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CFD analysis of the impact of geometrical characteristics of building balconies on near-façade wind flow and surface pressure

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ABSTRACT

The presence of building balconies can significantly modify the near-façade wind flow pattern and surface pressures. The present study evaluates the impact of building balcony geometry on mean wind speed on balcony spaces and wind-induced mean surface pressure for generic high-rise buildings. The focus is on balconies that extend along the entire width of the building façade. Large-eddy simulations (LES), validated with wind tunnel experiments, are conducted to investigate the impact of (i) balconies present or not, (ii) balcony depth, (iii) balcony parapet walls, (iv) balcony partition walls, and (v) density of balconies. The results indicate that the balcony geometry can greatly affect the mean wind speed on balcony spaces and the local and façade-averaged mean pressure coefficient ($C_p$). The presence of balconies can increase the façade-averaged $C_p$ over the windward and leeward façades by 5.2% and 8.9%, respectively. These numbers rise to 23.5% and 23.3% when two partition walls are added at the lateral edges of the façades. Adding five partition walls can reduce the overall area-averaged wind speed on balcony spaces by 68.0% compared to the case without partition walls. These findings can be useful in developing, designing and constructing buildings with façade geometrical details that improve building ventilation, air quality and wind comfort.

1. Introduction

The presence of large-scale roughness on building façades can significantly influence the near-façade wind flow and surface pressure distributions [1,2]. For example, balconies on the windward façade of a high-rise building can change the local mean surface pressure coefficient ($C_p$) from $-0.36$ to $0.34$ [3]. In addition, the geometrical characteristics of building balconies can strongly affect not only the wind speed on balcony spaces [4], but also the peak and mean surface pressures [3,5]. This is especially the case for high-rise buildings where the high wind speed around the building can lead to wind discomfort or even wind danger on balcony spaces [4,6]. Therefore, knowledge on the impact of the geometrical characteristics of building balconies on the near-façade wind flow is crucial to assess wind comfort and safety on balcony spaces [4,7,8], wind-induced natural ventilation [9] and infiltration in buildings [10], local and façade-averaged convective heat transfer coefficients on building façades [11–13], and wind loads on building surfaces [14].

Several studies have been performed to investigate the impact of the presence of balconies and of their geometrical characteristics. Tables 1 and 2 provide overviews of wind tunnel and computational fluid dynamics (CFD) studies on buildings with balconies, respectively. They list the number of stories, the objective of the study, whether or not different geometrical characteristics have been evaluated and if so, which ones, and the wind directions and performance indicators used. For studies using CFD, additional information about the turbulence modeling approach and building scale is also provided. The following observations are made:

- In these wind tunnel studies, the focus has been on either surface pressures (mean, rms and peak) or aerodynamic forces. While the vast majority of CFD studies focused on either the mean surface pressure or mean wind velocity, only a few studies have investigated mean surface pressure and mean wind speed simultaneously.
- The majority of CFD studies focused on the presence of balconies, which means that only one specific balcony geometry was evaluated. The impact of the geometrical characteristics of balconies for isolated buildings has been investigated only in a few studies [9,15–17], with the focus on the balcony depth [9,15,16], the height of parapet walls [15] and the presence and shape of partition walls [9,17]. Note

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that in these studies, different boundary conditions and building dimensions were considered, and the conclusions were not always consistent.

- The CFD studies generally adopted the 3D steady Reynolds-Averaged Naviar-Stokes (RANS) approach, while the use of large-eddy simulation (LES) was limited to only a few studies [18–20]. An earlier study on a building with balconies found that steady RANS can accurately predict the mean pressure coefficient ($C_p$) on the windward façade of a building for both perpendicular ($\theta = 0^\circ$) and oblique ($\theta = 45^\circ$) wind directions, while it systematically underestimated the absolute value of $C_p$ on the leeward façade for these two wind directions ($\theta = 0^\circ$ and $\theta = 45^\circ$) [1]. This is mainly because of the deficiencies of steady RANS in capturing the complexities of the near-façade wind flow, which include multiple areas of flow separation, recirculation and reattachment generated by the balconies [21–23]. LES, on the other hand, is capable of predicting the inherently unsteady wind flow [24–27]. The superior performance of LES compared to steady RANS and unsteady RANS has been shown for mean and instantaneous flow fields around isolated buildings (e.g. Refs. [21–24, 28–30]) and in urban areas (e.g. Refs. [23, 25, 31–35]). LES can provide accurate descriptions of surface $C_p$, wind velocities, turbulence, and pollutant concentrations.

Table 1: Overview of CFD studies on wind flow around buildings with balconies.

| Reference                  | Building stories (height in full scale (m)) | Building stories (height (m)) | Research objective | Geometrical characteristic | Turbulence modeling approach | Wind direction (°) | Performance indicator |
|----------------------------|-------------------------------------------|------------------------------|--------------------|---------------------------|-----------------------------|---------------------|----------------------|
| Stathopoulos & Zha, 1988  | 30 (120)                                   | GB                           | Dep, PW            | 0, 90, 180                | Mean/r.m.s./peak $C_p$     |                     |                      |
| Maruta et al., 1998        | 26 (75)                                    | GB                           | Dep, Par           | 0, 5, 10, 15, 13, 20     | Mean/r.m.s./peak $C_p$     |                     |                      |
| Chand et al., 1998         | 5 (15)                                     | PB                           | N/A                | 0, 45                      | Mean $C_p$                 |                     |                      |
| Ludena et al., 2016        | 15 (55)                                    | GB                           | Par                | 0-180                     | Mean/peak $C_p$            |                     |                      |
| Chowdhury et al., 2017     | 15 (55)                                    | GB                           | Par                | 0-180                     | Mean/peak $C_p$            |                     |                      |
| Yuan et al., 2018          | - (150)$^a$                                | GB                           | Con, Den, Dep      | 0-45 (5 intervals)       | Mean/peak $C_p$            |                     |                      |
| Hui et al., 2019           | - (150)$^b$                                 | GB                           | Con, Den, Dep      | 0-45, (5 intervals)      | AF                          |                     |                      |

GB = Geometrical characteristic of balconies, Dep = Depth of balconies, PW = Parapet wall, $C_p$ = Pressure coefficient, Par = Partition wall, PB = Presence of balconies (a specific balcony geometry was considered), N/A = Not applicable, Con = Horizontal continuity of balconies, Den = Density of balconies, AF = Aerodynamic forces.

