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The CFD simulation of porous claddings using the pressure-velocity jump approach: A prism surrounded by lamellar screens

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SUMMARY:
The evaluation of the aerodynamic behavior of structures presenting porous claddings involves difficulties for both wind tunnel experiments and numerical simulations. In particular, when using physical reduced-scale models, small pores cannot be scaled down by simply preserving geometrical similarity, as this would lead to excessively small details, and anyway break aerodynamic similarity. Considering now computational fluid dynamics, the strong scale separation between the overall structure and the pores, forces to adopt extremely fine meshes and small time-steps if the complete geometry is reproduced. This leads to prohibitive computational costs. In this work, we investigate the numerical simulation of porous claddings through homogenization techniques and, in particular, the Pressure-Velocity Jump, PVJ, approach. The approach allows to consider the forces exchanged between the fluid and the cladding in a simplified way, allowing to represent their interaction. Results obtained by adopting the PVJ approach are compared to experimental results, showing good agreement.

Keywords: double-skin façade, porous elements, cladding loads, pressure-velocity jump, homogenized models

1. INTRODUCTION

Porous claddings are increasingly used in architecture, often appearing in technical solutions which optimally combine energy-efficiency, aesthetics, cost-effectiveness and comfort. For instance, a popular use is represented by Permeable Double Skin Façades (PDSFs), in which a porous cladding is added at the exterior of the building. Early research works in this field can be traced back to (Gerhardt and Janser, 1994), who established that the net pressures on a porous façade critically depend on the edge sealing. Recent contributions can be found in (Zasso et al., 2019), (Pomaranzi et al., 2021, 2020, 2022) and, more recently, in (Aguinaga, 2023) and (Catania et al., 2024). In these works, the shielding effects of PDSFs with different geometries and characteristics have been studied, highlighting also their positive effects in moderating vortex induced vibrations.

However, despite their high technical interest, the study of porous claddings is hindered by difficulties arising from their multiscale nature. In particular, a major challenge is represented by the management of the wide scale separation between the building and the pores, that makes accurate analyses difficult via both Wind Tunnel Tests, WTTs, and Computational Fluid Dynamics, CFD, simulations. In fact, in WTTs the geometrical scaling of the pores usually leads to unmanageable small details and, additionally, makes it hard to position pressure taps without interfering with the flow. Regarding CFD simulations, explicitly modelling the pores requires to mesh the permeable elements with adequate precision, leading to numerous small cells. The situation gets even worse when pores produce velocity concentrations, which may require to adopt very small time-steps to preserve the stability of the simulation. In these conditions, the resulting computational costs rapidly become insurmountable.

In this work, the challenge of numerical simulation of porous claddings is addressed by relying on homogenization techniques, which allow to model the permeable elements, seen as a porous medium, without explicitly reproducing their details. Between them, the Pressure-

Velocity Jump PVJ approach is a model which extends the commonly adopted Pressure Jump, PJ, method (Xu et al., 2020). Specifically, it is designed to account for the exchange of both normal and shear stresses between the porous cladding and the fluid, even at highly skewed orientations. This homogenized model eliminates the need of fine meshes in the porous elements, drastically reducing the computational effort. In particular, we investigate the aerodynamic behavior of a rectangular prism, representing an idealization of a high-rise building, composed of a permeable surface, which might be seen as the external layer of a PDSF, in which the internal building is removed for simplicity. The permeable elements consist of lamellar screens that exchange both normal and shearing stresses with the surrounding fluid, making the case a good validation for the proposed numerical method.
In the study, first, the PVJ model is calibrated based on simulations of an elementary portion of cladding. Then the calibrated model is used to evaluate the overall aerodynamic forces acting on the porous cladding using Large Eddy Simulation, LES. Results are compared to Explicit-LES, in which the complete detailed geometry is reproduced, as well as WTTs performed at Polytechnic of Milan, showing the good potential of the proposed methodology.

