CFD simulations of wind flow and mean surface pressure for buildings with balconies: Comparison of RANS and LES

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1. Introduction

Building façade geometrical details such as balconies can significantly affect the near-façade airflow patterns and the surface pressure distributions on building façades [1–5]. For example, the presence of balconies can change the local mean pressure coefficient \(C_p\) on the windward façade of a high-rise building by about 0.7 [2]. Similarly, it can lead to a reduction of about 30% in the surface-averaged \(C_p\) on the windward façade of a low-rise building [4]. Therefore, a better understanding of the impact of façade geometrical details in general, and building balconies in particular on the near-façade airflow patterns and the surface pressure distributions on the façade is of primary importance for the accurate evaluation of wind-induced natural ventilation [6,7], wind comfort on balcony spaces [8], pollutant dispersion [9], wind loads on building walls and building components [10] and convective heat transfer at building surfaces [11–13].

Apart from wind-tunnel testing [1–3,5,14,15], computational fluid dynamics (CFD) has been also used to investigate the impact of building façade geometrical details on the near-façade airflow and the local and surface-averaged wind-induced pressure on the façades. An overview of CFD studies on buildings with façade geometrical details is given in Table 1. It can be seen that the vast majority of these studies focused on buildings with balconies. In addition, steady Reynolds-averaged Navier-Stokes (RANS) simulations have been widely used in these studies, while the use of more advanced scale-resolving turbulence modeling approaches is scarce, and limited to the studies by Ai and Mak [16], Llaguno-Munitxa et al. [17] and Murena & Mele [18] in which large-eddy simulation (LES) and scale-adaptive simulation (SAS) have been used. The good performance of RANS approach in predicting the \(C_p\) on the windward façade of a building with balconies for both perpendicular \((\theta = 0^\circ)\) and oblique \((\theta = 45^\circ)\) wind directions was shown in Ref. [5]. However, such good performance could not be shown for the leeward façade, where steady RANS systematically underestimated the absolute value of \(C_p\) by about 0.096, while these are 0.161 and 0.038 for \(\theta = 0^\circ\) and \(\theta = 180^\circ\), respectively. Large differences are found in the computed flow fields on the balcony spaces. Because RANS systematically underestimates the absolute values of both \(C_p\) and mean wind speed on the balconies, it is suggested that building design based on RANS might result in excessive ventilation and in too high wind nuisance level.

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the steady RANS deficiencies on the calculated façade geometrical features introduce a multitude of areas with flow separation, recirculation and reattachment which can amplify the corresponding to 0.04 m at full scale), and the reference wind speed exposure with aerodynamic roughness length of 0.0001 m (model scale, corresponding to 250 m at full scale). The incident longitudinal turbulence intensity I, modified from Ref. [2].

Fig. 1. Measured profiles of (a) normalized mean wind speed $U/U_{ref}$ and (b) turbulence intensity $I$, modified from Ref. [2].

Table 1: Overview of CFD studies on airflow around buildings with façade geometrical details.

| Reference | Building configuration (building height) | Façade geometrical details | Turbulence modeling approach | Wind direction | Validation | Investigated parameter |
|-----------|----------------------------------------|----------------------------|-------------------------------|----------------|------------|------------------------|
| (Murakami, 1990) [27] | 19-story (~19 m) | Balconies | Steady RANS | $0^\circ$ | No | $V$ |
| (Pianto & Depecker, 2002) [58] | 2-story (8.5 m) | Balconies | Steady RANS | $0^\circ$ | No | $V$ |
| (Ai et al., 2011) [59] | 5-story (15 m) | Balconies | Steady RANS | $0^\circ$, $22.5^\circ$, $45^\circ$, 67.5°, 90° | Yes [1] | $V$, $C_p$ |
| (Montazeri et al., 2013) [61] | 5-story (15 m) | Balconies | Steady RANS | $0^\circ$ | Yes [1] | $V$, ACH |
| (Karkoulias et al., 2019) | 5-story (15 m) | Balconies | Steady RANS | $0^\circ$, $45^\circ$ | Yes [1] | $V$, PC |
| (Llaguno-Munitxa et al., 2017) [17] | 5-story (~18 m) | Balconies | LES | $0^\circ$, $45^\circ$, $90^\circ$ | Yes [62] | ACH, PC |
| (Omrani et al., 2017) [63] | 36-story (~100 m) | Balconies | SAS | $0^\circ$, $180^\circ$ | No | $PC$ |
| (Karkoulias et al., 2019) [9] | 7-story (28 m) | Balconies | RANS | $0^\circ$, $45^\circ$, $90^\circ$ | Yes [9] | $PC$ |

V = Mean velocity, $C_p$ = Mean pressure coefficient, ACH = Air change rate per hour, PC = Pollutant concentration, CHTC = Convective heat transfer coefficient, SAS = Scale-adaptive simulation.