$^a$ Information about wind direction intervals was not reported.

$^b$ Information about building stories was not reported.

Table 2: Overview of wind tunnel studies on wind flow around buildings with balconies.

| Reference                  | Building scale | Building stories (height in full scale (m)) | Building stories (height (m)) | Research objective | Geometrical characteristic | Turbulence modeling approach | Wind direction (°) | Performance indicator |
|----------------------------|----------------|--------------------------------------------|------------------------------|--------------------|---------------------------|-----------------------------|---------------------|----------------------|
| Murakami, 1990             | Full           | 19 (.)$^c$                                 | PB                           | N/A                | RANS                      | 0$^e$                      | V                   |                      |
| Priendi & Depecker, 2002   | Full           | 2 (8.5)$^c$                                | PB                           | N/A                | RANS                      | 0                           | V                   |                      |
| Blocken & Carmeliet, 2008  | Full           | 8 (26)$^c$                                 | GB                           | N/A                | RANS                      | 0-360 (30 intervals)        | V                   |                      |
| Ai et al., 2011            | Reduced        | 5 (15)$^c$                                 | PB                           | N/A                | RANS                      | 0                           | Mean $C_p$, V       |                      |
| Ai et al., 2011            | Reduced        | 5, 10, 15, 15, 30 (45)                     | GB                           | Dep, PW            | RANS                      | 0-90 (22.5 intervals)       | Mean $C_p$          |                      |
| Ai et al., 2013            | Reduced        | 5 (15)$^c$                                 | PB                           | N/A                | RANS                      | 0                           | V, ACH               |                      |
| Montazeri et al., 2013     | Full           | 22 (78)$^c$                                | GB                           | DS                 | RANS                      | 0-360 (30 intervals)        | V                   |                      |
| Montazeri & Blocken, 2013  | Reduced        | 5 (15)$^c$                                 | PB                           | N/A                | RANS                      | 0, 45                       | Mean $C_p$          |                      |
| Ai & Mak, 2016             | Reduced        | 5 (13.5)$^c$                               | PB                           | N/A                | LES                       | 0, 45, 90                   | ACH, PC              |                      |
| Murena & Mele, 2016        | Full           | 4 (18)$^c$                                 | GB                           | Con, Dep           | SAS                       | 0$^e$                      | PC                  |                      |
| Laguno-Munitxu et al., 2017| Reduced        | 5 (.)$^{d, e}$                             | PB                           | N/A                | LES                       | 0$^e$                      | V                   |                      |
| Omrani et al., 2017        | Full           | 36 (.)$^c$                                 | GB                           | Dep, Par           | RANS                      | 0, 45, 90, 180              | V                   |                      |
| Karkoulas et al., 2019     | Full           | 7 (28)$^c$                                 | GB                           | BF                 | RANS                      | 0$^e$                      | PC                  |                      |
| Cui et al., 2020           | Full           | 4 (12)$^c$                                 | PB                           | N/A                | RANS                      | 0$^e$                      | V, PC               |                      |
| Irajiyar et al., 2020      | Full           | 13 (42)$^c$                                | GB                           | Dep                 | RANS                      | 0                           | V                   |                      |
| Ghadikolaei et al., 2020   | Full           | 6 (20.4)$^c$                               | GB                           | Par                | RANS                      | 0, 45                       | V, ACH               |                      |
| Zheng et al., 2020         | Reduced        | 30 (120)$^c$                               | PB                           | N/A                | LES, RANS                  | 0                           | V, Mean $C_p$        |                      |

PB = Presence of balconies (a specific balcony geometry was considered), N/A = Not applicable, V = Mean velocity, GB = Geometrical characteristic of balconies, $C_p$ = Pressure coefficient, Dep = Depth of balconies, ACH = Air exchange rate, DS = Double skin, Con = Horizontal continuity of balconies, SAS = Scale adaptive simulation, PC = Pollutant concentration, Par = Partition wall, BF = Balconies on different façades.

$^c$ Information about building height was not reported.

$^d$ Approximately 0$^°$.

$^e$ The focus was on street canyons.

$^f$ Perpendicular to the long street axis.

that the in these studies, different boundary conditions and building dimensions were considered, and the conclusions were not always consistent.
This paper contains six sections. In Section 2, the wind tunnel experiments by Stathopoulos and Zhu [3] and the validation study are briefly outlined. Section 3 describes the computational settings and parameters for the CFD simulations. Section 4 presents the CFD results. Finally, limitations and future work (Section 5) and conclusions (Section 6) are provided.

2. CFD validation study

In this study, the wind tunnel experiments by Stathopoulos and Zhu [3] are used for the CFD validation. Since this validation study has been published as a separate paper [18], only the outline is briefly mentioned here.

2.1. Wind tunnel experiment

In the wind tunnel experiments, the surface pressure on the façades of a reduced-scale model of a high-rise building with balconies was measured in an open-circuit atmospheric boundary layer wind tunnel. Fig. 1 illustrates the building model with dimensions: width × depth × height = 0.152 × 0.152 × 0.3 m³ (1:400 scale, w:d:h ≈ 1:1:2, 60.8 m × 60.8 m × 120 m in full scale). Balconies with 0.01 m depth (4 m in full scale) and 0.0025 m high (1 m in full scale) parapet walls were installed on one of the building façades where the surface pressures were measured along 7 vertical lines. In the present validation study, the measured data along two of the lines will be used. They will be referred to as line A (located 0.061 m from the left edge of the building model) and line B (located 0.0015 m from the left edge of the building model), as shown in Fig. 1. The overall uncertainty of the mean pressure coefficient ($C_p$) measurements was estimated to be less than 5% [48].

