THE BENEFITS OF DOUBLE–SKIN FACADES TO FACILITATE NATURAL VENTILATION IN TALL OFFICE BUILDINGS

Abstract

Tall buildings (i.e., buildings of, or taller than, 200 m [656 ft]) are on a rise worldwide and their energy efficiency and healthy environment has become an important concern, given the current environmental challenges and health considerations. Natural ventilation has proven to be an effective passive strategy in saving energy and improving the working environment in many types of buildings. However, it is still a challenge to apply the strategy in tall office buildings due to the unique unfavorable outdoor conditions, such as strong winds, that are experienced at upper levels. Double-skin facade (DSF) systems can provide an opportunity to apply natural ventilation strategy to tall office buildings, as they can regulate the wind speed and pressure through the openings. This study will investigate the benefits of DSFs to improve indoor airflow and facilitate natural ventilation in tall office buildings in two cities, Chicago and Shanghai, with different climatic conditions. In order to maximize the accuracy of the results as well as evaluate natural ventilation performance of tall office buildings with DSFs, computational fluid dynamics (CFD) simulation and wind tunnel tests will be conducted. The proper DSF configurations with quantified natural ventilation performance will lead to better understanding of how DSFs should be designed for tall office buildings under different climatic conditions in which DSFs have not been commonly applied. The qualified conditions of indoor spaces can make a natural ventilation strategy with DSFs more feasible for tall office buildings which still highly rely on mechanical systems.

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Keywords

Double-skin facade, natural ventilation, CFD simulation, tall office building

Introduction

To date, 1,521 tall buildings (taller than 200 m [656 ft]) have been erected worldwide; a 148% increase since 2010 (CTBUH, 2019). The United Nations predicts nearly two-thirds of the world's population will live in urban areas by 2050 (The United Nations, 2018). In order to accommodate this rapidly increasing population in high-density cities, more tall buildings will be developed. Therefore, their energy efficiency and healthy environment has become an important concern, given the current environmental challenges and health considerations. Double-skin facade (DSF) systems with a natural ventilation strategy have been applied in many types of buildings as they can regulate the wind speed and pressure through the openings. However, it is still a challenge to apply the strategy to tall office buildings due to the strong winds and their fluctuations that are possibly experienced at upper floors and the wide lease span determined by economic, floor planning, and structural aspects. Many studies have already proven that natural ventilation is highly correlated with occupant health and productivity (Sundell et al., 2011; Fisk et al., 2012).

In spite of the advantages of DSFs and natural ventilation, there are only few naturally ventilated tall office buildings with DSFs that are built and studied in practice and research, respectively. Most studies on DSFs have investigated the energy performance of low or mid-rise buildings, or naturally ventilated air cavities without the air movement between the cavities and the adjacent indoor spaces (ArchDaily; BestFacade; Japan Sustainable Building Database; Lee et al., 2002; Oesterle et al., 2001; Poirazis, 2004). The stack effect, rather than the wind effect, as a driving force in the cavity, was usually dealt with by the studies. Even if the wind effect was considered in some studies, they concluded that the wind can help remove the heat from the cavity and thus, reduce overheating risks while not considering the wind as a driving force for ventilating indoor spaces. Pasquay (2004) stated that the impact of the pressure difference (i.e., wind effect) is likely to be an important factor for natural ventilation as much as the temperature difference (i.e., stack effect) based on the extensive field measurements in office buildings with DSFs (Pasquay, 2004).

As mentioned above, both wind and stack effects are helpful for the airflow behavior in the cavity in terms of reducing overheating risks and enhancing the vertical force respectively. However, in the case of tall office buildings, the facade design for natural ventilation is a challenge due to the potential magnitudes of driving forces created by wind and stack effects, and also their variations over a wide range in tall buildings (Etheridge & Ford, 2008). Thus, DSF components should be carefully designed to avoid possible discomfort at upper floors of tall office buildings with respect to overheating and high wind pressure. Depending on the DSF configuration, the proportion between stack effect and wind effect as a driving force for natural ventilation may be different specifically in the cavity due to the height of tall office buildings.

The current research and practice faces several barriers: (1) lack of information on design aspects of tall office buildings with DSFs to account for airflow behavior, including wind and stack effects, (2) lack of understanding of specific climates in which relatively many tall buildings are located, but only few DSFs are applied, (3) limitations in inputs to conduct simulations and experiments for naturally ventilated tall office buildings with DSFs, and (4) the difficulty of assessing natural ventilation performance in early design stage.

Objectives

This study will investigate the benefits of DSFs to enhance indoor airflow and facilitate natural ventilation in tall office buildings in Chicago and Shanghai. The building stock in these cities entails tall office buildings with only few DSFs. Specifically, this project will: (1) use an integrated framework to quantify and assess the natural ventilation performance of a tall office building with a DSF configuration, as climatic and design parameters vary, (2) assess parametric design configurations, including building and cavity segment, opening size and location, and cavity depth, based on desirable indoor operative temperature, indoor air speed, airflow rate, and air change rate under specific climatic conditions in the two different cities, (3) identify the parameters which affect the indoor airflow behavior in both the cavity and the indoor spaces more than other parameters, and (4) develop a DSF design assessment method for architects to conveniently qualify the designed indoor spaces affected by the variations of several specific elements of tall office buildings with DSFs with respect to natural ventilation performance and thermal comfort.

