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Numerical modelling of a louvered balustrade with angled slats as porous media to improve windiness on small balconies

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SUMMARY:
Wind comfort assessments of pedestrian spaces are carried out for balconies of tall buildings using CFD or wind tunnel testing. When adverse wind impacts are identified, wind mitigations are considered and tested. These may include small architectural elements like louvered balustrades, which allow design permeability and wind protection. Modelling these elements is however challenging. Their reduced scale and the location of the balconies makes wind tunnel testing difficult. While CFD can provide the wind flow on several balconies simultaneously, modelling louvered balustrades effectively requires an accurate representation of their geometrical and aerodynamic properties. This paper illustrates a practical application, where the impact of a louvered balustrade on the windiness of a corner balcony was studied in CFD. This is achieved using a porous -medium for representing their porosity. A comparative analysis between the theoretical model and the case study is proposed.

Keywords: CFD, wind mitigation, louvers, implicit modelling, porosity, Darcy-Forchheimer

1. INTRODUCTION

Wind comfort and safety assessments are frequently performed at various stages of the design process to evaluate the influence of a new development on the urban wind flow. In addition to windiness at pedestrian level, the wind comfort on residential balconies and shared terraces of high-rise buildings are of interest. Mitigation options for relatively small balconies are, however, limited to architectural variations of the design of balustrades to satisfy the aspects of fire safety, daylighting, views on the surroundings and sufficient wind shelter. Louvered balustrades with angled slats are a valid mitigation option as they are a good trade-off between daylight permeability and wind shelter.

Pedestrian wind comfort assessments are typically carried out either using wind tunnel testing or Computational Fluid Dynamics (CFD) simulations (Blocken and Carmeliet, 2004). However, the accurate modelling of small-scale porous elements such as louvered balustrades is non-trivial. The problem is intrinsically multi-scale, as the interactions of the wind with the large-scale building massing and the small-scale building elements need to be captured simultaneously. Wind tunnel testing has limited capabilities to reproduce small geometrical details and to instrument a large number of balconies in the same model. CFD simulations can resolve the wind flow on several balconies simultaneously, but the accurate and efficient modelling of the louvers is still a challenging task due to their multi-scale nature. Two different approaches are available. The first consists of the explicit representation of the louvers in the model, which however affects the efficiency of the computational grid. The second relies on the implicit description of the louvered balustrade using a porous medium with the louvers aerodynamic properties. The implicit modelling is generally based on the Darcy-Fochheimer model. This approach has been effectively used to model flow interaction with simple porous geometries that are not responsible for flow deflection (Xu et al., 2020; Feichtner et al., 2021). Current modelling practice rarely refers to more complex situations, like angled-slats, mainly due to the lack of an identification procedure for all the parameters governing the implicit modelling.

To overcome this limitation, Pomaranzi et al. (2021) proposed a novel implementation of the implicit model that includes both the main diagonal components and the mixed terms of the Forchheimer tensor. As a result, the momentum sink acts on all velocity components. The linear terms of the Darcy-Forchheimer equation and therefore the tensor containing the Darcy coefficients are neglected as the applications are assumed to be in a flow regime of high Reynolds numbers such that the inertia is predominant over the viscous forces. The Forchheimer mixed term coefficients are derived in two steps. First, the lift and drag forces are calculated on one element (e.g. one louver slat) modelled explicitly in CFD for various angles of attack. Second, the Forchheimer Tensor coefficients are calibrated using a least squared method to match the forces of the explicit element. This method was applied and tested on different geometries of porous panels and resulted in a good agreement between explicit and implicit modelling in terms of forces.

This paper illustrates a case study where the methodology by Pomaranzi et al (2021) was applied to the model of a corner balcony with a louvered balustrade made of vertical slats with an inclination of 45°. The Forchheimer tensor values representing the porosity of the balustrade were derived from the results of a cyclic CFD model of a single 45° angled slat. The resulting values were tested on a similar cyclic CFD model where a porous medium was used to represent the angled slat. Then, the same tensor values were adopted in a full-scale sectional model of the corner balcony with a porous medium representing the louvered balustrade and the results were compared with a corresponding case of fully resolved louver slats.