2.2. CFD validation: computational settings and parameters

Two computational grids are made of the reduced-scale building model in the wind tunnel measurements for approaching wind directions $\theta = 0^\circ$ (wind flow perpendicular to the windward façade with balconies) and $\theta = 180^\circ$. The computational domains and grids are made based on the best practice guidelines [49–52]. The grids are generated with the surface-grid extrusion technique [53]. Cubic cells are applied near the building, with 120 and 8 cells along the width and depth of the balconies, respectively. The total number of cells is 19,267,200. More information about the computational domain and grid can be found in Ref. [18]. The boundary conditions are listed in Table 3.

| Boundary                    | Boundary conditions          |
|-----------------------------|-----------------------------|
| Inlet                       | Velocity inlet              |
|                             | $U(z) = \frac{u^*}{\kappa} \ln \left( \frac{z + z_0}{z_0} \right)$ |
|                             | $k(z) = a(Iu(z) U(z))^2$    |
|                             | $\varepsilon(z) = \frac{\nu_l^2}{\kappa(z + z_0)}$ |
| Outlet                     | Pressure outlet             |
| Top and lateral sides       | Slip conditions             |
| Ground and building walls   | No-slip conditions          |
|                             | Static gauge pressure = 0 Pa|
|                             | Normal gradients of all variables = 0|
|                             | Werner-Wengle wall functions [54]|

[Fig. 2. CFD validation: comparison between $C_p$ obtained by CFD and wind tunnel (a) for $\theta = 0^\circ$, note that the measured data at point 8 was not reported in Ref. [3], and (b) $\theta = 180^\circ$.]
vertical profiles of mean wind speed $U$ and longitudinal turbulence intensity $I_u$ [3]. The mean wind velocity $U$ is given by Eq. (1), where the atmospheric boundary layer friction velocity, $u^*_\text{ABL}$, and aerodynamic roughness length, $z_0$, are 0.7 m/s and 0.0001 m, respectively. $\kappa$ is the von Karman constant ($= 0.41$). The turbulent kinetic energy is computed using Eq. (2), where $a = 1$ is chosen according to Tominaga et al. [50], the longitudinal turbulence intensity $I_u$ takes the measured value. The turbulence dissipation rate $\varepsilon$ is based on Eq. (3). The vortex method [55] is adopted to impose a time-dependent velocity profile at the inlet of the domain. The number of vortices $N_V$ is 8500, which is based on the recommendation by Ref. [36], i.e., $N_V = N/4$ where $N$ is the number of grid cells at the inlet plane.

The commercial CFD code ANSYS/Fluent 18.0 is used to perform the simulations. The simulations are isothermal. LES simulates the transient flow by solving the filtered Navier-Stokes equations and modeling the turbulence of the sub-filter scales by a subgrid-scale model. The filtered Navier-Stokes equations are:

\[
\begin{align*}
\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j} \left( \bar{u}_i \bar{u}_j \right) &= - \frac{1}{\rho} \frac{\partial p}{\partial x_i} - \frac{\partial}{\partial x_j} \left( 2 \tau_{ij} \right) \frac{\partial \tau_{ij}}{\partial x_j} \\
\end{align*}
\]
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where the overbars indicate the filtered variables, and $s_{ij}$ is the rate of strain tensor. The subgrid-scale Reynolds stresses ($\tau_{ij}$) appear due to the filter operation:

$$\tau_{ij} = u_i u_j$$

Subgrid-scale (SGS) models used to provide closure usually adopt the Boussinesq hypothesis:

$$\tau_{ij} = 0$$

where $\mu_{SGS}$ is the SGS turbulent viscosity. The isotropic part of the SGS stresses $\tau_{kk}$ is not modeled but added to the filtered static pressure term. In the present study, the wall-adapting local eddy viscosity (WALE) subgrid-scale (SGS) model [57] is used to obtain $\mu_{SGS}$ (Eq. 7):

$$\mu_{SGS} = \rho \left( C_w \Delta \right)^2 \left( \frac{\phi_{ij} \phi_{ij}}{\phi_{ii} \phi_{jj}} \right)^{3/2} \left( \frac{\phi_{ii} \phi_{jj}}{\phi_{ii} \phi_{jj} + \phi_{ij} \phi_{ij}} \right)^{1/4}$$

(7)

where the WALE constant $C_w = 0.325$ [58]. Grid filter width $\Delta = \sqrt{V^{1/3}}$, where $V$ is the volume of the computational cell. $\phi_{ij}$ is defined as:

**Fig. 4.** Case L-1: (a) building geometry, (b) computational domain and boundary conditions, (c) basic computational grid (16.6 million cells) at building surfaces and part of the ground surface, and (d) details of the basic grid near the bottom of the building. Details of grids for grid-sensitivity analysis: (e) coarse grid (7.9 million cells) and (f) coarser grid (3.9 million cells).
The simulations are initialized with the solution from 3D steady RANS simulations with the realizable k-ε turbulence model \[59\]. Then the LES initialization runs for \(T_{\text{init}} = 1.52\) s, corresponding to approximately 5 flow-through times \(T_{\text{flow-through}} = L_{x}/U_{\text{max}}\), where \(L_{x}\) is the length of the computational domain. After the initialization, the LES simulation and sampling are conducted for \(T_{\text{avg}} = 6.67\) s, which is approximately 21 flow-through times. Further information about the other settings and parameters are reported in Ref. \[18\].

### 2.3. CFD validation: results

Fig. 2 compares the simulated and measured \(C_p\) along lines A and B for \(\theta = 0^\circ\) and \(\theta = 180^\circ\). \(C_p\) is computed as:

\[
C_p = \frac{P - P_g}{0.5 \rho U_{\text{ref}}^2}
\]

(9)

where \(P\) is the mean pressure on the building surface, \(P_g\) is the reference static pressure, \(\rho\) is the air density \((1.225 \text{ kg/m}^3)\), and \(U_{\text{ref}}\) is the mean wind speed at the gradient height in the wind tunnel \((H_g = 0.625 \text{ m})\). For \(\theta = 0^\circ\), a fairly good agreement can be observed between the CFD and wind tunnel results along line A with an average absolute deviation of 0.027. Note that the measured data at point 8 was not reported in Ref. \[3\]. The average absolute deviation along line B is 0.133. The possible reason for this deviation could be due to the measurement uncertainty associated with the exact location of the pressure taps given the large vertical \(C_p\) gradients on the balcony spaces. More detailed information on the sensitivity of the absolute deviation of \(C_p\) to the vertical position of the measurement points has been provided in Ref. \[18\]. For \(\theta = 180^\circ\), the agreement is good with the average absolute deviations of 0.041 and 0.036 for lines A and B, respectively.