$^a$ Building height was not reported.

$^b$ Approximately $0^\circ$.

$^c$ Cases were considered as street canyons.

$^d$ Perpendicular to the long street canyon axis.

2. Description of the wind-tunnel experiment

Stathopoulos and Zhu [2] measured mean surface pressures on the façade of a reduced-scale model of a high-rise building with different types of balconies and for different approach-flow wind directions at a scale 1:400. The measurements were performed in the atmospheric boundary layer open-circuit wind tunnel of the Centre for Building Studies at Concordia University. The wind-tunnel test section was 12.2 m long and had a cross-section of $1.8 \times 1.8 \text{ m}^2$. The approach-flow mean velocity and longitudinal turbulence intensity profiles were measured at the center of the turntable in the empty tunnel (i.e. without building model present) [2], and hence represent the so-called incident profiles [65]. The profiles (shown in Fig. 1) reproduced an open country terrain exposure with aerodynamic roughness length of 0.0001 m (model scale, corresponding to 0.04 m at full scale), and the reference wind speed ($U_{ref}$) of approximate 14 m/s at gradient height ($H_g = 0.625 \text{ m}$, corresponding to 250 m at full scale). The incident longitudinal turbulence intensity ranged from 20% near ground level to about 7% at gradient height [2].

The 30-story isolated building model had dimensions $W \times D \times H = 0.152 \times 0.152 \times 0.3 \text{ m}^3 (60.8 \times 60.8 \times 120 \text{ m}^2$ at full scale). Balconies were provided only on one façade (Fig. 2).

Four types of balcony were tested: (i) balconies with 0.005 m depth...
(2 m at full scale) without a parapet wall, (ii) balconies with 0.01 m depth (4 m at full scale) without a parapet wall, (iii) balconies with 0.01 m depth and 0.0025 m (1 m at full scale) parapet walls, and (iv) balconies with 0.01 m depth (4 m at full scale) and 0.005 m parapet walls (2 m at full scale). The measurements were performed for 3 approach-flow wind directions relative to the facade with the balconies: 0°, 90°, and 180°. In the present study, the focus will be on the case with balconies of 0.01 m depth and with 0.0025 m parapet walls (Fig. 2). The pressure measurements were performed along 7 vertical lines located on the facade with balconies. In the present study, the measured data along two of these lines will be used. Note that the measured data along the other five lines were not reported in Ref. [2]. In the remainder of this paper, we will refer to the two lines as line A (located 0.0015 m (0.6 m in full scale) from the left edge of the facade with balconies) and line B (located 0.061 m (24.4 m in full scale) from the left edge of the facade with balconies). The measurements were performed using a SETRA-237 pressure transducer. The overall uncertainty of the $C_p$ measurements was estimated to be less than 5% [66].

3. CFD simulations: computational settings and parameters

3.1. Computational domain and grid

The CFD simulations are performed at the reduced scale (wind-tunnel scale). For the RANS simulations, the dimensions of the computational domain are based on the best practice guidelines by Franke et al. [67] and Tominaga et al. [68]. The upstream and downstream domain lengths are 5H and 15H, respectively, where H is the height of the building model (= 0.3 m). The height of the domain is 5H. The computational grids are generated using the surface-grid extrusion technique developed by van Hooff and Blocken [69]. The RANS domain for $\theta = 0°$ is shown in Fig. 3a, and the grid on the building and
ground surfaces is shown in Fig. 3 b–d. The grid consists of 5,230,396 hexahedral cells. 31, 8, and 4 cells are used along the width and depth of the balconies and along the height of parapet walls, respectively (Fig. 3 c). The maximum stretching ratio of 1.2 controls the cells in the whole computational domain, which is in line with the best practice guidelines [67, 68]. The grid resolution is based on a grid-sensitivity analysis using three different grids generated by coarsening and refining the basic grid. The details of the grid-sensitivity analysis will be provided in Section 3.4. Note that the grid shown in Fig. 3 a–d is also used for \( \theta = 90^\circ \), while another grid with the same topology and resolution is made for \( \theta = 180^\circ \).