2. METHODOLOGY

2.1. Porous model

Within the computational fluid dynamic framework, the porous media approach proposes to represent the porous element by means of a 3D volume, where a momentum sink term is used to account for the porosity effects. Such momentum sink, introduced on the right-hand side of the Navier-Stokes Equation, is based on Darcy-Forchheimer law (Darcy, 1856; Forchheimer, 1901):

$$S_i = -\sum_{j=1}^{3} d_{ij}\mu u_j + \frac{1}{2}\sum_{j=1}^{3} f_{ij}\rho U u_j \tag{1}$$

The first term of Equation 1 can be dropped in the present application, being the viscous stresses negligible (Chen and Christensen, 2016). This is a valid simplification for modelling windscreens on building facades as a porous medium. Thus, assuming incompressible steady-state flow, the governing equation becomes:

$$\rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_j^2}\partial_j - \frac{1}{2} f_{ij}\rho U u_i \tag{2}$$

Each fij coefficient relates i-th component of the force experienced by the porous screen due to the j-th component of the fluid velocity vector.
To proceed with the application of the porous media model, the parameters (f_{ij}) defining the aerodynamic property of the porous volumes must be computed.
To obtain them we can refer to the ideal case with a set of louvers immersed in an incoming flow, as depicted in Figure 1. This case can be easily represented in the computational domain by considering a single louver along with cyclic boundary conditions. Then it can be noticed that louvers plates satisfy mirror symmetry with respect to xy plane. As a consequence, f_{xz}, f_{zx}, f_{yz}, f_{zy} coefficients are set equal to zero. Moreover, no flow deflections in the xz-plane are expected, and therefore $f_{zz} = 0$. Conversely, flow is deviated in the y-direction, thus requiring f_{xy} and f_{yx} different from zero.

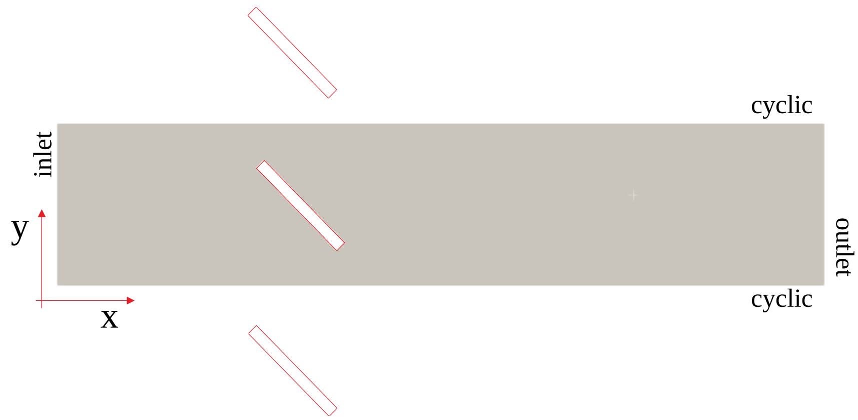

Figure 1. Numerical setup considered for the preliminary simulations aimed at computing the coefficients of the tensor.

The computation of the tensor's coefficients reduces to f_{xx}, f_{xy}, f_{yy} and f_{yx}. Hence, the following procedure is applied:

- a set of preliminary steady-state simulations is run, by considering a louver slats at 45° angle, explicitly modelled in the computational domain using a cyclic domain to represent a series of louvers with infinite height (here called *explicit simple model*)
- forces on such louvers are extracted, varying the angle of attack (from -80° to +80° in the x-y plane with 10° intervals)
- by relying on the analytical solution for Eq. 2 written for an inviscid flow, as proposed by (Pomaranzi et al., 2021), a relation between the set of forces measured in the high-fidelity model and model coefficients is obtained
- a least-squares optimization evaluates Forchheimer tensor resistance coefficients considering as input the forces computed from the *explicit simple model*

Finally, a second cyclic CFD model is constructed using the porous medium with computed coefficients to represent the effects of the series of louvers on the wind flow (here referred to as *implicit simple model*). The full formulation of the Forchheimer tensor values was enabled in OpenFOAM 2206 to account for the mixed terms. Results of the forces, velocity and pressure fields are compared.
All the simulations are run using a 3D RANS approach and the k-ω SST turbulence model.

2.2. Case Study – Sectional model

At a second stage, the porous media model was applied to a more realistic scenario. Specifically, a section of a high-rise building with small corner balconies (3 x 3.2 m) was built in CFD, as shown in Figure 2. As a simplification the inlet condition is set to a fixed velocity assuming that it is representing a section of the building in which the flow approaches horizontal and vertical deflections can be neglected.

