THE IMPACT OF DOUBLE-SKIN FACADE CONFIGURATIONS ON WIND-DRIVEN VENTILATION IN TALL OFFICE BUILDINGS

Author

Yohan Kim
Illinois Institute of Technology

Keywords

Double-skin facade, wind-driven ventilation, CFD simulation, tall office building, parametric study

Abstract

Natural ventilation has proven to be an effective passive strategy in improving energy efficiency while providing healthy environments. However, such a strategy has not been commonly adopted in tall office buildings due to the high wind pressure that causes excessive air velocities and occupant discomfort at upper floors. Double-skin facades (DSFs) can provide an opportunity to facilitate natural ventilation in tall office buildings, as they can regulate the direct impact of wind pressure, creating a buffer. This study investigates the impact of DSF configurations on wind-driven ventilation at upper floors of tall office buildings. Computational fluid dynamics (CFD) analysis was performed to simulate indoor airflow at the top 10 floors of a 40-story tall office building under isothermal conditions and assess the performance of 16 DSF configurations with respect to opening size, the number of outer skin openings per floor, cavity depth, and cavity segmentation. The results indicate that the size of outer skin openings is the most influential parameter on indoor airflow, while the cavity depth and segmentation do not significantly affect it. However, the size of inner skin openings and the number of outer skin openings are more important factors in enhancing airflow distribution and regulating the concentration of high air velocity near the windows. This study aims to develop a performance-based DSF design guideline through CFD simulations of indoor airflow behavior in tall office buildings with DSFs.

Introduction

Many tall office buildings (i.e., buildings of 150 m [492 ft] or taller) are on the rise around the world. As interpreted from the database of the U.S. Department of Energy in Wood and Salib (2013), the Heating, Ventilation, and Air Conditioning (HVAC) systems in typical tall office buildings built after 1980 in 16 U.S. cities are responsible for 33% or more of overall building energy consumption. Due to the use of new types of electronic equipment and existing technologies such as computers, office equipment, etc., the total amount of electricity consumed in commercial buildings has been increasing over the years (U.S. Energy Information Administration, 2012). In addition to energy consumption, the sealed tall office buildings relying on mechanical ventilation can cause Sick Building Syndrome (SBS) which consists of various nonspecific symptoms. According to some studies, there is a relationship between SBS symptoms occupants experience and insufficient ventilation in buildings. Moreover, insufficient ventilation can cause occupant health problems and the decrease in occupant productivity (Sundell et al., 2011; Fisk et al., 2012). Therefore, the energy-efficiency and healthy environment of tall office buildings has become an important concern, given the current environmental challenges and health considerations.

Natural ventilation has proven to be one of the effective strategies to reduce the load on HVAC systems and enhance the work environment in buildings. However, such a strategy has not been commonly adopted in tall office buildings due to the high wind pressure that is particularly experienced at the upper floors. The additional skin of DSFs can reduce the wind pressure on the facades of tall office buildings to allow the windows on the inner skin to open. However, more importantly, the wind pressure should be regulated by the variations of openings and cavities as it is an important driving force of natural ventilation. There are plenty of studies (e.g., Radhi et al., 2013; Sanchez et al., 2016; Larsen et al., 2015) that investigated stack effect caused by temperature differences between outdoors and the cavities of DSFs. On the other hand, only a few studies (e.g., Nasrollahi & Salehi, 2015) focused on wind-driven ventilation and the impact of design components, such as openings, cavities, and chimneys, on the indoor airflow behavior in the buildings with DSFs. The wind speed affects the mass flow inside the cavity of DSFs as much as the temperature difference based on the long-term measurement in some low and mid-rise office buildings with DSFs (Pasquay, 2004). Because tall buildings dynamically respond to winds with respect to high wind pressure and turbulent characteristics around the buildings, wind effect can be more dominant than stack effect within the DSFs designed for tall buildings. However, the design aspects of DSFs in naturally ventilated tall office buildings to account for wind-driven ventilation have not been extensively studied despite the importance of wind effect.

This parametric study investigates the impact of DSF configurations, including opening size, number of outer skin openings per floor, cavity depth, and cavity segmentation, on indoor airflow at upper floors of a tall office building with DSFs under isothermal conditions. Besides, the research develops a performance-based DSF design guideline which addresses the proper design of DSF components for tall office buildings.

