

# Modeling Porous Envelopes on Square Prisms: Validation of Darcy-Forchheimer Approach via Wind Tunnel Testing

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## Summary

The aerodynamic optimization of bluff bodies is critical to mitigate local cladding loads and global aeroelastic instabilities such as Vortex-Induced Vibrations (VIV). This study investigates the effectiveness of porous envelopes as passive flow control devices on a square prism. The research integrates wind tunnel experiments (static and aeroelastic) with 2D URANS simulations to provide a comprehensive analysis of the fluid-structure interaction. The experimental data quantify the impact of porosity on integral forces and wake topology, revealing a significant suppression of shedding-induced fluctuations. Complementarily, the numerical analysis validates the capability of the homogenized Darcy-Forchheimer model to capture these unsteady flow features, including the transition to a disorganized wake regime. By demonstrating the reliability of simplified numerical tools in predicting complex dynamic phenomena, this work offers valuable insights for the design of porous façades, bridging the gap between steady-state modeling and dynamic wake physics.

**Keywords:** *Square Prism, Porous Façade, Vortex Shedding, VIV, Darcy-Forchheimer, Wind Tunnel Testing*

## 1 INTRODUCTION

The aerodynamic design of bluff bodies, such as high-rise buildings and civil engineering structures, poses significant challenges regarding both local cladding loads and global structural stability. The interaction between incident flow and sharp edges generates flow separation with high-intensity suction peaks, driving the dimensioning of façade elements. Simultaneously, slender structures are prone to aeroelastic instabilities, specifically Vortex-Induced Vibrations (VIV), where synchronization between vortex shedding and structural natural frequencies can lead to large-amplitude oscillations [1].

To address these issues, porous envelopes, such as Permeable Double Skin Façades (PDSF) or mesh screens, act as effective passive flow control devices by enabling a bleed flow into the cavity. This momentum transfer alters the shear layer curvature and stabilizes the near wake, effectively disrupting the spanwise correlation of aerodynamic forces that drives VIV lock-in [2]. However, a systematic understanding of how specific porosity parameters quantitatively govern the transition from a canonical bluff-body shedding to a permeability-dominated flow regime is currently lacking.

From a computational perspective, modeling porous envelopes presents a complex multi-scale problem. Resolving the detailed geometry of individual pores within a full-scale domain is computationally prohibitive. Consequently, homogenized approaches, such as the Darcy-Forchheimer model, are required to mimic pressure drops via momentum sink terms. While these models are well-established for steady-state pressure losses [3], their reliability in capturing unsteady wake dynamics, such as vortex shedding frequency and oscillating lift forces, remains largely unvalidated.

This study addresses these gaps by combining wind-tunnel testing and CFD simulations on a benchmark square prism with porous coverings. The primary objective is to quantify the influence

of porosity on separated-flow dynamics and to assess the capability of the homogenized Darcy–Forchheimer model in reproducing unsteady fluid–structure interaction physics.