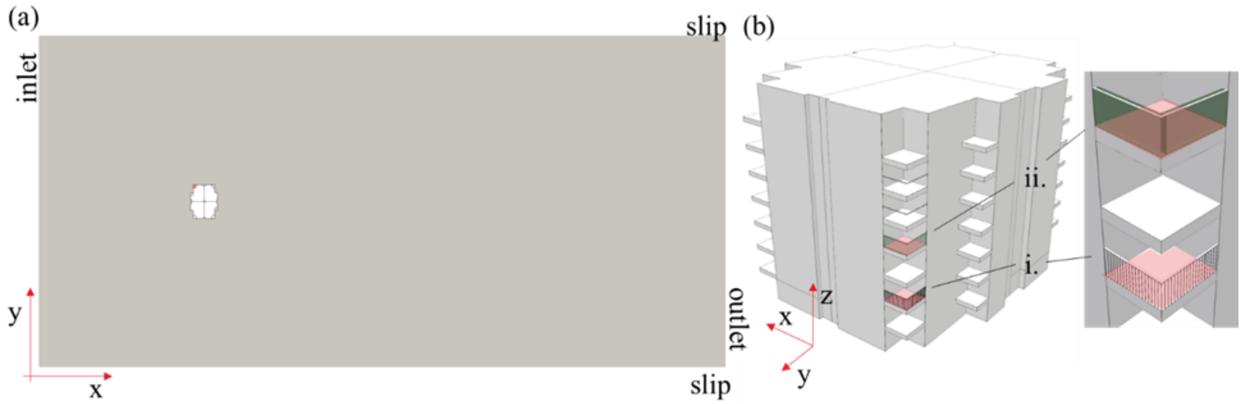

Figure 2. Top view numerical setup considered for sectional model for 270° wind direction (a) and detailed view of North-west corner balconies considered for explicit louvers (b i.) and implicit louver respresentation (b ii.).

The louvered balustrade on the North-west corner balconies was fully resolved in the CFD model ('explicit sectional model', Figure 2b i.) and modelled using a porous medium and the Forchheimer tensor values obtained using the cyclic model ('implicit sectional model', Figure 2b ii.). The simulations were carried out using a 3D RANS approach and the k- ω SST turbulence model. Incoming wind directions ranging from 225° to 0° in 45° increments were considered, supplemented by the wind directions 337.5° and 22.5°.

5. RESULTS AND DISCUSSION

In the present section, the main results are shown. We first introduce the comparison between explicit and implicit modelling for the cyclic domain cases. Then the case of the building sectional model is described. The comparison between explicit and implicit modelling of porous media is carried out by considering pressure and velocity fields, along with the comparison of the forces experienced by the louvers and the ones extracted from the porous volume for the implicit simple model.

Figure 3 shows the aerodynamic forces obtained from both explicit and implicit simple models for inflow directions ranging from -80° to +80°. The implicit simple model effectively replicates the forces for inflow angles between -50° to +10° and for +40°, although deviations occur at other angles.

A comparison of pressure and mean velocity field obtained using the explicit and implicit models for an inflow direction of +40° and +70° is shown in Fig. 4 and Fig. 5, respectively.

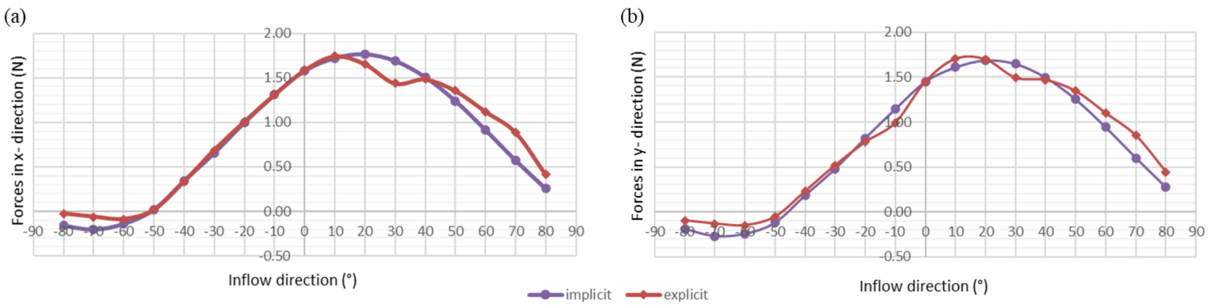

Figure 3. Comparison of the aerodynamic forces along the x (a) and y (b) directions obtained with the implicit and explicit simple models for inflow directions ranging from -80° to 80°.

