

CFD analysis of wind comfort on high-rise building balconies: validation and application

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ABSTRACT: High-rise buildings can cause wind discomfort on the building balconies, necessitating remedial action. In this paper, a new facade concept is evaluated that is intended to significantly improve wind comfort on the balconies of a 78 m high-rise building. The concept consists of a staggered semi-open second-skin facade that partly shields the balconies from the wind. Evaluation of the concept is performed by steady Reynolds-Averaged Navier-Stokes (RANS) CFD simulations with the realizable k- ϵ turbulence model in combination with the Dutch wind nuisance standard. First, some results of a CFD validation study for buildings with balconies are briefly presented. Next, similar simulations are used to evaluate the new facade concept by comparing the wind comfort at the balconies with and without application of this concept. It is shown that the new facade concept is quite effective in improving wind comfort at the balconies.

KEYWORDS: Pedestrian wind environment, wind conditions, Computational Fluid Dynamics (CFD), building balconies

1. INTRODUCTION

High-rise buildings can cause high wind speed near ground level and on building balconies, necessitating remedial action. In order to reduce wind discomfort on balconies, different measures can be taken; such as closing the balcony, adding partition walls, etc. Recently a new facade concept was developed by ELD Partnership (ELD 2011). It consists of a staggered semi-open second-skin facade that partly shields the balconies from the wind. It is intended to significantly improve wind comfort on the building balconies. In this paper, the performance of this concept is evaluated by validated CFD simulations and by application of the Dutch wind nuisance standard for a case study with and without application of this new concept.

In the past, several CFD studies have been performed to investigate pedestrian-level wind conditions in complex urban environments (e.g. Stathopoulos and Baskaran 1996, Yoshie et al. 2007, Blocken et al. 2012). The use of CFD for complete wind comfort studies however is still relatively scarce, and this especially holds for studies of wind comfort at building balconies. Indeed, most of the previous CFD studies focused on wind comfort at pedestrian level around buildings. To the best of our knowledge, no CFD study has yet been published with focus on wind comfort on building balconies.

This paper presents the evaluation of the new second-skin facade concept by ELD Partnership to improve wind comfort at building balconies. First, some results of a CFD validation study for buildings with balconies are briefly presented. Next, the new concept is evaluated for the case of

a high-rise (78 m) building in the city of Antwerp. CFD simulations are performed for the building with and without second-skin facade concept implemented. The CFD simulations are performed with the 3D steady Reynolds-Averaged Navier-Stokes (RANS) approach and the realizable k- ϵ model (Shih et al. 1995). The obtained CFD results are combined with wind speed statistics and a comfort criterion to judge wind comfort on the balconies, according to the Dutch wind nuisance standard.

2. DESCRIPTION OF BUILDING AND URBAN AREA

The new high-rise building of the so-called EPA project is located in the northern part of the city of Antwerp, Belgium. It is north-south oriented and surrounded by other high-rise and low-rise buildings (Fig. 1a). It has dimensions $L \times B \times H = 21.8 \times 50.8 \times 78.2 \text{ m}^3$. The depth of the balconies on the north, east, south and west side of the tower is 1.32 m, 1.3 m, 1.59 m and 1.56 m, respectively. The facade concept is a second-skin concept, with a first and inner skin that acts as traditional facade and a second outer skin that acts as a wind shield for the balconies. The second skin consists of a staggered semi-open glass facade, as indicated in Figure 1b. It has a permanent solid glass balustrade of 1.2 m high, while above this 1.2 m, solid glass facade panels are applied in a staggered configuration. For the comparison study, a reference high-rise building with only the 1.2 m high balustrade will be considered.