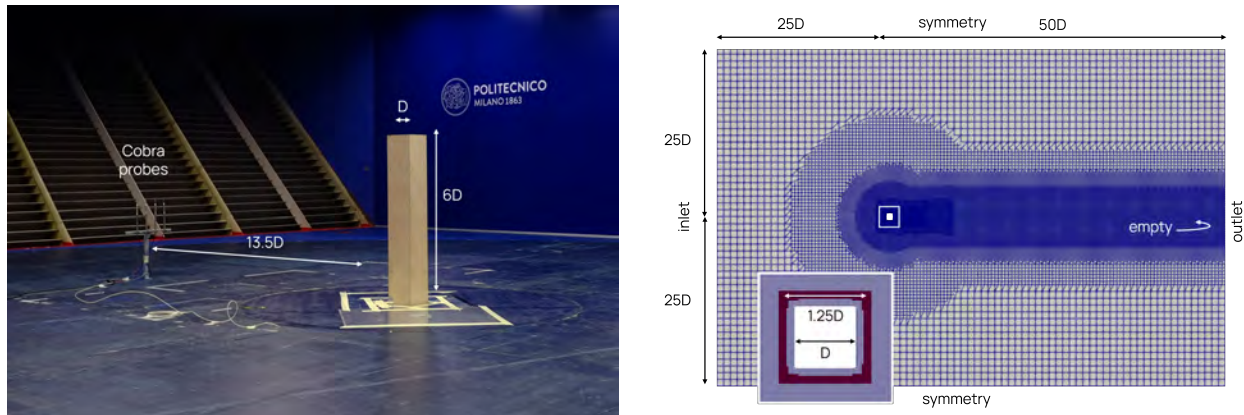
## 2 METHODOLOGY

The research framework adopts a rigorous cross-validation strategy integrating wind tunnel experiments with Computational Fluid Dynamics (CFD). A parametric experimental campaign characterized a reference solid square prism and five façade configurations, ranging from 2D perforated plates to 3D louvers. Rigid and aeroelastic tests provided time-averaged coefficients, pressure distributions, and dynamic VIV response, while downstream wake mapping correlated integral force variations with topology modifications. Complementarily, a 2D Unsteady Reynolds Averaged Navier Stokes (URANS) numerical approach was employed to simulate the flow physics, ensuring computational efficiency for shape-dominated shedding mechanisms. A central focus is the validation of the homogenized Darcy–Forchheimer (DF) porous media model for unsteady flows and 3D façade geometries. By cross-referencing global forces, shedding frequencies, and local pressure drops against experimental data, the methodology assesses the model’s reliability in predicting wake dynamics and VIV mitigation.

## 3 SETUP

### 3.1 Experimental Setup

The experimental campaign was conducted in the boundary layer wind tunnel of Politecnico di Milano (GVPM). The tests were performed in smooth flow conditions, characterized by a Turbulence Intensity  $I_u \approx 2\%$  and an integral length scale  $L_{ux} \approx 0.2$  m.



(a) Experimental setup, naked configuration.

(b) Numerical setup, zoom on the model.

**Figure 1:** Setup overview.

The model is a rigid square prism with a side length  $D = 0.2$  m and a height-to-width ratio  $H/D = 6$ , representative of a high-rise building (Figure 1a). A total of six configurations were tested to assess the sensitivity to envelope properties: a reference “Naked” case and five porous variations. The perforated sheets differ in pore shape (Square “Q” vs. Circular “T”) and porosity ratio ( $\beta = 50\%, 70\%$ ), resulting in configurations Q50, T50, and Q70. Additionally, two louvered configurations (LV) were tested, featuring slats inclined at  $45^\circ$ . These differ by the relative angle at the edges (LV9:  $90^\circ$ , LV0:  $0^\circ$ ) to evaluate the specific effect of flow deviation at the corners (see

Figure 2).

The measurement setup varied according to the test phase. In the rigid configuration, time histories of total base forces were acquired via a high-frequency dynamometric balance, while the surface pressure field was mapped using 128 pressure taps distributed over 4 levels. To characterize the wake topology, the velocity field was scanned  $13.5D$  downstream using an array of four traversing Cobra probes. In the aeroelastic configuration, the setup was equipped with accelerometers to monitor structural response. Crucially, the porous covers were instrumented with specific pressure taps to compute the net aerodynamic load acting on the envelope itself.