2. PVJ HOMOGENIZED MODEL

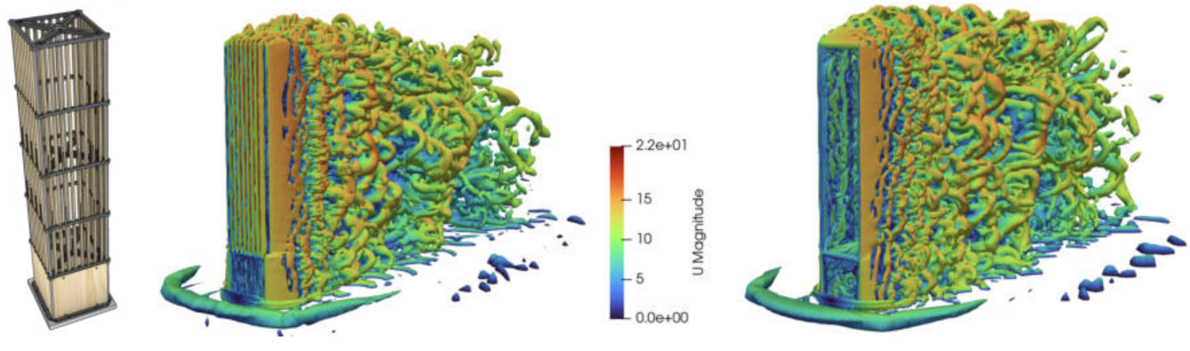
The Pressure-Velocity Jump (PVJ) model defines the pressure and tangential velocity jumps across a permeable surface. By applying conservation of mass and momentum in the normal and tangential directions, the pressure and tangential velocity jumps are calculated based on the aerodynamic forces per unit area exchanged between the porous element and the fluid.
The aerodynamic force vector $\vec{f}(\alpha) = [f_n(\alpha), f_t(\alpha)]^\mathrm{T}$ is modeled as a function of the incidence angle α:

$$\vec{f}(\alpha) = \frac{1}{2}\rho\,|\vec{u}|^2\,|\hat{u}_n|^\gamma\,\vec{c}(\alpha) \tag{1}$$

where $\vec{u} = [u_n, u_t]^\mathrm{T}$ is the upstream velocity vector, $\hat{u}_n$ is its versor component in the normal direction, and γ is a calibration coefficient. The coefficients $\vec{c}(\alpha)$ are expressed via a Fourier expansion, whose parameters can be determined through data fitting or, in simpler cases, from theoretical considerations. Further details on the model can be found in (Xu et al., 2023, 2024).
Finally, in this work we modify the original PVJ formulation by introducing a limiting strategy for the tangential velocity jump to ensure simulation stability. The limiting strategy imposes that the jump in tangential velocity cannot lead to an increase in fluid energy when crossing the porous cladding.

3. CASE STUDY AND RESULTS

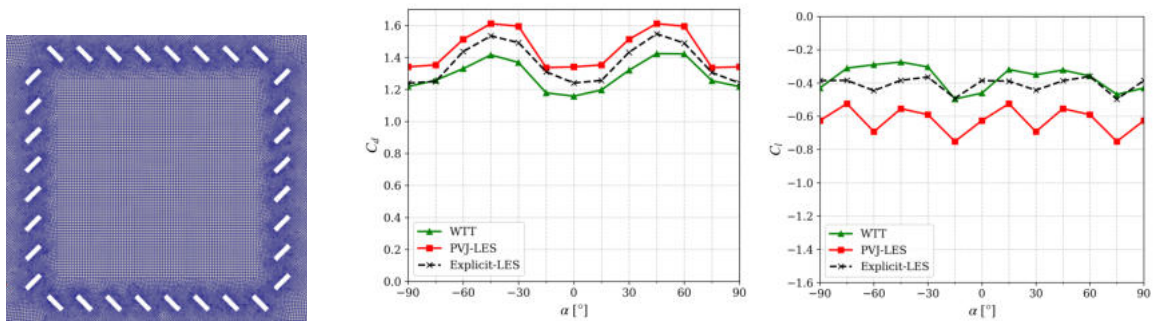
A sketch of the geometry considered in the present study is shown in Fig. 1(a). The porous cladding is built as a prism with square cross-section and with an aspect ratio of 5. Its surfaces are composed of lamellar screens inclined at 45°, with eight lamellae per side. These lamellae have a rectangular cross-section with an aspect ratio of 4 and span the full height of the model building.
Preliminary two-dimensional URANS of a section of the geometry reported in Fig. 2(a), using explicit analyses, have been run with two purposes: (i) to make a preliminary assessment of the PVJ calibration on simpler cases and (ii) to perform a mesh-sensitivity analysis, which established an optimal minimal resolution to be adopted in the proximity of the lamellae. All simulations were performed under periodic boundary conditions over an incidence angle range of −90° to 90° with 15° increments. An overview of the flow fields obtained using the explicit