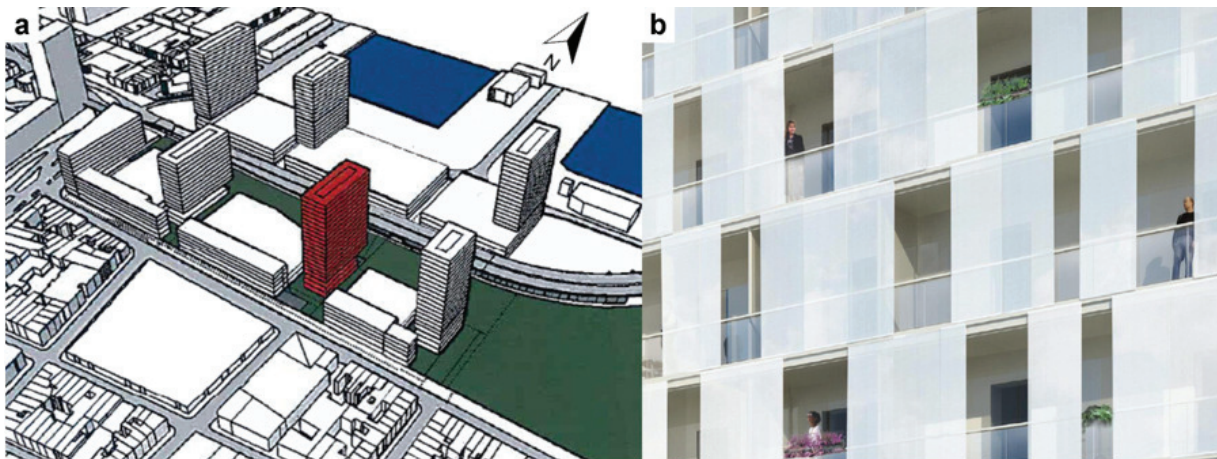


Figure 1. (a) High-rise building under study (red) and nearby urban surroundings. (b) Building facade with second-skin staggered facade concept.

3. CFD VALIDATION

CFD simulations based on the 3D RANS equations in combination with a turbulence model require validation. Validation can be performed by comparison of the CFD results with either full-scale measurements or wind tunnel data. Experimental data of wind conditions for buildings with balconies are very scarce. In this paper, a unique set of wind tunnel measurements of surface pressures on the facade of a building with balconies is used for validation purposes.

3.1. Wind tunnel measurements

Atmospheric boundary layer wind tunnel measurements of wind-induced surface pressure on the facade of a reduced-scale model (1:30) of a medium-rise building were conducted by Chand et al (1998). The incident vertical profile of mean wind speed (i.e. at the location of the test model) can be described by a logarithmic law with aerodynamic roughness length $z_0 = 0.008$ m and friction velocity $u^* = 0.72$ m/s. Longitudinal turbulence intensity ranged from 13% near ground level to about 3% at gradient height. The building had dimensions $w_m \times d_m \times h_m = 0.25 \times 0.60 \times 0.50$ m³ (reduced scale, see Fig. 2a) corresponding to full-scale dimensions $W_m \times D_m \times H_m = 7.5 \times 18 \times 15$ m³. To evaluate the effect of building balconies on mean pressure, the measurements were carried out for an isolated building with and without balconies. Three balconies each with length 0.15 m, width 0.05 m and height 0.03 m were positioned at each floor (Fig. 2a). Surface pressures were measured along three vertical lines on the windward and leeward facade. Each line was in the middle of the balconies and 45 pressure taps were implemented along these lines. Pressure coefficients were related to the incident wind speed at building height (7.1 m/s).

3.2. Comparison of CFD results and wind tunnel measurements

The wind tunnel experiments are reproduced by solving the 3D steady RANS CFD simulations combined with the realizable $k-\epsilon$ model (Shih et al. 1995) and following the best practice guidelines by Franke et al. (2007) and Tominaga et al. (2008a). The computational grid was fully structured and was created using the surface grid extrusion technique presented by van Hooff and Blocken (2010). Figure 2b compares the numerically simulated and measured pressure coefficients at the windward facade of the building with balconies for wind direction 0°. It should be noted that in this validation study, only results for the windward facades are considered. It is important to note that steady RANS CFD is deficient in reproducing the wind flow pattern downstream of windward facades (Murakami 1993, Tominaga et al. 2008b). Nevertheless, this approach is used in this paper, because the accuracy of the wind-flow pattern at side and the leeward facades is less important in wind comfort studies. The reason is that wind comfort studies typically focus on high wind speed positions, i.e. where a certain threshold wind speed is exceeded. Other positions do not contribute to the exceedance probabilities. Figure 2b shows that for the windward facades, the trends are well predicted by the CFD simulations. For the building without balconies, the deviations between the experimental and CFD results are generally less than 10%, while for the building with balconies, they are generally less than 20%.