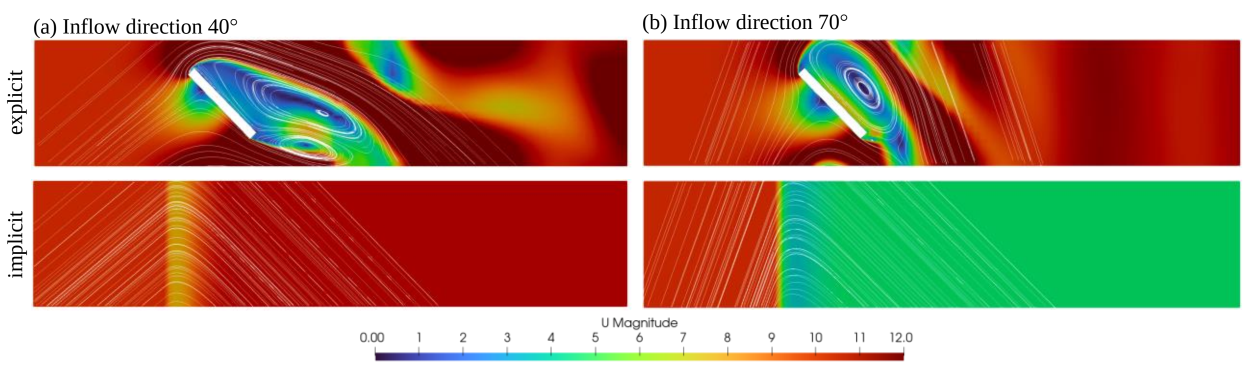

Figure 4. Comparison of the mean velocity field through the louvers obtained with the implicit and explicit simple models for a wind direction of +40° (a) and +70° (b).

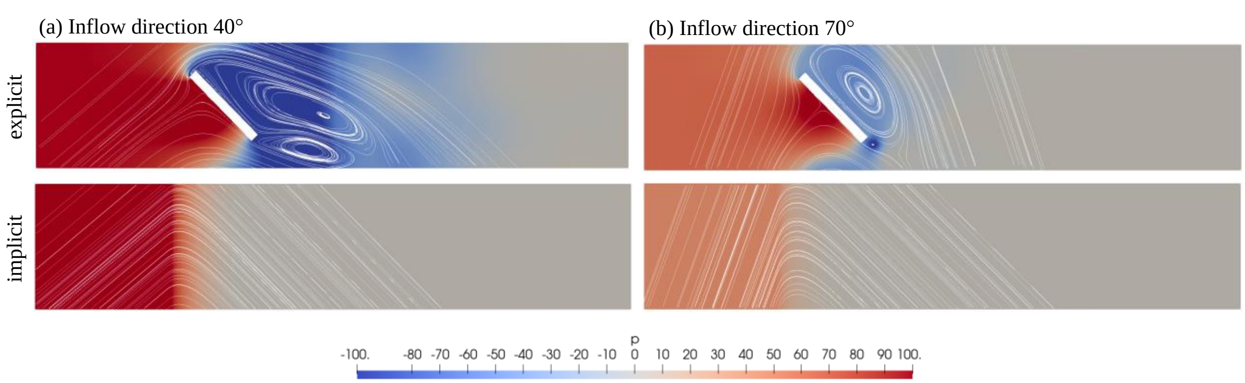

Figure 5. Comparison of the pressure field through the louvers obtained with the implicit and explicit simple models for a wind direction of +40° (a) and +70° (b).

At +40°, the implicit simple model accurately predicts the flow field, with streamlines from both models closely resembling each other, except in regions directly affected by the solid louvers in the explicit simple model (Figure 4(a)). The total pressure drop caused by the louvers is captured by the implicit model, as shown in Fig 5(a), though it does not replicate the separated flow region due to the absence of solid elements.

For the +70° inflow direction, the implicit simple model underpredicts the mean velocity field downstream of the porous medium (Figure 4(b)), and the total pressure drop is slightly underestimated. This discrepancy is aligned with the mismatch we observed for the forces.

To evaluate the implicit model's ability to simulate flow behaviour post-louver interaction, Table 1 compares the orientation of the velocity vector downstream of the louvers (explicit simple model) and the porous volume (implicit simple model). The implicit simple model demonstrates less dependency on the inflow direction compared to the explicit simple model, with significant differences observed at angles previously identified as having the largest force deviations. Improved force curve fitting could enhance the accuracy of the implicit model’s mean velocity field.