Fig. 3 e–h displays the domain and the grid for the LES simulation for \( \theta = 0^\circ \). The upstream domain length is limited to 4H to reduce the extent of unintended streamwise gradients in the approach-flow profiles [70–72]. The downstream domain length is 10H [67, 68]. The height of the domain is 4H, which is smaller than the one recommended by Franke et al. [67] and Tominaga et al. [68], in order to reduce the total number of cells and the computational time. The resulting blockage ratio is 1.4%, which is well below the maximum value of 3.0% recommended by the aforementioned guidelines [67, 68]. A non-conformal grid is employed, where the whole domain is discretized into two subdomains: \( \Omega_1 \) (the inner grid) and \( \Omega_2 \), where subdomain \( \Omega_1 \) is extended up to a distance of approximately H/6 away from the building surfaces (Fig. 3b). The grid refinement ratio between the adjacent subdomains is 1:2, which is in line with recommendations by Iousef et al. [70]. Cubic cells (cells with the same x, y, z lengths) are applied in subdomain \( \Omega_1 \), with 120, 8, and 2 cells along the width and depth of the balconies and along the height of parapet walls, respectively (Fig. 3g). In subdomain \( \Omega_2 \) hexahedral cells with a stretching ratio of 1.05 are used. In this case, the total number of cells is 19,267,200. The quality of the LES grid is evaluated using LES index of quality (LES\(_{IQ}\)), which will be presented in Section 3.5. Note that additional grids with the same topology and the same grid resolution are made for \( \theta = 90^\circ \) and \( \theta = 180^\circ \).

### 3.2. Boundary conditions

For \( \theta = 0^\circ \), in both Fig. 3a and e, plane 1 is the inlet plane, plane 4 is the outlet plane, and planes 2 and 3 are the side planes. For the RANS simulation, for \( \theta = 90^\circ \) (Fig. 3a), planes 3 and 2 are the inlet and the outlet planes, respectively, and planes 1 and 4 are the side planes.

The inlet boundary conditions are based on the measured data (Fig. 1). Eq. (1) is employed to fit the measured vertical profile of the mean wind speed \( U \), where \( \kappa \) is the von Karman constant (≈ 0.41). Note that \( u^*_{ABL} \) is estimated to be 0.7 m/s based on the measured mean wind speed, while the aerodynamic roughness length \( z_0 \) has been reported in Ref. [2]. The turbulent kinetic energy \( k \) is calculated according to Eq. (2), based on the mean wind velocity \( U \) from Eq. (1) and the measured longitudinal turbulence intensity \( I_u \) [2]. In Eq. (2), \( a = 1 \) is chosen according to Tominaga et al. [68]. The turbulence dissipation rate \( \epsilon \) is calculated using Eq. (3). For LES, the vortex method [73,74] is adopted to impose a time-dependent velocity profile at the inlet of the domain. It was shown that this method could accurately reproduce the mean velocity field [75] and mean pressure coefficients on building surfaces [47]. The number of vortices \( N_v \) is 8500, which is based on \( N_v = N/4 \) where \( N \) is the number of grid cells at the inlet plane [76].

\[
U(z) = \frac{u^*_{ABL}}{k} \ln \left( \frac{z + z_0}{z_0} \right)
\]  

\[ (1) \]
For the RANS simulations, the standard wall functions by Launder and Spalding [77] with roughness modification by Cebeci and Bradshaw [78] are applied at the ground surface. The sand grain roughness height $k_s$ and the roughness constant $C_s$ are determined according to their consistent relationship with the aerodynamic roughness length $z_0$ (Eq. (4)) derived by Blocken et al. [79].

$$k_s = \frac{9.793 z_0}{C_s}$$ (4)

For the LES, the Werner-Wengle wall functions are applied [80], which assumes either a linear or 1/7 power law distribution of instantaneous velocity in the first cell [81]. Zero static gauge pressure is applied at the outlet plane and symmetry boundary conditions (zero

$$k(z) = a'u(z) U(z)^2$$ (2)

$$\epsilon(z) = \frac{\frac{u_{\text{abl}}^3}{k(z + z_0)}}{k(z)}$$ (3)
normal gradients of all variables) are imposed at the top and lateral sides of the domains in both RANS and LES simulations.

3.3. Solver settings

The commercial CFD code ANSYS Fluent 18.0 is employed to perform the simulations. The RANS simulations are performed on the HPC cluster of the Unit Building Physics & Services at the Department of the Built Environment of Eindhoven University of Technology. The cluster has a 16-core node (Intel(R) Xeon(R) CPU - X5650 @ 2.7 GHz). The LES simulations are performed on the Dutch national supercomputer SURFSARA, Cartesius (www.surfsara.nl) with a 24-core node (Intel(R) Xeon(R) CPU - E5-2690 v3 @ 2.6 GHz).