Methodology

ANSYS Fluent® (CFD simulation software) was used to analyze airflow behavior at the top 10 floors of a hypothetical 158-meter, 40-story tall office building with DSFs as CFD can make comprehensive predictions and provide detailed information on airflow distributions, such as air velocity and airflow pattern. As shown in the workflow (Figure 1), the CFD simulation consists of four steps, such as 'opening size simulation,' 'cavity depth simulation,' 'number of openings simulation,' and 'cavity segmentation simulation.' All the steps interact with each other as the tested configurations in each step are selected based on the results from the previous step. The performance (e.g., air velocity and indoor airflow pattern) of the DSF configurations in each step was assessed based on the average subjective reactions to various velocities suggested by Auliciems and Szokolay (1997) as all the simulations were performed under isothermal conditions (Table 1).

Air Velocity	Average Reactions
< 0.25 m/s	Unnoticed
0.25–0.5 m/s	Pleasant
0.5–1.0 m/s	Awareness of Air Movement
1.0–1.5 m/s	Drafty
> 1.5 m/s	Annoyingly Drafty

Table 1: Average subjective reactions to various velocities. (Source: Auliciems & Szokolay, 1997.)

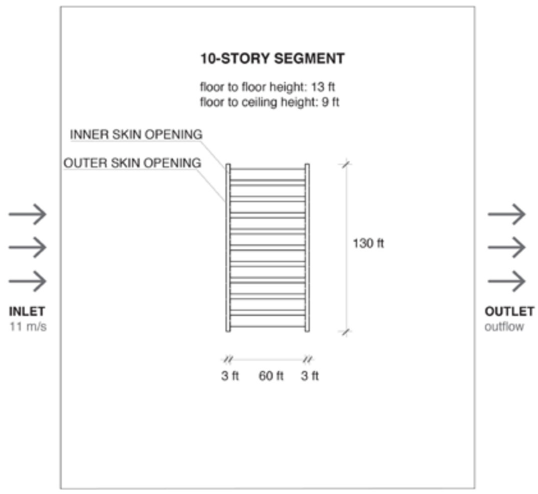

Figure 2: A 2D CFD model of the top 10 floors with the external environment. (Source: Author.)

Because cavity segmentation varies only in the last step, a 2D CFD model of the top 10 floors with the external environment was used for the first three steps (Figure 2). Also, the 2D CFD model was modified for each simulation to examine the variations of other design parameters, except for cavity segmentation. The open office layout was chosen for the indoor spaces on the 10 floors. The multi-story facade was selected for this study among four types of DSFs that Oesterle et al. (2001) classified, including box window facade, shaft-box facade, and corridor facade. Moreover, a modified multi-story DSF with multiple openings was created to analyze only wind effect as the typical multi-story DSF is the most appropriate type for stack effect due to the vertically continuous cavity with only two openings at the top and the bottom. Assuming the difference in wind speed

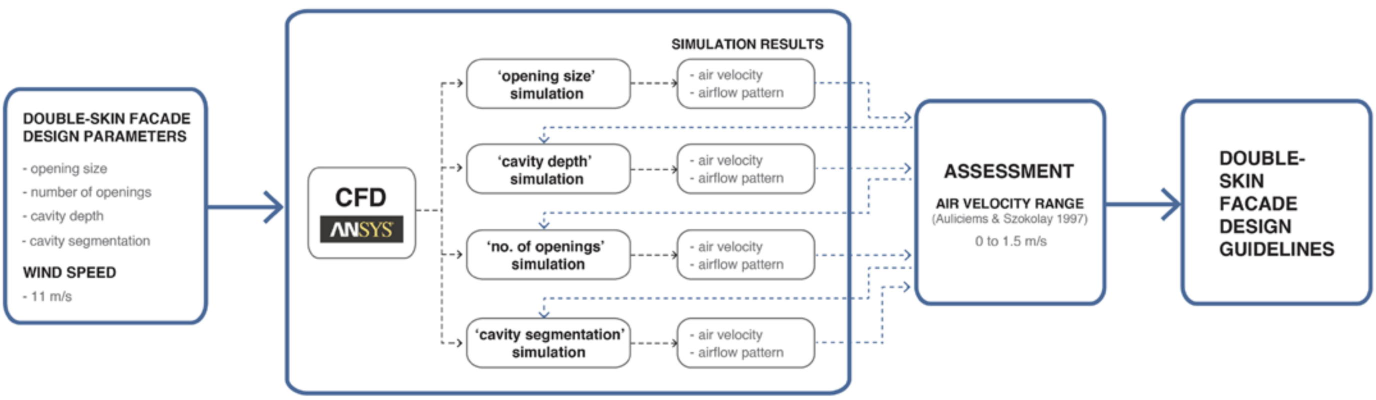

Figure 1: Workflow. (Source: Author.)