Table 1. Comparison of the velocity vector orientation downstream the louvers (for the explicit simple model) or the porous volume (for implicit simple model).

Inflow	Explicit	Implicit
-80°	-71.1°	-46.7°
-70°	-62.1°	-46.5°
-60°	-51.0°	-46.4°
-50°	-47.4°	-46.3°
-40°	-48.0°	-46.2°
-30°	-48.7°	-46.1°
-20°	-44.6°	-46.1°
-10°	-44.0°	-46.0°
0°	-43.42°	-45.9°
+10°	-43.8°	-45.8°
+20°	-44.25°	-45.7°
+30°	-43.0°	-45.6°
+40°	-46.0°	-45.5°
+50°	-49.6°	-45.3°
+60°	-56.6°	-45.1°
+70°	-71.7°	-44.8°
+80°	-71.8°	-38.4°

The same implicit modelling approach was applied to a realistic scenario involving a corner balcony with a louvered balustrade. Figure 6 shows a comparison of the streamlines and mean velocity field on a northwest corner balcony obtained for the explicit and implicit sectional model at half height of the balustrade for the wind directions 225° (Figure 6a) and 337.5° (Figure 6b), corresponding to an inflow angle of +69.2° and +38° respectively. Figure 7 shows the same comparison but for the mean pressure field.

Regarding the implicit louver representation, the mean velocity field downstream the porous medium is locally underpredicted for both wind directions, especially for the corner where the two porous zones connect. The mean pressure field is underestimated to both ends of the scale, for negative pressure at 225° wind direction and positive pressure at 337.5° wind direction.

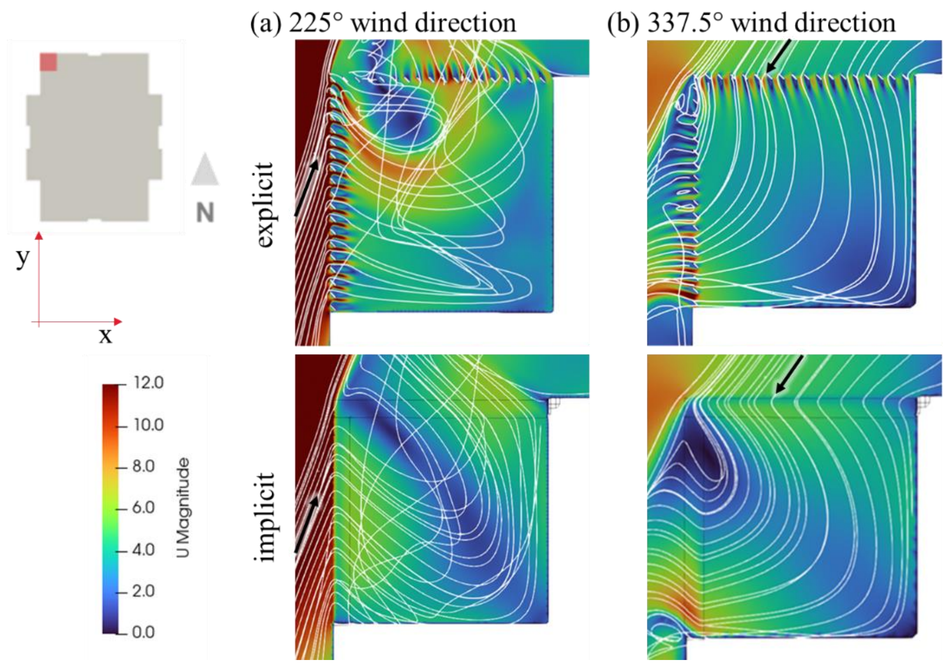

Figure 6. Comparison of the streamlines and mean velocity field across a northwest corner balcony obtained with the explicit and the implicit sectional models for 225° wind direction (a) and 337.5° wind direction (b).