### 3. CFD simulations

#### 3.1. List of cases

In this study, twelve cases are considered. For all the cases, a 12-story building with dimensions width \(\times\) depth \(\times\) height = 24 \(\times\) 24 \(\times\) 48 m\(^3\) \((w:d:h = 1:1:2)\) is used, inspired by the building geometry in the wind tunnel measurements mentioned in subsection 2.1. In all the cases the building is assumed to be perfectly airtight, hence ventilation and infiltration are zero. Based on the position and geometrical characteristics of the balconies, the cases can be classified into five groups (Fig. 3):

- **Group 1** (to investigate the impact of the presence of balconies): a reference case without balconies (case Ref.) and case L-1. For case L-1, twelve balconies are located at equidistant points on both windward and leeward façades (Fig. 4a). The balconies are 24 m wide and 3 m deep and have 1 m high parapet walls. Note that the balcony on level 12 is roofed.

- **Group 2** (to investigate the impact of balcony depth): case D-1 (building with 1 m deep balconies), case D-2 (2 m deep balconies), case L-1 (3 m deep balconies) and case D-3 (4 m deep balconies). Note that for case D-3, the depth of the balconies is larger than the values commonly used in real buildings. Nevertheless, in the present study, a rather wide range is investigated to gain insight into the impact of balcony depth on the near-façade wind flow and surface pressure, which is in line with previous studies on the impact of balcony depth \[3,9,47\].

- **Group 3** (to investigate the impact of the presence and height of parapet walls): case W-1 (without parapet wall), case L-1 (1 m high parapet walls) and case W-2 (2 m high parapet walls). Note that in real buildings, balcony spaces are mostly equipped with parapet walls with the height of about 1 m. Case W-1 represents the balconies with parapet walls consisting of pipe railing \[60\], which allows...
Fig. 7. Distributions of $K$ and 2D velocity vector field in the vertical centerplane for (a) the reference case and (b) case L-1.

Fig. 8. Distributions of $C_p$ on windward façades of (a) the reference case, (b) case L-1, and (c) $\Delta C_p (L-1) = C_p (L-1) - C_p (Ref.)$. (d–f) Same for leeward façades.
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airflow to pass through. Some balconies on high-rise buildings are equipped with glass parapet walls taller than an adult for safety reasons, which is represented by case W-2.

- Group 4 (to investigate the impact of the presence and number of partition walls): case L-1 (without partition walls), case P-1 (two partition walls on lateral edges of the façades), case P-2 (three partition walls, two on the lateral edges and one in the middle of the façades) and case P-3 (five partition walls at equidistant locations). Note that such partition walls in-between are commonly used to divide units for residential buildings.

- Group 5 (to investigate the impact of the density of balconies): case L-1 (balconies on all 12 levels), case I-1 (balconies on levels 3, 5, 7, 9 and 11) and case I-2 (balconies only on levels 5 and 9). Note that cases like I-1 or I-2 can be found on split-level apartments.

3.2. Computational domain and grid

The simulations are performed in full scale. Fig. 4a shows the building geometry of case L-1. Fig. 4b displays the computational domain. The upstream domain length, lateral domain length, downstream domain length, and domain height are 4h, 4h, 10h, and 5h (h, height of the building), respectively (Fig. 4b). Note that the upstream domain length is limited to 4h to reduce the extent of unintended streamwise gradients in the inlet profiles [51,61]. The domain height (5h) is smaller than the one recommended by Tominaga et al. [50], in order to reduce the total number of cells and the computational time. The resulted blockage ratio is 1.18%, which is well below the maximum value recommended by the above-mentioned guidelines [50], i.e. 3%. A non-conformal grid is employed, where the whole domain is discretized into two subdomains: $\Omega_1$ (the inner subdomain) and $\Omega_2$ with a 1:2 grid refinement ratio between the adjacent subdomains as suggested by Ref. [52]. Subdomain $\Omega_1$ consists of cubic cells and it is extended up to a distance of h/6 away from the building surfaces (see Fig. 4c and d), i.e. from the location where high velocity gradients are expected to occur. The edge length of the cubic cells is h/192 (i.e. 16 cells per floor, and 4 cells along the height of parapet walls for case L-1). In subdomain $\Omega_2$, hexahedral cells with a stretching ratio of about 1.04 are used. The same topology and resolution are used for all the cases. The total number of cells is 16,566,528 for all cases, except for case D-3, where it is 17,543,792. The adequacy of the grid resolution is confirmed by a grid-sensitivity study that will be provided in subsection 3.5.

3.3. Boundary conditions

At the inlet of the domain, the neutral atmospheric boundary layer inlet profiles of mean wind speed (Eq. (1) and Fig. 5a), turbulent kinetic energy (Eq. (10) with empirical constant $C_\mu$ equal to 0.09 and Fig. 5b) and turbulence dissipation rate (Eq. (3) and Fig. 5c) proposed by Richards and Hoxey [62] are imposed.

Fig. 9. $C_{p,avg}$ for windward and leeward façades of buildings in groups 1–5 as presented in Fig. 3.
It is assumed that the building is situated on a large grass-covered terrain with an aerodynamic roughness length $z_0 = 0.03$ m [63] and an atmospheric boundary layer friction velocity $u_*^{ABL} = 0.3$ m/s. The corresponding mean wind velocity at 10 m height $U_{10} = 4.15$ m/s and the reference mean wind velocity at building roof height (48 m) $U_{ref} = 5.27$ m/s. All simulations are performed for $\theta = 0^\circ$ (approach flow perpendicular to the windward façade). The vortex method [55,64] is adopted at the inlet of the domain to generate a time-dependent velocity profile. The number of vortices $N_V = 11426$, following Ref. [56]. As shown in Fig. 4b, zero static gauge pressure is applied at the outlet plane and slip conditions are applied on the top and lateral sides. The building and ground surfaces are modeled as no-slip conditions. The Werner-Wengle wall functions are applied for modeling flow parameters in the near-wall regions [54].

$$k(z) = \frac{u_*^{ABL}^2}{\sqrt{\frac{C_\mu}{\nu}}} $$ (10)

Fig. 10. Impact of balcony depth: $K$ distributions in vertical centerplane near windward façades for (a) D-1 ($D = 1$ m), (c) case D-2 ($D = 2$ m), (e) case L-1 ($D = 3$ m), and (g) case D-3 ($D = 4$ m), (b, d, f and h) $K$ distributions in horizontal planes at the pedestrian height on windward balconies for the same cases.