		Outer skin height - % of floor-floor ht	Inner skin height - % of floor-ceiling ht	Number of outer skin openings per floor	Cavity depth (ft)	Cavity segmentation	Wind speed (m/s)
'Opening size' simulation	A1	2 % (3.12 in)	10 % (10.8 in)	1	3.0	10-story	11.0
	A2		20 % (21.6 in)	1	3.0	10-story	11.0
	A3		30 % (32.4 in)	1	3.0	10-story	11.0
	A4	5 % (7.8 in)	10 % (10.8 in)	1	3.0	10-story	11.0
	A5		20 % (21.6 in)	1	3.0	10-story	11.0
	A6		30 % (32.4 in)	1	3.0	10-story	11.0
	A7	10 % (15.6 in)	10 % (10.8 in)	1	3.0	10-story	11.0
	A8		20 % (21.6 in)	1	3.0	10-story	11.0
	A9		30 % (32.4 in)	1	3.0	10-story	11.0
'Cavity depth' simulation	B1	2 % (3.12 in)	10 % (10.8 in)	1	1.0	10-story	11.0
	B2			1	5.0	10-story	11.0
'No. of openings' simulation	C1	2 % (3.12 in)	10 % (10.8 in)	0.5	3.0	10-story	11.0
	C2			0.33	3.0	10-story	11.0
'Cavity segmentation' simulation	D1	2 % (3.12 in)	10 % (10.8 in)	0.5	3.0	5-story	11.0
	D2			0.5	3.0	15-story	11.0
	D3			0.5	3.0	20-story	11.0

Table 2: Design parameters and variables. (Source: Author.)

between the 10 floors is insignificant and the wind speed is 4.5 m/s at a reference height of 10 m (33 ft), the wind speed at the top of the building was set at 11 m/s calculated from the logarithmic wind profile equation. These sequential CFD simulations and the 2D CFD models help to reduce the number of configurations to be tested and the computational time, respectively. Table 2 shows the design parameters and the variables defined for the overall CFD simulation process. From B1 to D3, the range of variables was determined by the results of the 'opening size' simulation.

Results

As seen in Figure 3, the air velocity in the indoor spaces near the inner skin openings (windows) on the windward side (left) increases with the size of inner skin openings (A1–A3). The impact of the outer opening size on the air velocity is more significant than the inner skin opening size on the windward side (A1, A4, and A7). In addition, the increase in the outer opening size exacerbates airflow imbalances in the indoor spaces from the windward side (left) to the leeward side (right). The larger outer skin openings (A4 and A7) seem to increase the area of high velocity zones than A1, but on the leeward side, A1 shows the higher air velocities. Thus, the results indicate that the size of outer skin openings highly affects the air velocity on the windward side and the indoor airflow pattern compared to that of inner skin openings. A5, A6, A8, and A9 are not included in Figure 3 as A1–A3 with the smallest outer skin opening already perform better than others, with respect to the air velocity range at 0–1.5 m/s.

Due to the better airflow distribution than other configurations, A1 was selected as a base model for the next CFD simulation to examine the variations of cavity depth and the number of outer skin openings per floor. However, the performance of A1 still needs to be improved as the air velocity exceeds 1.5 m/s (i.e., annoyingly drafty) at 1.8 m (6 ft) (i.e., occupied zones) mostly near the windows. Figure 4 demonstrates the results of 'cavity depth' and 'number of outer skin openings' simulations. The results show that cavity depth is unlikely to be an important factor in enhancing the airflow distribution as the wide cavity depth (B2) marginally affected the indoor airflow. Also, the narrow one (B1) slightly increases the air velocity near the windows on both sides and causes airflow imbalances at some floors. There is no meaningful difference between A1, C1, and C2, with respect to the number of outer skin openings per floor.

Compared to A1, the air velocity near the windows on the windward side decreases in the cases of C1 and C2 even though the air velocity is somewhat higher at some floors on the leeward side. Furthermore, more spaces in C1 meet the criteria like 'pleasant reaction' (0.25–0.5 m/s) (Table 1). The results indicate that reducing the number of outer skin openings per floor is helpful to improve the indoor airflow and that C1 seems to be better than C2 due to the more consistent airflow pattern. For the next CFD simulation, C1 was selected to compare four configurations with respect to the influence of cavity segmentation on the indoor airflow.