For the RANS simulations, the realizable k-\(\epsilon\) turbulence model is used for closure [82]. This turbulence model has been successfully used on many occasions in the past for CFD simulations of wind flow around buildings and in urban areas [4,83–87]. Second-order discretization schemes are utilized for both the convection and the viscous terms of the governing equations. The SIMPLE algorithm is used for the pressure-velocity coupling. Convergence is assumed to be obtained when the scaled normalized residuals stabilize at a minimum of 10\(^{-4}\) for continuity, 10\(^{-7}\) for x, y and z momentum and 10\(^{-6}\) for k and \(\epsilon\). In addition, values of the mean surface static pressures at all measurement points along lines A and B (shown in Fig. 2b) are monitored to ensure that they remain constant throughout the iterations near the end of the iterative process.

For the LES simulations, the wall-adapting local eddy viscosity subgrid-scale model (WALE) is employed with the constant \(C_{\text{wale}} = 0.325\). Pressure-velocity coupling is performed using the Fractional Step method in combination with the non-iterative time advancement

| Angle | Ideal value | Line A RANS | Line A LES | Line B RANS | Line B LES | Overall RANS | Overall LES |
|-------|-------------|-------------|------------|-------------|------------|-------------|-------------|
| 0°    | Absolute deviation | 0.172 | 0.133 | 0.026 | 0.027 | 0.113 | 0.091 |
| 0°    | NMSE        | 0.313 | 0.023 | 0.363 | 0.028 | 0.371 | 0.025 |
| 0°    | FB          | 0.537 | 0.141 | 0.575 | 0.164 | 0.581 | 0.151 |
| 0°    | Absolute deviation | 0.157 | 0.036 | 0.147 | 0.041 | 0.161 | 0.038 |
| 0°    | NMSE        | 0.275 | 0.009 | 0.224 | 0.013 | 0.305 | 0.010 |
| 0°    | FB          | 0.501 | 0.086 | 0.455 | 0.110 | 0.525 | 0.096 |

Fig. 7. The sensitivity of absolute deviation of C\(_p\) to the vertical position for (a) Point 2; (b) Point 3; (c) Point 4 and (d) Point 5 along line A shown in Fig. 2b.
scheme [81]. For pressure interpolation and time discretization, second-order schemes are applied. The time step is $\Delta t = 4 \times 10^{-5}$ s. The resulting maximum and volume-averaged Courant-Friedrichs-Lewy number (CFL) are 1.287 and 0.046, respectively. Note that the CFL number larger than 1 occurs only in a few cells close to the leading edge of the building roof. The LES simulations are initialized with the solution of steady RANS simulations. Then the LES initializations run for $T_{\text{init}} = 1.52$ s, corresponding to approximately 5 flow-through times ($T_{\text{flow-through}} = L_x/U_{\text{ref}}$, where $L_x$ is the length of the computational domain, $U_{\text{ref}}$ is the reference wind speed that is taken at the gradient height). After the initialization, the statistical sampling is conducted for $T_{\text{avg}} = 6.67$ s, which is approximately 21 flow-through times.

3.4. Grid-sensitivity study for the RANS grid

The grid-sensitivity analysis for the RANS grid is performed for $\theta = 0^\circ$. Two additional grids are generated: a fine grid and a coarse grid, where the coarsening and refining is performed with an overall linear factor of approximately 1.3. The fine and coarse grids have 8,421,600 and 2,310,016 cells, where 10 and 6 cells are used along the depth of each balcony, respectively. Fig. 4 presents $C_p$ along line A (Fig. 4a and b) and line B (Fig. 4c) obtained from the three grids. The average absolute difference between the $C_p$-coarse grid and the $C_p$-basic grid is 0.036, while this is 0.016 between the $C_p$-basic grid and $C_p$-fine. The grid-convergence index (GCI) proposed by Roache [88], given by Eq. (5), is also used to estimate the error in the $C_p$-basic and $C_p$-coarse:

$$\text{GCI} \% = \frac{r}{1 - \frac{r}{100}} \times 100\% \quad (5)$$

where $r$ is the linear grid refinement factor, $p$ is the formal order of accuracy, which in this analysis is considered to be 2 since second-order discretization schemes are used for the simulations. The safety factor $F_s = 1.25$ is taken, which is the recommended value when three or more grids are considered [88]. $C_p^{-1}$ is the mean pressure coefficient from a relatively coarse grid and $C_p^{-2}$ is the mean pressure coefficient from a relatively fine grid. For the windward façade, the surface-averaged GCI$_{\text{basic}}$ and GCI$_{\text{coarse}}$ are 2.35% and 3.42%, respectively. It indicates that the basic grid provides nearly grid-independent results and it is, therefore, used in the remainder of the study for the RANS simulations.