3.4. Solver settings

Following the validation study reported in subsection 2.2, LES with the wall-adapting local eddy viscosity (WALE) SGS model is employed for the simulations. The time step ($\Delta t$) is 0.02 s for all the cases. The maximum CFL number ranges from 0.957 to 1.255, which mainly occurs close to the leading edge of the building roof. The other solver settings are identical to those in the validation study. All the LES simulations are started from the solution of 3D steady RANS simulations with the realiziable $k$-$\varepsilon$ turbulence model [59], and the computation is run during
averaged over a period of 1920 s (approximately 20 flow-through times) to remove the influence of the initial condition before data sampling. Then, data are sampled and averaged over a period of 1920 s (approximately 20 flow-through times).

3.5. Grid-sensitivity study

A grid-sensitivity analysis is carried out for case L-1. A basic (Fig. 4d), coarse (Fig. 4e) and coarser (Fig. 4f) grid are made based on the same overall grid topology. For the basic, coarse and coarser grid, 4, 3 and 2 cells are used along the height of parapet walls, respectively, and the length of the cubic cells near the building is h/192, h/144 and h/96, respectively. The total number of cells for the basic, coarse and coarser grid is 16.6, 7.9 and 3.9 million, respectively. The corresponding time steps are 0.02, 0.025 and 0.042 s, respectively, resulting in the maximum CFL number of 1.11, 0.99 and 1.00, respectively.

The results of the $C_p$ along vertical lines ($x/w = 0.125$ and $x/w = 0.5$) on the windward and leeward façades obtained by the three grids are compared in Fig. 6a–d. Only a limited dependency of $C_p$ on the grid resolution is observed. The overall absolute difference (the two lines combined) between the coarse grid and the basic grid is 0.016. This is 0.027 between the coarser grid and the basic grid. Therefore, the basic grid is adopted for the remainder of this study.

4. Results

The following target parameters are selected:

- **Mean wind speed ratio ($K$) in the vertical centerplane.** It is defined as the mean wind speed divided by $U_{ambient} (= 2.92 \text{ m/s})$, the “undisturbed” mean wind speed at the inlet plane at 1.75 m above the ground level.
- **Mean wind speed ratio ($K$) in horizontal planes at the pedestrian height ($= 1.75 \text{ m}$) on balcony spaces.** The focus will be on (i) the $K$ distribution and (ii) the maximum and area-averaged $K$, denoted as $K_{max}$ and $K_{avg}$, respectively.
- **$C_p$ on the windward and leeward façades.** The $C_p$ is calculated according to Eq. (9), where $P$ is the mean pressure on the building surface, $\rho$ is the air density (1.225 kg/m³), and $P_0$ is the reference static pressure = 0.5 Pa, taken 100 m upstream of the building at the roof height where the streamwise static pressure gradients are almost negligible. $U_{ref}$ is 5.27 m/s. The façade-averaged $C_p$ is denoted as $C_p$, avg.

4.1. Impact of balconies present or not

The impact of the presence of balconies on $K$ and $C_p$ is investigated by comparing the results of the reference case (building without balconies) and case L-1 (with balconies on both façades). The results are presented in Figs. 7, 8 and 9a. The following observations are made:

- **Fig. 7a** and b illustrates the distributions of $K$ and the velocity vector field in the vertical centerplane. For the reference case without balconies, the stagnation point on the windward façade is located at about 0.7h (h is the building height). For case L-1, multiple stagnation areas are found near the parapet walls, and at the upper part of the balcony spaces of levels 8–10 (Fig. 7b). On levels 9–12, the upwash flow separates at the edges of the parapet walls and introduces a clockwise vortex on each balcony space. For levels 6–8, two vortices are visible between the balconies: a counterclockwise vortex in the upper part, and a clockwise vortex in the lower part on each balcony space. Note that the presence of the balcony and its roof at level 12 significantly affects the reattachment point on the roof. For the reference case, the reattachment occurs at around 0.8d (d is the depth of the building) in relation to the leading edge of the building (Fig. 7a), while for case L-1, it occurs at 0.6d (Fig. 7b).

- **Fig. 8a** and b displays $C_p$ on the windward façade of the reference case and case L-1, respectively. **Fig. 8c** presents the $C_p$ difference between the two cases, i.e., $\Delta C_p (L-1) = C_p (L-1) - C_p (Ref)$. Fig. 8a–c shows that the presence of balconies leads to high-pressure areas close to the lateral edges of the façade behind the parapet walls, which is due to the impingement of the accelerated wind flow...
towards the lateral edges onto the lateral parapet walls yielding stagnation areas. This is in line with the results in Ref. [3]. For level 12, $C_p$ increases at the upper part of the façade where $\Delta C_p$ reaches its maximum value ($\Delta C_p = 1.63$). In the lower part of the façade on level 12, however, $C_p$ decreases to the extent that $\Delta C_p$ experiences a local minimum of $-0.362$. For the ground level, the presence of the balconies results in a mild reduction of $C_p$ on a large part of the façade. For the entire windward façade, however, the presence of balconies increases $C_{p,avg}$ from 0.616 to 0.648 (about 5.2%, shown in Fig. 9 a).

Fig. 8 d and e displays $C_p$ over the leeward façade of the two cases. $\Delta C_p (L-1) = C_p (L-1) - C_p (Ref.)$ is presented in Fig. 8f. By adding balconies on both façades (case L-1), $C_p$ either increases (i.e. becomes less negative) or remains unchanged across the leeward façade. The increase is more pronounced at the upper part of the façade. The maximum $\Delta C_p$ is 0.285, which occurs close to the edges behind the parapet walls on level 7. The presence of balconies increases $C_{p,avg}$ from $-0.486$ to $-0.443$ (about 8.9%, shown in Fig. 9 a).