Figure 5 illustrates the indoor airflow pattern and the air velocity contour in the four cases. The air velocity near the windows and the indoor airflow pattern does not constantly change with the increase in the size of continuous cavities. For instance, the similar airflow pattern on the windward side is observed in both cases of the largest and the smallest cavities. Therefore, the results show that there would be no clear relationship between cavity segmentation and the indoor airflow. Among the four cases, the indoor airflow in the case of D2 (15-story segment) would be more desired than the others as the air velocities in the indoor spaces mostly lie within the range at 0.25–0.5 m/s (Table 1).

Conclusion and Discussion

The size of outer skin openings is the most influential parameter on the indoor airflow at upper floors of the 40-story tall office building. Furthermore, there is a clear relationship between the increase in the size of outer skin openings and the concentration of high air velocity on the windward side. However, adjusting the size of inner skin

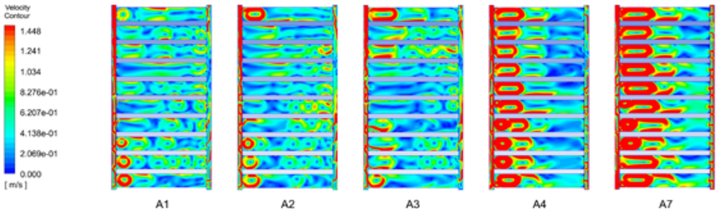

Figure 3: CFD simulation results – 'opening size.' (Source: Author.)

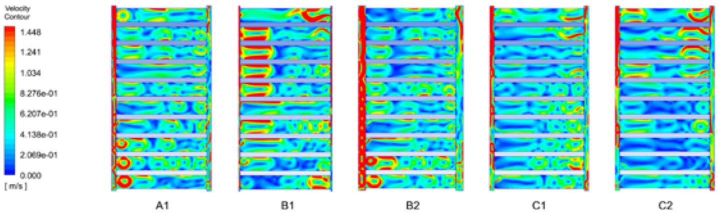

Figure 4: CFD simulation results – 'cavity depth' and 'number of outer skin openings.' (Source: Author.)

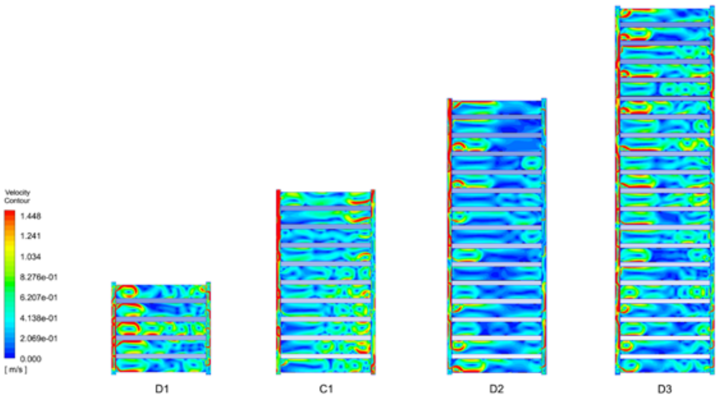

Figure 5: CFD simulation results – 'cavity segmentation.' (Source: Author.)

openings and the number of outer skin openings per floor is more helpful to improve airflow distribution and simultaneously reduce the concentration of high air velocity near the windows. The cavity depth and segmentation do not significantly affect indoor airflow under isothermal conditions despite the impact on air velocity near the windows on the windward side in some cases. Although this paper investigates the indoor airflow behavior only between the windward and leeward sides, using 2D CFD models, the proper DSF configurations discussed in this study lead to a better understanding of how DSF components regulate high wind pressure.

Based on the results, the conclusions address several important issues in DSFs, wind-driven ventilation, and tall office buildings: (1) the potential effects of each DSF component on indoor airflow at upper floors of tall office buildings, (2) the benefits of DSF applications to regulate high wind pressure and improve indoor airflow, and (3) the method for predicting the performance of DSFs in the early design stage.

The next step of this study is to conduct 3D CFD simulations to analyze not only indoor airflow, but also the airflow around the tall office building in the external environment. 3D CFD models will demonstrate the dynamic air movement between the windward and the side facades, as well as the windward and the leeward facades. More accurate wind pressure at various heights can be obtained from the simulation of airflow in the external environment, in which the logarithmic wind profile is used to specify the boundary conditions.

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