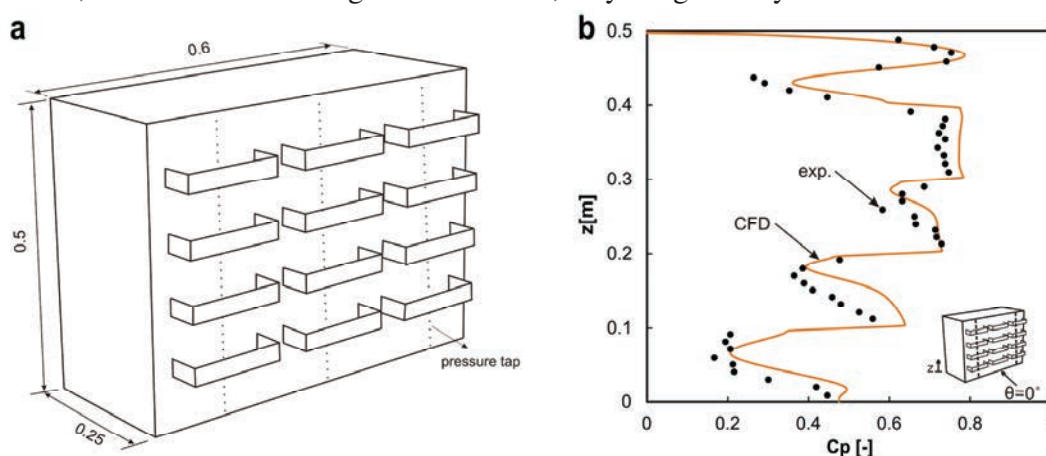


Figure 2. (a) Wind tunnel model of building with balconies and three vertical lines for pressure measurements (reduced-scale dimensions in m); (b) Comparison of wind tunnel and CFD results: pressure coefficient C_p along vertical line near building edge.

4. CASE STUDY: COMPUTATIONAL MODEL AND COMPUTATIONAL PARAMETERS

4.1. Computational geometry and grid

A computational model has been made of the tower and its urban surroundings, which are placed in a computational domain with dimensions of $2080 \times 1770 \times 400 \text{ m}^3$. The explicitly modeled buildings are the tower itself and the surrounding buildings in a radius of 350 m around the tower. Because of the existing densely built area to the east side of the tower, the buildings placed at that part within a distance of 670 m from the tower are also modeled. The tower is modeled in detail, including staggered facade elements, while the surrounding buildings are included only with their main shape. Special attention was given to the generation of a high-quality and high-resolution grid. The grid was constructed using the surface grid extrusion technique presented by van Hooff and Blocken (2010), which allows a large degree of control over the quality of the grid and its individual cells. It consists of only hexahedral and prismatic cells and does not contain any tetrahedral or pyramid cells. In addition, the grid was constructed following the best practice guidelines by Franke et al. (2007) and Tominaga et al. (2008a). The two grids for building with application of the second-skin facade and the reference building consist of 16,292,495 cells and 15,536,529 cells, respectively (Fig. 3).

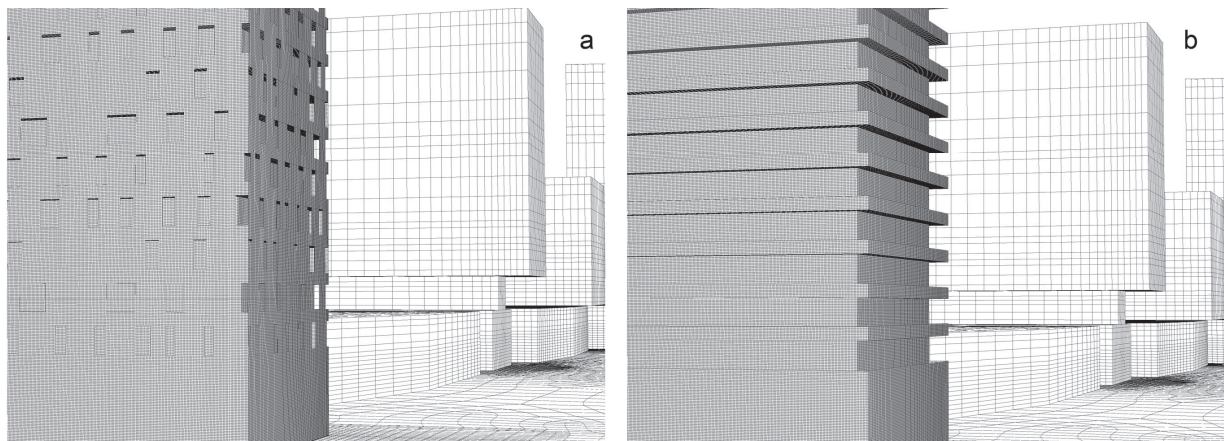


Figure 3. View from north-east at high-resolution computational grid on surfaces of high-rise building tower and surrounding buildings for (a) building with second-skin facade concept (16,292,495) and (b) reference building (15,536,529).