3.5. Index of quality for the LES grid

The LES index of quality ($\text{LES}_{IQ}$) is used to measure the quality of the LES grid. This index is defined as the ratio of the resolved turbulent kinetic energy to the total turbulent kinetic energy, which will be examined with the equation by Celik et al. [89] involving the molecular viscosity $\nu$ and turbulent viscosity $\nu_{\text{tsgs}}$.

$$\text{LES}_{IQ} = \frac{k_{\text{resolved}}}{k_{\text{total}}} = \frac{1}{1 + 0.05 \left(\frac{\nu_{\text{tsgs}}}{\nu}\right)^{0.37}} \quad (6)$$

According to Pope [90], in a well-resolved computation, at least 80% of the turbulent kinetic energy is resolved. Fig. 5 shows profiles of $\text{LES}_{IQ}$ along 5 vertical lines in the vertical centerplane for $\theta = 0^\circ$. The results indicate that the computation clearly resolves a large portion of the total turbulent kinetic energy along the 5 lines, with the overall average and minimum $\text{LES}_{IQ}$ of 92.6% and 79.4%, respectively. For the whole domain, the volume-averaged amount of total kinetic energy resolved is 92.9%. As a result, if the threshold of 80% is used, it may conclude that the LES simulations resolve a sufficient amount of turbulent kinetic energy.

4. CFD simulations: validation

The $C_p$ predicted by RANS and LES are compared with the measured data [2] for the three wind directions. Note that for $\theta = 0^\circ$ and $\theta = 90^\circ$, the measured data at point 8 (the second point on line B as shown in Fig. 2) was not reported in Ref. [2]. The $C_p$ is computed as:

$$C_p = \frac{P - P_0}{0.5\rho U_{\text{ref}}^2} \quad (7)$$

where $P$ is the mean static pressure on the building surface, $P_0$ is the reference static pressure, $\rho$ is the air density (1.225 kg/m$^3$), and $U_{\text{ref}}$ is the reference wind speed that is taken at the gradient height. Note that, according to the information provided in Ref. [66], the Pitot-static tube was mounted at the gradient height above the test-section floor, while its exact distance relative to the building model was not reported. This is because the wind tunnel at Concordia University has a test section roof that can be adjusted to enable a zero longitudinal static pressure gradient. Therefore, the actual measurement location for the reference pressure was not that important in the measurements. However, in the CFD simulations, the top of the computational domain is a horizontal surface, which causes streamwise gradients along the domain length. In the present study, the static pressure obtained by the CFD simulations at the point 0.6 m upstream of the building and at the same height of the Pitot-static tube in the measurements is taken as the reference pressure ($P_0$). Note that at this point, small streamwise static pressure gradients are observed in both RANS and LES results. The resulting $P_0$ values are 4.1 Pa and 3.5 Pa for RANS and LES, respectively.

![Fig. 8. Distributions of $C_p$ on the façade with balconies at $\theta = 0^\circ$ obtained by (a) RANS and (b) LES, and (c) $\Delta C_p$ (LES-RANS).](image-url)
In order to quantify the agreement between the CFD (RANS and LES) results and the wind-tunnel results, absolute deviations and two other validation metrics are used: fractional bias (FB) and normalized mean square error (NMSE) \[91\]. The metrics are calculated using Eqs. (8) and (9):

\[
\text{NMSE} = \frac{[C_{p(WT)} - C_{p(CFD)}]^2}{[C_{p(WT)}][C_{p(CFD)}]} \tag{8}
\]

\[
\text{FB} = \frac{2[C_{p(WT)}] - [C_{p(CFD)}]}{[C_{p(WT)}] + [C_{p(CFD)}]} \tag{9}
\]

where the square brackets indicate averaging over the data points.

Table 2 lists the values of the validation metrics and Fig. 6 compares the simulated and measured \(C_p\) along lines A and B for the three approach-flow wind directions.

For \(\theta = 0^\circ\), the overall average absolute deviations (lines A and B combined) for RANS and LES are 0.113 and 0.091, respectively. A fairly good agreement can be seen between CFD and wind tunnel along line B for both RANS and LES (Fig. 6b), with the average absolute deviations of 0.026 and 0.027. For line A, these deviations increase to 0.172 and 0.133, respectively (Fig. 6a). Note that FB and NMSE cannot be used for variables that have both positive and negative values within the same set \([70, 91, 92]\), hence, they are not reported for this situation.

For \(\theta = 90^\circ\), both steady RANS and LES tend to overpredict \(C_p\) along the vertical lines but this overprediction is much more pronounced for steady RANS with an overall average absolute deviation of 0.302, while this is 0.096 for LES. The overall agreement of LES remains fairly good in terms of NMSE = 0.025 (Table 2), which is about one order of magnitude smaller than RANS.