(a) (b) (c)

Figure 1. Overview of the considered porous prism: (a) geometry tested at Polytechnic of Milan, (b) LES with explicit model (Q-criterion) and (c) LES PVJ-based model.

and the PVJ-based models are shown in Fig. 1(b)-(c), while a comparison between WTTs, explicit and PVJ based results is reported in Fig. 2(b)-(c) in terms of aerodynamic coefficients at varying angle of attack. A good correspondence between the explict-LES and WTTs is observed in terms of drag and lift coefficients. The PVJ-based model drag data show good agreement with the trends of both explicit simulations and WTTs, exhibiting a maximum deviation of roughly 18% from the corresponding WTT values. On the other hand, for the lift coefficient, differences are more marked, although predictions remain consistent, at least in their general trend. As a reference, we also report the mean-velocity contour and streamline plots in the streamwise direction, in which the same flow behaviours can be identified (Fig. 3). The averaged computational time required by the PVJ-LES was found to be approximately 20% of that of the explicit LES for the considered case study.



(a) (b) (c)

Figure 2. Force coefficients comparison and mesh definition: (a) 2D-section of the lamellae configuration, (b) drag and (c) lift coefficient.

4. CONCLUSIONS

In this contribution, the applicability of the PVJ approach in the simulation of porous lamellar screens has been assessed on a simplified building model, representative of a high-rise building with a porous façade. For simplicity, in this preliminary study, only the outer porous cladding is modelled. Within the simulations, the need to modify the original PVJ formulation introducing a limiter for velocity deflections emerged, aiming at avoiding stability issues which arise at highly skewed angles. Overall the PVJ-LES results well agree with explicit-LES in terms of drag coefficient and flow organisation. Moreover, the simulations results satisfactory align with the WTTs data. Stronger differences emerge when comparing the normalized lift force,

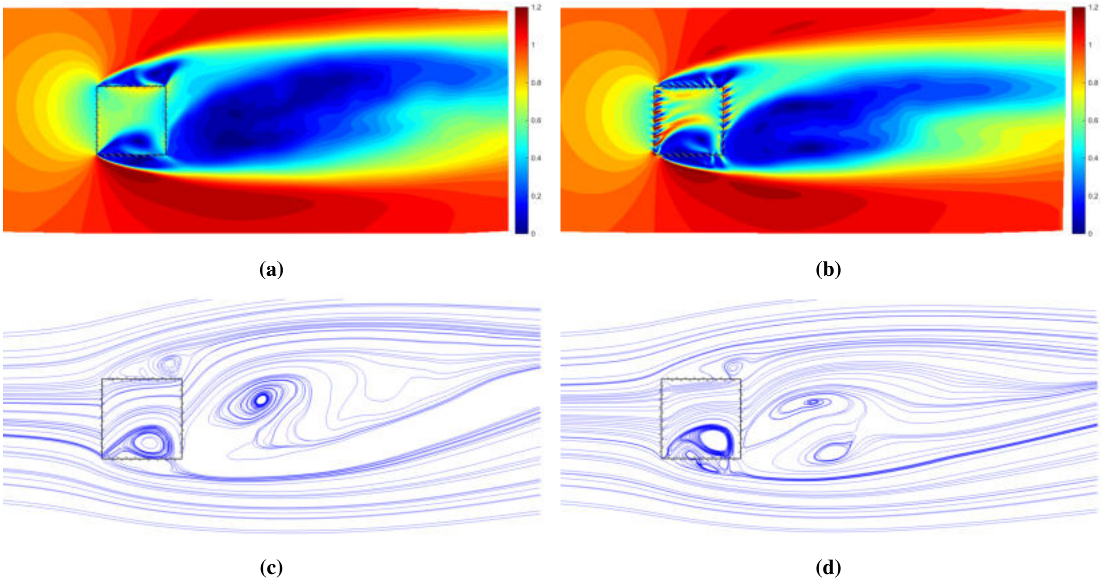


Figure 3. Velocity contour and streamline plots of PVJ-LES (a,c) and explicit-LES (b,d).

which need further consideration. However, the proposed approach appears to be a promising simulation tool for building presenting porous claddings.

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