4.2. Boundary conditions

At the inlet of the domain, neutral atmospheric boundary layer inflow profiles of mean wind speed, turbulent kinetic energy and turbulence dissipation rate are imposed. These profiles are based on the aerodynamic roughness length z_0 of the upstream terrain that is not included in the computational domain. At the outlet, zero static pressure is specified. At the sides and the top of the domain, symmetry boundary conditions are imposed (i.e. zero normal velocity and gradients). At the ground surface, the standard wall functions by Launder and Spalding (1974) with the sand-grain roughness modification by Cebeci and Bradshaw (1977). The equivalent sand-grain roughness height k_s and roughness constant C_s are determined based on their relationship with z_0 according to Blocken et al. (2007). At the building surfaces, also standard wall functions are used, with the assumption of smooth walls ($k_s = 0 \text{ m}$).

4.3. Solver settings

The CFD simulations are performed using the commercial CFD code Fluent 6.3.26. The 3D steady RANS equations are solved with the realizable k - ϵ turbulence model (Shih et al. 1995). The choice for this turbulence model is based on the recommendations by Franke et al. (2007) and on earlier successful validation studies for pedestrian-level wind conditions with this turbulence model (Blocken and Persoon 2009, Blocken et al. 2012). Pressure velocity-coupling is taken care of by the SIMPLE algorithm. Pressure interpolation is second order. Second-order discretisation schemes are used for both the convection terms and viscous terms of the governing equations. The simulations are performed for the 12 wind directions $\theta = 0$ - 330° in 30° intervals.

5. CASE STUDY: CFD SIMULATION RESULTS

Figure 4 shows the local amplification factor U/U_{ref} in a horizontal plane at a height of 1.7 m at the 15th floor of the tower for the two situations and for southwest wind direction. The local amplification factor is defined as the ratio of the local mean wind speed U to the reference wind speed U_{ref} at the same height but in undisturbed (free-stream) conditions. It can be seen that the new concept provides a significantly reduced amplification factor on the balconies two at the windward facades. At the west facade, the amplification factor reduces from a value of about 1.0 to a value of about 0.6.

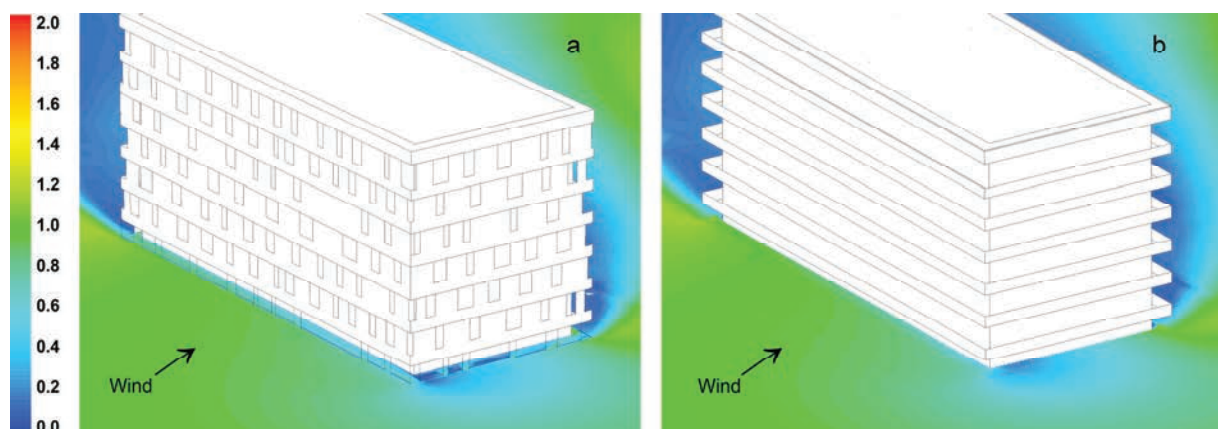


Figure 4. Contours of amplification factor for wind direction 210° in a horizontal plane at a height of 1.7 m above 15th floor for: (a) the building with application of the second-skin facade concept. (b) The reference building.

6. CASE STUDY: WIND COMFORT ASSESSMENT RESULTS

The wind speed amplification factors are used in combination with the Dutch wind nuisance standard for the assessment of wind comfort. For brevity, only some main items of this standard are given here, more details can be found in Willemsen and Wisse (2002, 2007), NEN (2006a, 2006b). The threshold wind speed in the standard is 5 m/s for all activities, while the maximum allowed exceedance probabilities of this threshold vary based on the activity, see Table 1.

