when trying to simplify the problem by uncoupling external and internal pressures. Furthermore, the difference between the mean pressures measured inside and outside the cavity in the presence of the PBE suggests a complex mechanism of interaction between internal and external flows. On the other hand, global effects caused by the PBE were evaluated by pressure integration, and they were more evident when the wind direction was slightly different from the one perpendicular to the face equipped with the PBE. These results are in general concurrence with a previous two-dimensional study conducted by the authors (Giachetti et al., 2019). Moreover, in certain configurations tested in the current research, global quantities, such as the frequency at which the main vortices detach from the building edges, seem to be affected by the presence of the PBE, even for a perpendicular oncoming flow.

Discussion and Interpretation of Results

The reported results show that a PBE can cause remarkable aerodynamic effects. As previously mentioned, it is not possible to know *a priori* if the evaluation of the wind effects on a building equipped with a PBE can be simplified by uncoupling external and internal pressures. Indeed, in certain configurations, such as those discussed in the present work, local and global aerodynamic quantities are affected by the presence of the PBE; in these cases, a "new" fluid-dynamic system occurs, and it behaves under the wind action as a unique object that cannot be uncoupled.

This research stresses the importance of the envelope characteristics in the definition of the aerodynamic performance of the tall building, by exploring the relations between the façade geometry and the possible mutual interaction between internal and external flows. This interaction can affect the wind loads, but at the same time suggests high potentialities for

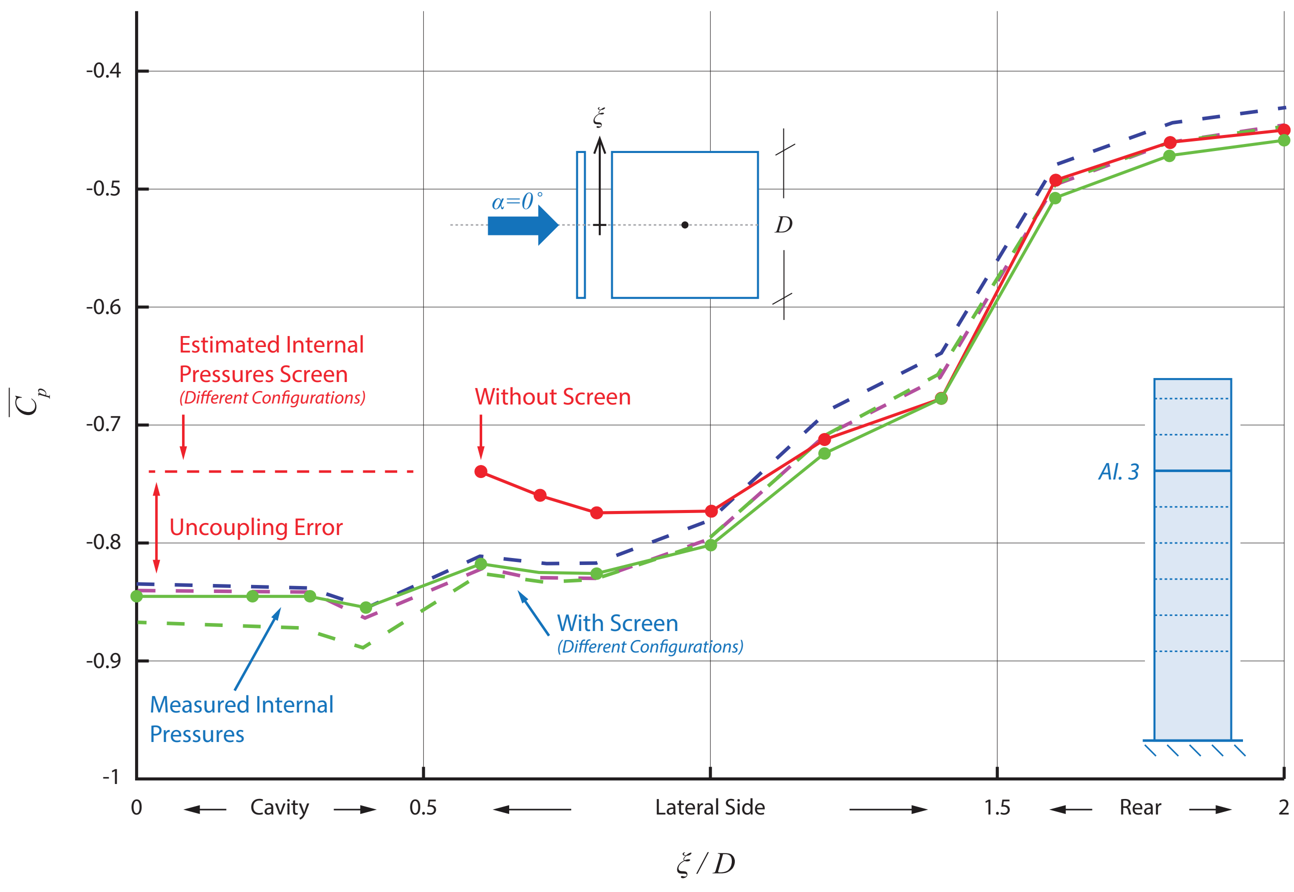

Figure 12. Mean pressure coefficients ($\overline{C}_p$) around a specific alignment (ξ/D) at 75% of the total building height. The difference between the pressure coefficients in the cavity that can be estimated by neglecting the presence of the screen, and that of the values actually measured in the wind tunnel, is shown.

> "The local and global aerodynamic quantities of a building are affected by the presence of the permeable building envelope. In these cases, a 'new' fluid-dynamic system occurs, and it behaves under wind action as a unique object that cannot be uncoupled."

wind-driven natural ventilation or energy-harvesting devices. Therefore, a number of opportunities for future study have been opened by the work presented here. In order to exploit, or simply to control, the external/internal flow interaction in the design phase, it will be necessary to deeply understand the driving parameters involved in the aerodynamics of the system building + PBE in different configurations. In particular, the next steps required to advance the scientific knowledge of this topic will be:

- Test different tall building shapes (in terms of aspect ratios and cross-sectional shapes).
- Investigate the influence of external layer porosity (e.g., related to the presence of sunshades or louvers).
- Examine the effects of different arrangements of openings.

This study focuses on a simple tall building geometry with a simple PBE and does not refer to a specific case study. However, it aims to call attention to a "new" point of view in the design process of tall buildings with PBEs. For future tall buildings, a holistic multidisciplinary approach will be necessary to design safer building envelopes with improved aerodynamic performance, combining energy efficiency, acoustic insulation and fire safety without losing aesthetic quality. The façade geometry should be the result of an iterative dialogue between experts in building physics, fire engineering and building aerodynamics. ■

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