For \(\theta = 180^\circ\), the deficiency of RANS in reproducing \(C_p\) can also be clearly observed, where the overall absolute deviation goes up to 0.161, while this is 0.038 for LES. The underprediction of the absolute value of \(C_p\) on the leeward façade by RANS is in line with the results of previous studies (e.g., Refs. [4, 93, 94]).

5. CFD simulations: comparison between RANS and LES

The results provided in Section 4 clearly show the different performance of RANS and LES in predicting the \(C_p\) at the measurement points, especially for \(\theta = 90^\circ\) and \(180^\circ\). In this section, a detailed analysis of (i) \(C_p\), (ii) mean wind speed ratio (K), and (iii) maximum mean wind speed ratio (K\text{max}) is provided to better understand the performance of the two approaches and to provide more insight into the distribution of \(C_p\), K, and K\text{max} on the balcony areas. The analysis is performed for the three approach-flow wind directions.

5.1. RANS versus LES at \(\theta = 0^\circ\)

Fig. 8a and b present \(C_p\) on the windward façade by RANS and LES, respectively. Fig. 8c shows the difference between \(C_p\) by the two approaches, i.e., \(\Delta C_p = C_p(\text{LES}) - C_p(\text{RANS})\). It can be seen that a strong suction acts on the top floor for both RANS and LES. The largest differences occur at this level where the maximum underestimation and
overestimation of the LES results by RANS occur in the middle ($\Delta C_p^{(\text{LES-RANS})} = 0.610$) and near the edges ($\Delta C_p^{(\text{LES-RANS})} = -0.461$) of the façade, respectively. For the other parts of the façade, RANS and LES perform fairly similar with local absolute $\Delta C_p^{(\text{LES-RANS})}$ lower than 0.150. For the entire windward façade, the surface-averaged $C_p$ values obtained by RANS and LES are 0.507 and 0.511, respectively ($\Delta C_p^{(\text{LES-RANS})} = 0.004$), indicating a very close agreement between the two approaches.

Fig. 9a and b display contours of the mean wind speed ratio $K$ in horizontal planes at pedestrian height (1.75 m in full scale above balcony level) for levels 2, 11, 20 and 29 predicted by RANS and LES, respectively. $K$ is defined as the local mean wind speed normalized by $U_{\text{ambient}} (= 6.347 \text{ m/s})$, which is the “undisturbed” mean wind speed at pedestrian height above ground level. Fig. 9c shows the difference $\Delta K^{(\text{LES-RANS})} = K^{(\text{LES})} - K^{(\text{RANS})}$. Both RANS and LES predict high wind-speed regions at the edges of the balconies, while low wind-speed regions can be observed in the middle of the planes (Fig. 9a and b).

Compared to LES, RANS underestimates the local $K$ for all levels (also those not shown in Fig. 9). The area-weighted average $K$ for levels 2, 11, 20 and 29 by LES are 0.959, 0.815, 0.6667 and 1.038, respectively. They are underestimated by RANS by 34.9%, 33.3%, 17.4% and 38.9%, respectively.

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Fig. 10. Distribution of mean wind speed ratio $K$ and 2D velocity vector field in the vertical centerplane near the balconies of levels 2, 11, 20, and 29 for $\theta = 0^\circ$ obtained by (a) RANS and (b) LES.

Fig. 11. Maximum mean wind speed ratio $K_{\text{max}}$ in horizontal planes at pedestrian height (1.75 m in full scale above balcony level) for levels 2, 11, 20 and 29 predicted by RANS and LES, respectively. $K$ is defined as the local mean wind speed normalized by $U_{\text{ambient}} (= 6.347 \text{ m/s})$, which is the “undisturbed” mean wind speed at pedestrian height above ground level. Fig. 9c shows the difference $\Delta K^{(\text{LES-RANS})} = K^{(\text{LES})} - K^{(\text{RANS})}$. Both RANS and LES predict high wind-speed regions at the edges of the balconies, while low wind-speed regions can be observed in the middle of the planes (Fig. 9a and b).