**Figure 2:** Experimental porous configurations tested in the wind tunnel.

### 3.2 Numerical Setup

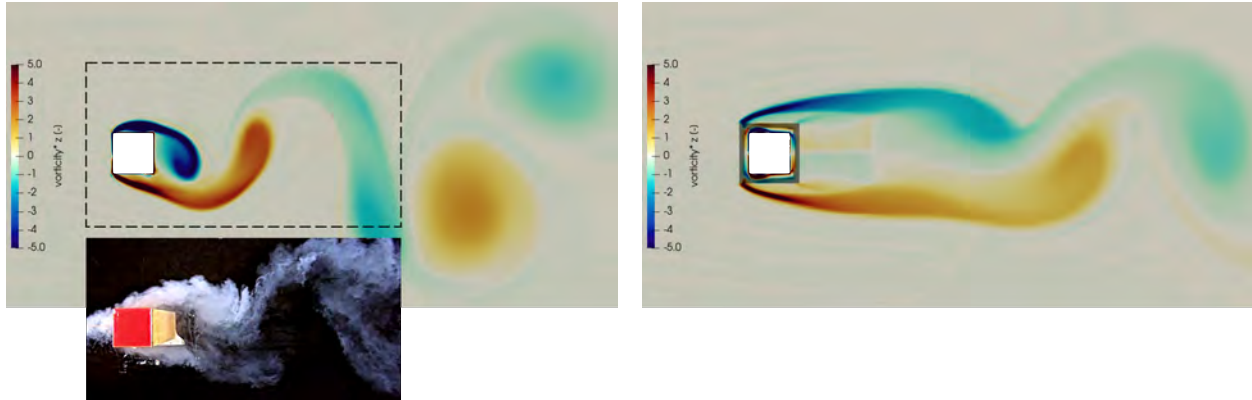
The numerical investigation employs a 2D URANS approach employing  $k - \omega$  SST turbulence model. The porous envelope is modeled via the Darcy–Forchheimer method, neglecting viscous effects and applying a momentum sink  $\mathbf{S}$  dependent on the velocity magnitude  $|\mathbf{u}|$  and the Forchheimer tensor  $\mathbf{F}$ :

$$\mathbf{S} = -\frac{1}{2}\rho|\mathbf{u}|\mathbf{F}\mathbf{u}, \quad \text{with } \mathbf{F} = \begin{bmatrix} f_{xx} & f_{xy} & f_{xz} \\ f_{yx} & f_{yy} & f_{yz} \\ f_{zx} & f_{zy} & f_{zz} \end{bmatrix} \quad (1)$$

For standard perforated plates (Q, T), geometric symmetry allows for a simplified diagonal tensor ( $f_{ij} = 0$  for  $i \neq j$ ), where the normal resistance  $f_{xx}$  is derived from the experimental loss coefficient  $k$ . Conversely, for louvered configurations (LV), the full tensor formulation is retained to capture the strong flow anisotropy and deviation effects induced by the slat inclination [4]. A sketch of the computational domain is reported in Figure 1b.

## 4 RESULTS AND DISCUSSION

Experimental data analysis reveals that porous covers significantly alter the fluid-structure interaction compared to the reference solid prism. The primary benefit is a substantial reduction in the fluctuating lift and the attenuation of suction peaks on the side faces. The bleed flow through the pores promotes pressure equalization, resulting in a more homogeneous chord-wise pressure distribution. This aerodynamic stabilization effectively reduces the structural demand on façade elements. These force variations stem from a modification of the wake topology. As shown in Figure 3, porosity delays the shear layer roll-up and elongates the vortex formation region. The numerical vorticity contours for the solid case (Figure 3a) accurately reproduce the Von Kármán structures visualized experimentally, confirming the solver’s capability to capture the shedding pattern and spatial periodicity. In contrast, the porous configuration T50 (Figure 3b) exhibits a disorganized wake with reduced vorticity magnitude, indicating a damped shedding mechanism.



(a) Configuration Naked: numerical vorticity vs experimental smoke visualization.

(b) Configuration T50: numerical vorticity showing wake disorganization.

**Figure 3:** Comparison of instantaneous wake topology. Numerical vorticity is saturated at  $\omega_z^* = \omega_z D/U \in [-5, 5]$  to highlight large-scale coherent structures.

The 2D URANS model equipped with the Darcy–Forchheimer source term accurately reproduces unsteady wake topology, aerodynamic coefficients, and surface pressure distributions. This agreement validates the numerical method for probing the experimentally inaccessible flow within the porous gap, establishing it as a reliable tool for parametric optimization of the façade.

The full paper will provide a comprehensive quantitative comparison, including mean and fluctuating aerodynamic coefficients, shedding frequencies, and local pressure distributions. Furthermore, for the aeroelastic case, oscillation amplitudes and the phase lag between lift and displacement will be discussed. Ultimately, this work aims to provide a high-fidelity experimental dataset and a validated numerical methodology for predicting the unsteady interaction of wind with porous structures.

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