Table 1: Criteria for wind nuisance according to NEN 8100 (2006a)

P($U_{THR} > 5$ m/s (in % hours per year))	Grade	Activity		
		Traversing	Strolling	Sitting
< 2.5	A	Good	Good	Good
2.5 – 5.0	B	Good	Good	Moderate
5.0 – 10	C	Good	Moderate	Poor
10 – 20	D	Moderate	Poor	Poor
> 20	E	Poor	Poor	Poor

For the wind comfort analysis, the wind statistics of the nearby city of Eindhoven are used. Figure 5 illustrates the exceedance probability of the 5 m/s threshold on the 15th floor. Because southwest is the prevailing wind direction, the pattern of exceedance probabilities resembles that of the wind speed amplification factor for southwest wind direction (see Fig. 4). Figure 5 clearly shows that the second-skin facade concept improves wind comfort for a large part of the west facade and also for part of the south facade.

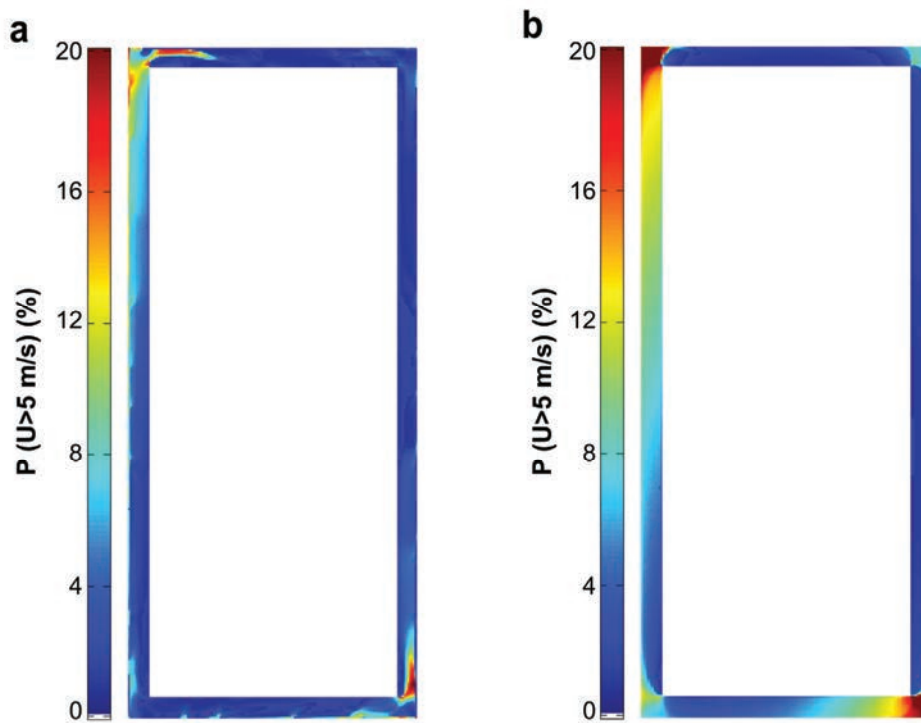


Figure 5. Contours of exceedance probability in a horizontal plane at a height of 1.7 m above 15th floor for: (a) the building with application of the second-skin facade concept. (b) The reference building.

7. DISCUSSION

Some important limitations of this study are mentioned.

- The 3D steady RANS equations have been solved with the realizable k- ϵ model. It is important to note that steady RANS CFD is generally deficient in reproducing the wind-flow pattern downstream of windward facades (Murakami 1993, Tominaga et al. 2008b).

Nevertheless, this approach is used in this paper, because the accuracy of the wind-flow pattern at side and the leeward facades is less important in wind comfort studies. The reason is that wind comfort studies typically focus on high wind speed positions, i.e. where a certain threshold wind speed is (5 m/s in the present study) is exceeded. Other positions do not contribute significantly or do not contribute at all to the exceedance probabilities.

- No grid-sensitivity analysis was performed. However, the computational grid has been made based on the best practice guidelines by Franke et al. (2007) and Tominaga et al. (2008a) and the grid resolution has been taken either similar or higher than in previous studies for which grid-sensitivity analyses were performed (van Hooff and Blocken 2010, Blocken et al. 2012)..

8. CONCLUSIONS

3D steady RANS CFD simulations have been used in combination with the new Dutch wind nuisance standard to evaluate the performance of a new facade concept. This concept consists of a staggered semi-open second-skin facade that partly shields the balconies from the wind. To achieve this particular purpose, the wind comfort at the balconies with and without application of this concept has been compared. It is shown that the new facade concept is very effective in shielding the balconies and improving the wind comfort.

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