Compared to LES, RANS underestimates the local $K$ for all levels (also those not shown in Fig. 9). The area-weighted average $K$ for levels 2, 11, 20 and 29 by LES are 0.959, 0.815, 0.6667 and 1.038, respectively. They are underestimated by RANS by 34.9%, 33.3%, 17.4% and 38.9%, respectively.
Fig. 10 presents the K distribution and 2D velocity vector fields in the vertical centerplane near levels 2, 11, 19 and 29. Both RANS and LES predict the flow separation from the top-edge of the parapet wall of the top floor that leads to a strong suction pressure on the façade (see Fig. 8a and b). The stagnation point occurs at around level 19. For balconies on levels 28 and 29, the interaction between the airflow directed from the stagnation region upward leads to clockwise recirculation areas on the balcony spaces. These recirculation areas can also be found for all balconies above level 21 (not shown in Fig. 10). Compared to LES, RANS underestimates the mean velocity on the balcony spaces. For the stagnation region (near level 19) where the wind speed is relatively low, RANS and LES predict fairly similar results. For the levels between level 17 and level 1, the downwash flow separates at the balcony parapet walls, leading to anticlockwise recirculation areas on each balcony space. Again, compared to LES, steady RANS underestimates the mean velocity on these balcony spaces.

Fig. 11 presents $K_{\text{max}}$ taken from the horizontal planes at pedestrian height for all balconies as obtained by RANS and LES. The maximum local mean wind speed ratio ($K_{\text{max}}$) that is sometimes used to evaluate the wind environment [95, 96] is defined as $K_{\text{max}} = \frac{U_{\text{max}}}{U_{\text{ambient}}}$, where $U_{\text{max}}$ is the maximum local mean wind speed at pedestrian height on each balcony space. Note that, as shown in Fig. 9, balconies on the high-rise building are partly exposed to strong winds, which may cause wind discomfort and wind danger for people on balcony spaces. It can be seen that, compared to LES, steady RANS underestimates the mean velocity on these balcony spaces.

Fig. 14 presents the $C_p$ distribution on the façade with balconies for $\theta = 180^\circ$ obtained by (a) RANS and (b) LES, and (c) $\Delta C_p (\text{LES-RANS})$.
all levels. In this case, the average absolute difference for all balconies is 0.249, while the maximum absolute difference is 0.457, which occurs on level 28.

5.2. RANS versus LES at $\theta = 90^\circ$

Fig. 12 presents the distribution of $C_p$ across the façade at $\theta = 90^\circ$ by RANS and LES, revealing large differences between the simulation results by the two approaches. RANS clearly underestimates the absolute value of local $C_p$ across the entire façade except in a small region close to the leading edge of the top floor (Fig. 12c). The surface-averaged $C_p$ obtained by RANS and LES are $-0.369$ and $-0.578$, respectively ($\Delta C_p (\text{LES} - \text{RANS}) = -0.209$).

Fig. 13 illustrates the $K_{\text{max}}$ in the horizontal planes at pedestrian height for all balconies obtained by RANS and LES. Compared to LES, RANS predicts substantially lower $K_{\text{max}}$ for all levels. In this case, the average absolute difference for all balconies is about 0.542, while the maximum absolute difference is 0.647 that occurs on level 6.

Fig. 14 presents the $C_p$ distribution obtained by RANS and LES for $\theta = 180^\circ$. Compared to LES, RANS underpredicts the absolute value of $C_p$ across the entire façade. The maximum and minimum underprediction occur in areas close to the façade edges and in the central region of the façade, respectively (Fig. 14c). The surface-averaged $C_p$ by RANS and LES are $-0.251$ and $-0.357$, respectively ($\Delta C_p (\text{LES} - \text{RANS}) = -0.106$).

Concerning $K$ in horizontal planes at pedestrian height for levels 2, 11, 20, and 29, compared to LES, RANS mostly predicts lower local $K$ for every level. The area-weighted average $K$ of levels 2, 11, 20, and 29 by LES are 0.313, 0.388, 0.380, and 0.229, which are underestimated by RANS by 34.9%, 32.5%, 46.2% and 67.9%, respectively.

Fig. 15 provides the mean wind speed ratio ($K$) and the 2D velocity vector field in the vertical centerplane. It can be seen that RANS significantly underestimates the wind speed near level 29. This underestimation leads to the overestimation of $C_p$ in this region (see Fig. 14c). A similar underestimation of the wind speed by RANS can be seen for levels 1 and 2, which is in line with previous CFD studies of ground-level wind conditions in the wake of buildings [56,97]. A likely reason for these discrepancies is the performance of RANS in overestimating the
turbulent kinetic energy in separation and recirculation areas, which generally leads to an underestimation of the mean wind speed in these areas \cite{19,20}.

Fig. 16 shows $K_{\text{max}}$ in the horizontal planes at pedestrian height for all balconies obtained by RANS and LES. RANS provides larger $K_{\text{max}}$ for levels 2, 3 and 4 than LES, where the maximum absolute difference of 0.122 occurs on the second level. For all other levels, RANS substantially underestimates $K_{\text{max}}$, where the maximum absolute difference is 0.343 that can be observed on level 18.