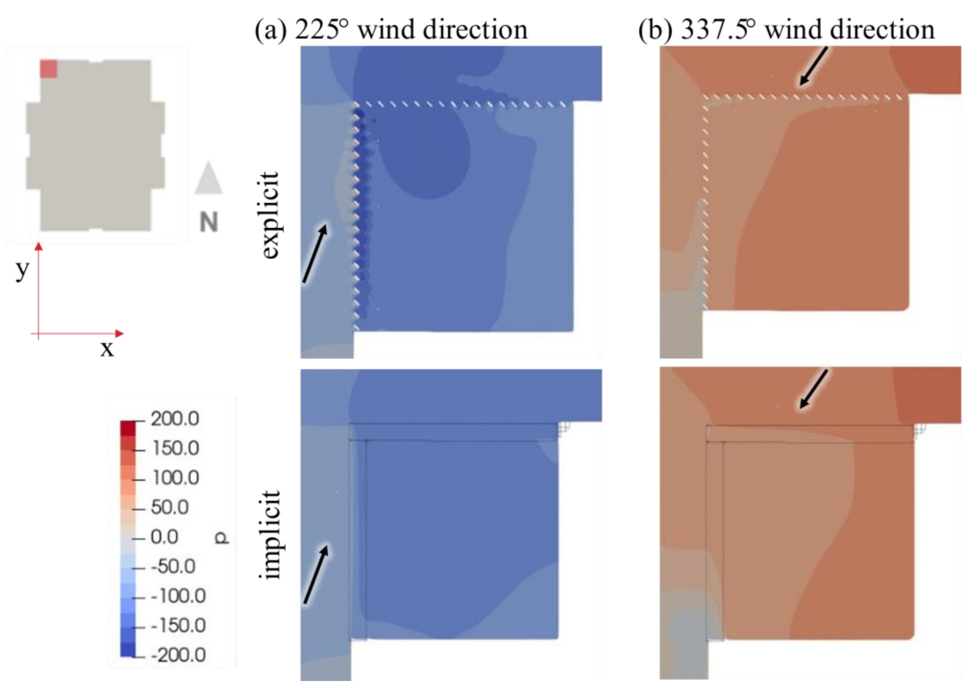

Figure 7. Comparison of the mean pressure field across a northwest corner balcony obtained with the explicit and the implicit sectional models for 225° wind direction (a) and 337.5° wind direction (b).

Table 2 compares the orientation of the velocity vector downstream of the louvers (explicit sectional model) and the porous volume (implicit sectional model) to evaluate the implicit model's ability to simulate flow behaviour post-louver interaction. The velocity vector orientation downstream the louvers (for the explicit sectional model) is given in a range as it is varying along the length of the balustrade.

Consistent with the results from the implicit simple model, the implicit sectional model shows less dependency on the inflow direction compared to the explicit model. The velocity vector orientations downstream the porous volume for the implicit sectional model are similar to those observed in the implicit simple model.

The differences and variation in the velocity vector orientations seen in the explicit sectional model results could be partially due to the complex three-dimensional flow pattern expected at the louvers' edge and through the louver gaps, that are not or not accurately captured by the implicit modelling.

Sensitivity studies on the three-dimensional features (louvers' edges and gaps, balcony dimension) could provide insights into their impact on the flow behaviour and the limitations of the proposed approach.

Table 2. Comparison of the velocity vector orientation downstream the louvers (for the explicit sectional model) or the porous volume (for implicit sectional model).

Wind direction	Resulting inflow	Explicit	Implicit
225°	69.2°	-15.1° … -47.9°	-42.6°
270°	65.7°	-9.5° … -17.8°	-41.6°
315°	-46.8°	-24.6° … -30.6°	-39.4°
337.5°	38.0°	-9.5° … -24.1°	-40.9°
0°	62.6°	-12.5° … -19.3°	-43.1°
22.5°	73.6	-50.9° … -71.1°	-42.1°

5. CONCLUSIONS

The present study applies an existing procedure for the identification of the Forchheimer tensor coefficients used to describe the aerodynamic characteristics of a louvered balustrade with angled slats. The performance of an implicit CFD model that represents the balustrade using a porous medium is evaluated by comparing the aerodynamic forces on the louvres and the mean flow field against the results obtained with an explicit model of the angled slats. Results show some discrepancies in the velocity field for those wind directions with a less accurate fit of the aerodynamic forces on the slat. An adapted calibration, e.g. a weighted approach, could be tested for improved curve fit on the forces. The same Forchheimer coefficients were used to simulate a realistic corner balcony with a louvered balustrade through a sectional CFD model. Some of the differences in the mean flow field in the sectional model could be due to the complex three-dimensional flow patterns at the louvers' edge and through the louvers' gap. The results suggests that the agreement on the sectional model will improve when improving the calibration of the Forchheimer Tensor. Furthermore, sensitivity studies on the three-dimensional features (louvers' edges and gaps, balcony dimension) could provide further understanding of the impact on the flow behaviour and the limitations of the proposed approach.

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