4.2. Impact of balcony depth

The impact of the balcony depth on $K$ and $C_p$ is investigated based on the simulations for the cases in group 2. Fig. 10 displays $K$ in the vertical centerplane near the windward façade and in horizontal planes at a height of 1.75 m above each floor level (pedestrian height). Fig. 11 a shows the $K_{avg}$ and $K_{max}$ for the same horizontal planes on balcony spaces. The following observations are made:

- Fig. 10 a, c, e and g indicates that by increasing the depth of balconies, larger recirculation zones with larger velocity are formed on
Impact of balcony parapet walls: K distributions in the vertical centerplane near windward façades for (a) case W-1 (W = 0 m), (c) case L-1 (W = 1 m), and (e) case W-2 (W = 2 m). (b, d and f) K distributions in horizontal planes at the pedestrian height on windward balconies for the same cases.

For level 12, the largest \( K_{\text{avg}} \) is obtained for case W-1 (W = 0 m), followed by case L-1 (W = 1 m) and case W-2 (W = 2 m), with values of 1.49, 1.26 and 1.18, respectively. In this case, \( K_{\text{max}} \) is 2.12, 1.91 and 1.96, respectively.

For levels 5–11, compared to the other two cases, case W-2 (W = 2 m) experiences higher local K on balcony spaces in the vertical centerplane (Fig. 13e). This is because of the airflow is forced to enter the balcony spaces through the small openings and is more confined by the parapet walls, which results in a strong flow recirculation on the balcony spaces. For balconies with higher parapet walls on levels 5–11, larger local K in the middle of the horizontal planes (Fig. 13b, d and f) and larger \( K_{\text{avg}} \) (Fig. 11b) is observed. It should be noted that \( K_{\text{max}} \) occurs near the lateral edges of the façade for all the cases on levels 5–11, and 2 m parapet walls can significantly reduce the local K close to the lateral edges, resulting in the smallest local \( K_{\text{max}} \) values (Fig. 11b).

For levels 1–4, unlike the other two cases, case W-2 experiences a relatively uniform K distribution. This leads to lower \( K_{\text{avg}} \) and \( K_{\text{max}} \) compared to cases W-1 and L-1 (Fig. 11b).

The impact of partition walls is investigated based on the simulations for group 4. Fig. 15 displays the K distributions in horizontal planes at the 1.75 m above each floor level on the windward balconies for case L-1 (without partition walls), case P-1 (with two partition walls on lateral all balcony spaces. In this case, \( K_{\text{avg}} \) increases for all levels, except level 12 (Fig. 11a).

By increasing the depth from 1 m to 2, 3 and 4 m, the overall \( K_{\text{avg}} \) (all balconies combined) increases from 0.62 to 0.77 (by 23.7%), 0.97 (by 56.0%) and 1.09 (by 75.6%), respectively.

Fig. 12 shows \( C_p \) and \( \Delta C_p \) (relative to the reference case) distributions across the windward and leeward façades of case D-1 (D = 1 m), case D-2 (D = 2 m), case L-1 (D = 3 m) and case D-3 (D = 4 m). Fig. 9b presents \( C_{p,\text{avg}} \). The following observations are made:

- Fig. 12e–g (windward façade) shows that similar \( \Delta C_p \) distributions are observed across the windward façades of cases D-1 (D = 1 m), D-2 (D = 2 m) and L-1 (D = 3 m). In this case, \( C_{p,\text{avg}} \) is 0.660, 0.643 and 0.648, respectively (see Fig. 9b), i.e. 7.1%, 4.4% and 5.2% larger than that for the reference case. For the case with D = 4 m (case D-3), a stronger impact on the \( C_p \) occurs in the region between levels 1 and 9, where the pressure decreases (Fig. 12h) because of the relatively larger wind speed on the balcony spaces (see Fig. 10g). In this case, \( C_{p,\text{avg}} \) is 0.609 (see Fig. 9b), which is only 1.1% smaller than the reference case.

- Fig. 12i–p (leeward façade) shows that by increasing the depth of the balconies, \( C_{p,\text{avg}} \) increases, i.e. becomes less negative (Fig. 9b). For D = 1, 2, 3 and 4 m, \( C_{p,\text{avg}} \) is −0.470, −0.460, −0.443, and −0.430, i.e. 3.3%, 5.4%, 8.9%, and 11.5% larger than the reference case, respectively.

4.3. Impact of balcony parapet walls

The impact of the presence and the height of parapet walls on K and \( C_p \) is investigated for the three cases in group 3: case W-1 (W = 0 m), case L-1 (W = 1 m) and case W-2 (W = 2 m). Fig. 13 displays the K distributions in the vertical centerplane near the windward façade and in the horizontal planes at 1.75 m above each floor level. Fig. 11b provides the \( K_{\text{max}} \) and \( K_{\text{avg}} \) in the same horizontal planes. The following observations are made:

- For level 12, the largest \( K_{\text{avg}} \) is obtained for case W-1 (W = 0 m), followed by case L-1 (W = 1 m) and case W-2 (W = 2 m), with values of 1.49, 1.26 and 1.18, respectively. In this case, \( K_{\text{max}} \) is 2.12, 1.91 and 1.96, respectively.

- For levels 5–11, compared to the other two cases, case W-2 (W = 2 m) experiences higher local K on balcony spaces in the vertical centerplane (Fig. 13e). This is because of the airflow is forced to enter the balcony spaces through the small openings and is more confined by the parapet walls, which results in a strong flow recirculation on the balcony spaces. For balconies with higher parapet walls on levels 5–11, larger local K in the middle of the horizontal planes (Fig. 13b, d and f) and larger \( K_{\text{avg}} \) (Fig. 11b) is observed. It should be noted that \( K_{\text{max}} \) occurs near the lateral edges of the façade for all the cases on levels 5–11, and 2 m parapet walls can significantly reduce the local K close to the lateral edges, resulting in the smallest local \( K_{\text{max}} \) values (Fig. 11b).

- For levels 1–4, unlike the other two cases, case W-2 experiences a relatively uniform K distribution. This leads to lower \( K_{\text{avg}} \) and \( K_{\text{max}} \) compared to cases W-1 and L-1 (Fig. 11b).