6. Discussion

It is important to highlight the limitations of this study:

- In this study, the validation is performed based on mean pressure coefficients. This is due to the lack of available high-resolution experimental data of wind velocity for buildings with balconies. Further research is required to (i) perform high-resolution wind-tunnel or on-site measurements of wind speed on balcony spaces, and (ii) conduct additional detailed CFD validation studies where the focus would be on wind speed on building balconies.

- The simulations are performed for only three approaching wind directions: $\theta = 0^\circ$, $90^\circ$ and $180^\circ$. This is due to the lack of available high-quality experimental data for buildings with balconies under oblique wind directions. Further research should focus on the performance of RANS and LES for oblique wind directions.

- The focus of the present study is on the comparison between RANS and LES. As RANS can only predict the mean pressure coefficients, the validation studies are performed for mean pressure coefficients. Future work should focus on the performance of LES in predicting surface r.m.s. and peak pressure coefficients for buildings with balconies. It should be noted that there is still a lack of high-resolution experimental data of surface r.m.s. and peak pressure coefficients for buildings with balconies. Therefore, high-quality wind-tunnel measurements should also be performed in the future.

- This study only focuses on an isolated high-rise building with balconies. The presence of surrounding buildings may lead to more airflow complexity such as additional recirculation and reattachment \cite{98}, and would modify the mean and r.m.s. surface pressure \cite{45, 99-101} and wind speed on balcony spaces \cite{102}. Therefore, the conclusions in this paper should be used with caution towards buildings surrounded by other buildings. Further evaluation of the performance of RANS and LES should be performed by considering the impact of building surroundings.

7. Conclusions

This paper evaluates the performance of steady RANS and LES in predicting the near-façade airflow patterns and mean surface pressure coefficient ($C_p$) for a building with balconies. Three wind directions are considered: $\theta = 0^\circ$, $90^\circ$, and $180^\circ$.

The evaluation is based on validation with wind-tunnel measurements of mean surface pressure on the façade with balconies. The results of the CFD validation show that LES can accurately predict $C_p$ on the building façade with balconies for $\theta = 0^\circ$, $90^\circ$, and $180^\circ$ with average absolute deviations of 0.091, 0.096 and 0.038, respectively. RANS predicts a satisfactory agreement with the experiments only for $\theta = 0^\circ$, with an average absolute deviation of 0.113. For $\theta = 90^\circ$ and $\theta = 180^\circ$, however, RANS substantially underestimates the absolute value of the $C_p$ with average absolute deviations of 0.302 and 0.161, respectively. Further detailed analysis is performed based on the RANS and LES results, and the following conclusions are obtained:

- For $\theta = 0^\circ$, RANS and LES generally predict similar local $C_p$ except at the top floor. The surface-averaged $C_p$ obtained by RANS and LES are 0.507 and 0.511, respectively. Compared to LES, RANS generally underestimates the absolute value of local $C_p$ on the façade at $\theta = 90^\circ$ and $\theta = 180^\circ$. The surface-averaged $C_p$ obtained by RANS and LES for $\theta = 90^\circ$ are $-0.369$ and $-0.578$, respectively, and for $\theta = 180^\circ$ they are $-0.251$ and $-0.357$, respectively.

- Compared to LES, RANS generally underestimates the mean wind speed ratio $K$ in horizontal planes at pedestrian height on all levels for $\theta = 0^\circ$ and $\theta = 180^\circ$. For example, the area-weighted average $K$ at levels 2, 11, 20 and 29 for $\theta = 0^\circ$ is underestimated by 34.9%, 33.3%, 17.4% and 38.9%, respectively, and for $\theta = 180^\circ$ it is underestimated by 34.9%, 32.5%, 46.2% and 69.9%, respectively. For $\theta = 90^\circ$, compared to LES, RANS overestimates $K$ in some regions, while providing underestimations in others.

- Compared to LES, RANS underestimates $K_{\text{max}}$ on all levels for $\theta = 0^\circ$ and $90^\circ$. For $\theta = 180^\circ$, RANS predicts larger $K_{\text{max}}$ for levels 2, 3 and 4, and smaller $K_{\text{max}}$ for the other levels.

These results suggest that for studies of natural ventilation of buildings and wind comfort on building balconies, for which distributions of building façade $C_p$ are required, using RANS instead of LES can result in underestimated computed ventilation airflow rates and in underestimated computed wind speed ratios. In other words, building design based on RANS might result in too high actual ventilation flow rates and in too high actual wind speed, resulting in too high wind nuisance level.

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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