Fig. 14 shows the \( C_p \) and \( \Delta C_p \) (relative to the reference case) distributions for the three cases. Fig. 9c presents \( C_{p,\text{avg}} \). The following observations are made:

- Fig. 14a–f (windward façade): compared to the case without parapet wall (case W-1), the presence of 1 m high parapet walls (case L-1) leads to higher-pressure areas near the lateral edges of the windward façade (see Fig. 14d and e), and \( C_{p,\text{avg}} \) increases from 0.599 to 0.648. By adding the 2 m high parapet walls (case W-2), the local \( C_p \) reduces significantly (Fig. 14c and f), and \( C_{p,\text{avg}} \) reduces to 0.595 (see Fig. 9c).

- Fig. 14g–l (leeward façade): by increasing W, \( C_p \) increases across the façade. As shown in Fig. 9c, for case W-1 (W = 0 m), case L-1 (W = 1 m) and case W-2 (W = 2 m), \( C_{p,\text{avg}} \) is −0.464, −0.443, and −0.423, i.e. 4.5%, 8.2% and 13.0% larger than the reference case, respectively.

4.4. Impact of partition walls

The impact of partition walls is investigated based on the simulations for group 4. Fig. 15 displays the K distributions in horizontal planes at the 1.75 m above each floor level on the windward balconies for case L-1 (without partition walls), case P-1 (with two partition walls on lateral
Fig. 14. Impact of balcony parapet wall: $C_p$ distributions on windward façades for buildings with balconies: (a) case W-1 ($W = 0$ m), (b) case L-1 ($W = 1$ m), and (c) case W-2 ($W = 2$ m), and (d–f) $\Delta C_p$ (pressure difference relative to the reference case) for the same cases. (g–l) Same for leeward façades.
For case L-1, without partition walls, a rather large stagnation region is formed upstream of the windward façade. The stagnation pressure forces the impinging wind flow to deviate horizontally, towards the lateral edges, which leads to higher wind speed near these edges. However, the presence of partition walls at the lateral edges of the façade (case P-1) impedes this horizontal flow and leads to small lateral pressure gradients on each balcony space (Fig. 16b), in turn yielding a significant reduction in both $K_{\text{max}}$ and $K_{\text{avg}}$ in the horizontal planes (Fig. 16b).

- By increasing the number of partition walls, $K_{\text{max}}$ and $K_{\text{avg}}$ decrease monotonically. The overall $K_{\text{avg}}$ (all the balconies combined) for cases P-1, P-2 and P-3 is 0.51, 0.47 and 0.31, i.e. 47.4%, 51.6% and 68.0% smaller than case L-1, respectively.

Fig. 16 shows the $C_p$ and $\Delta C_p$ (relative to the reference case) distributions for the four cases. Fig. 9d presents $C_{p,\text{avg}}$. The following observations are made:

- Fig. 16a–h displays the impact of partition walls on the $C_p$ distributions across the windward façade. The presence of partition walls on both lateral edges (case P-1) reduces the spanwise pressure gradients across the façade (Fig. 16b). A similar pressure distribution can also be observed for case P-2 (Fig. 16c) when additional partition walls are used in the middle. For case P-3 when three additional partition walls are used, larger spanwise pressure gradients are observed across the middle and side partitions (Fig. 16d).
- Adding only two partition walls (at the lateral edges) strongly increases $C_{p,\text{avg}}$ on the windward façade, from 0.648 to 0.761 (an increase by 17.4%, i.e. 23.5% larger than the reference case). However, by further increasing the number of partition walls, $C_{p,\text{avg}}$ on the windward façade decreases (Fig. 16g and h). For cases P-2 and P-3, $C_{p,\text{avg}}$ is 0.759 and 0.699, i.e. 23.2% and 13.5% larger than the reference case, respectively (Fig. 9d). Still, every case with partition walls has a much higher windward $C_{p,\text{avg}}$ than the reference case.

- By increasing the number of partition walls, on each balcony space, rather uniform-pressure regions are formed between consecutive partition walls on the leeward façade (Fig. 16i–l). Nevertheless, this has an insignificant impact on $C_{p,\text{avg}}$. For cases P-2 and P-3, $C_{p,\text{avg}}$ is $-0.379$ and $-0.376$, i.e. 22.0% and 22.6% larger than the reference case, respectively (Fig. 9d).

4.5. Impact of density of balconies

The impact of the density of balconies is investigated based on the simulations for group 5: case L-1 (balconies on all levels), case I-1 (balconies on levels 3, 5, 7, 9 and 11), and case I-2 (balconies on levels 5 and 9). Fig. 17 displays the distributions of the mean wind speed ratio (K) in the vertical centerplane near the windward façade (Fig. 17a, c and e) and horizontal planes at a height of 1.75 m above each floor level (Fig. 17b, d and f). Fig. 11d shows $K_{\text{max}}$ and $K_{\text{avg}}$ in the horizontal plane of each level. The density of balconies can significantly affect the flow pattern near the windward façade, and also on the balcony spaces. For the three cases, for balconies below level 8, the downwash flow separates at the edge of the balconies, and a counter-clockwise vortex with relatively high wind speed is formed below each balcony floor (Fig. 17a, c and e). For these balconies, by decreasing the density of balconies, the local K and $K_{\text{max}}$ in the horizontal plane at the pedestrian height decreases (Fig. 11d). The overall $K_{\text{avg}}$ (all the balconies combined) for cases I-1 and I-2 is 0.75 and 0.68, i.e. 22.7% and 29.9% smaller than that for case L-1, respectively.

Fig. 18 shows $C_p$ and $\Delta C_p$ distributions (relative to the reference case) for the three cases. Fig. 9e presents $C_{p,\text{avg}}$. The following observations are made:

- Fig. 18a–f shows that the impact of the density of balconies on $C_p$ on the windward façade on levels 7–10 is rather insignificant. For the
balconies located below level 7, however, a clear increase in $C_p$ can be observed close to the lateral edges of the façade behind the parapet walls while a reduction of $C_p$ can be observed below each balcony. This $C_p$ reduction effect is due to the counter-clockwise vortex with relatively high wind speed below each balcony floor (see Fig. 17a, c and e). $C_{p,\text{avg}}$ on the windward façade of cases L-1, I-1, I-2 is 0.648, 0.660 and 0.636 (Fig. 9e), i.e. 5.2%, 7.5% and 3.2% larger than the reference case, respectively.

5. Limitations and future work

Although this study has performed a systematic sensitivity analysis...
based on a large number of parameters and CFD simulations, there are still a number of limitations that provide opportunities for future work:

- In the present study, the focus is on the mean surface pressure coefficient and the mean wind speed. It should be noted that research on building ventilation and infiltration is mostly performed based on mean surface pressure coefficients [65–67]. In addition, studies on pedestrian-level wind comfort and wind safety assessment are generally performed based on the mean wind speed [6,23,28,68–70]. Given the importance of peak pressures for wind loads [71–73], future work should consider the impact of balcony geometry on peak surface pressures.

- In this study, all the cases are assumed to be fully closed, i.e. airtight buildings without any openings. The exterior surface pressure coefficients of enclosed buildings are widely used as input parameters in building energy simulation tools to predict ventilation and infiltration [65–67]. It should be noted, however, that earlier studies have shown that the presence of open windows (or doors) on building façades can affect the near-façade wind flow and the local and surface-averaged static pressure [74]. Therefore, future studies should consider cases for which building balconies coexist with open windows (or doors).

- This study is only performed for one inflow wind speed and for perpendicular wind directions (θ = 0° and 180°). For low wind speeds, natural or mixed (combined forced and natural) convection heat transfer may be dominant that can significantly affect the near-façade wind flow. Previous studies have indicated that balconies can also significantly affect the mean surface pressure under oblique wind directions [3,4]. Future work should focus on the impact of wind speed and wind direction.

- This study only focuses on an isolated high-rise building with balconies. The presence of surrounding buildings may lead to complexities of wind flow and would modify the surface pressure and near-façade flow field [75–78].

- This study focuses on balconies that extend along the entire width of the building façade. Future work should focus on other types of building balcony such as discontinuous balconies. Earlier studies have shown that façade and roof geometrical details can also significantly affect the near-façade airflow patterns [79–83]. The focus of this study is on building balconies, which are generally the most prominent façade elements. This work can be extended to include other types of building surface geometrical details.

6. Conclusions

In this study, the impact of geometrical characteristics of building balconies on the near-façade wind flow field, mean wind speed on balcony spaces, and wind-induced mean surface pressure for a high-rise building is investigated. The target parameters are the mean wind speed ratio at the pedestrian height on the balconies (local: K, area-averaged: K_{avg}, maximum: K_{max}) and the mean surface pressure coefficient (local: C_{p}, façade-averaged: C_{p,avg}). LES simulations are performed to investigate the impact of (i) balconies present or not, (ii) balcony depth, (iii) balcony parapet walls, (iv) balcony partition walls, and (v) density of balconies. Within the range of parameters evaluated in the present study, the following conclusions are made:

a. Balconies present or not

- The presence of balconies increases C_{p,avg} on both windward façade and leeward façade by 5.2% and 8.9%, respectively. Note that for negative C_{p} values, the term “increase” refers to a less negative value and hence a lower absolute value of C_{p}.

b. Impact of balcony depth

- Increasing the depth of balconies leads to larger recirculation zones with higher mean wind speed on windward balcony spaces, resulting in a larger K_{avg}. For example, by increasing the depth of balconies from 1 m to 4 m, the overall K_{avg} (all balconies combined) increases by 75.6%.

- In general, increasing the depth of balconies from 1 m to 2, 3 and 4 m reduces C_{p,avg} on windward façade. From 1 m to 4 m, C_{p,avg} reduces from 0.660 to 0.609.

- For the leeward façade, increasing the depth of balconies from 1 m to 4 m can increase C_{p,avg} from −0.470 to −0.430.

c. Impact of balcony parapet walls

- Adding 1 m high parapet walls has an insignificant impact on K_{avg} and K_{max} on the windward balconies.

- By increasing the height of the parapet walls from 1 m to 2 m, K_{max} on the windward balconies decreases substantially.

- For the windward façade, the presence of 1 m high parapet walls increases C_{p,avg} from 0.599 to 0.648. By increasing the height of
Fig. 18. Impact of density of balconies: $C_p$ distributions on windward façades for buildings with: (a) balconies on every level (case L-1), (b) balconies on levels 3, 5, 7, 9 and 11 (case I-1), and (c) balconies on levels 5 and 9 (case I-2), and (d–f) $\Delta C_p$ (pressure difference relative to the reference case) for the same cases. (g–l) Same for leeward façades.
the parapet walls from 1 m to 2 m, \( C_{p,\text{avg}} \) reduces from 0.648 to 0.595.

- For the windward façade, the presence of 1 m high parapet walls increases the \( C_{p,\text{avg}} \) from \(-0.464\) to \(-0.443\). As the height increases from 1 m to 2 m, \( C_{p,\text{avg}} \) increases further to \(-0.423\).

d. Impact of balcony partition walls

- Adding partition walls can significantly reduce the \( K_{\text{avg}} \) and \( K_{\text{max}} \) on the windward balconies. The maximum reduction in the overall \( K_{\text{avg}} \) (68.0\%) is achieved when five partition walls are used. This is about 51.6\% and 47.4\% when only three and two partition walls are implemented, respectively.

- Adding partition walls can significantly increase \( C_{p,\text{avg}} \). For example, by adding two partition walls at the lateral edges of the façades, \( C_{p,\text{avg}} \) increases from 0.648 to 0.761, and from \(-0.443\) to \(-0.373\) for the windward and leeward façades, respectively.

e. Impact of density of balconies

- For the windward façade, by decreasing the density of balconies, \( K_{\text{avg}} \) substantially reduces for balconies located below the stagnation area.

- For the three cases tested, no correlation between the density of the balconies and \( C_{p,\text{avg}} \) is observed for both windward and leeward façades. For the windward façade, the case with 5 balconies (on levels 3, 5, 7, 9 and 11) shows the largest \( C_{p,\text{avg}} \) (= 0.660). For the leeward façade, the largest \( C_{p,\text{avg}} \) is obtained for the case with 12 balconies (= -0.443).

The present findings can be useful in developing, designing and constructing buildings with façade details that improve ventilation, air quality and wind comfort.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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