Methodology

As it is shown in Figure 1, the workflow consists of several steps with respect to the CFD simulation, the wind tunnel test, and the assessment process. CFD (ANSYS Fluent) is the main tool to simulate the configurations under specific climatic conditions including temperature gradient and wind gradient. Wind tunnel tests will be conducted to validate the CFD simulation results. An important benefit the coupling of CFD and experiments has is that once validated, CFD can analyze detailed airflow information on the entire space compared to experiments which provide the data for only some points in the space (Omrani et al., 2017). Due to the time-consuming nature affected by the size of the computational domain and the 3D model (a tall office building with DSFs), the CFD simulation is divided into two parts such as the whole-building simulation and the typical floor simulation.

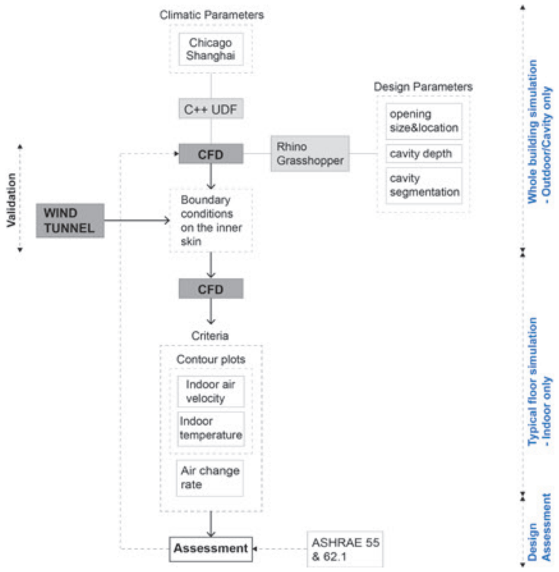

Figure 1: The overall workflow–CFD simulation and wind tunnel test.

Chicago and Shanghai were selected for this study to increase the applicability of this research as they have more tall buildings than other cities worldwide according to the Database of the CTBUH (CTBUH, 2019). Since the climate of Chicago and Shanghai are classified as Cool-Humid (Zone 5A) and Warm-Humid or Dry (Zone 3), respectively, Chicago may be representative of many cities such as Boston, New York, and Seoul, and Shanghai may be representative of Los Angeles, Sydney, and Tokyo (ASHRAE, 2010; ASHRAE, 2013). A 60-story and 780-ft typical tall office building with the depth of 120 ft and with the lease span of 30 ft will be tested in this study. The ratio of height and depth is preferably 6:1 (Choi, 2009). The floor-to-floor height is 13 ft with the ceiling height of 9 ft in case of steel structure. Due to the insufficient information on design elements of DSFs in research for tall office buildings taller than 200 m (656 ft), the range of variations is determined by case studies (i.e., Wood & Salib, 2013). As it is shown in Table 1, design parameters such as opening size and simulation, cavity depth, and building segmentation will be tested in the CFD simulation. A tall office building with DSFs will be simulated in the large CFD domain, which provides a similar environment to wind tunnel tests. As illustrated in Figure 2, multi-story DSFs were chosen for this study because enough vertical force for ventilation can be exploited through the extended space in the cavity.

However, in this study, the cavity is segmented into several zones based on the selected parameters as the extensive cavity of tall buildings may cause extreme stack flows (Wood & Salib, 2013). The airflow will be simulated only outside of the building and inside the cavity without any air coming through the indoor spaces to test only the building segmentation variables. The operable windows on the inner skin are not modelled in the CFD simulation at this step (Figure 2). The objectives of this first simulation are to (1) preliminarily assess the size/location of openings, cavity depth, and buildings segments in terms of the flow characteristics in the cavity and (2) obtain wind pressure and cavity/surface temperatures which can be the boundary conditions for the typical floor simulation. Based on the boundary conditions obtained in the whole building simulation, some typical floors will be simulated in CFD (e.g., one floor in each segment) to investigate the detailed information on the airflow and temperature distributions in the floors, and also the airflow rate and the air change rate through the operable windows.

For the simulation, only the indoor spaces will be modeled without DSFs (Figure 3), as the external environment and the cavity are already simulated in the previous simulations. In order to study the impact of the wind direction on ventilation types such as single-sided and cross-ventilation, which is a significant factor in estimating natural ventilation performance, four-sides of the square floor plan will be tested simultaneously with different boundary conditions (Figure 3). In this study, indoor air velocity, acceptable indoor operative temperature, airflow rate, and air change rate are taken into account for natural ventilation criteria. These criteria should meet the requirements established in ASHRAE standards: (1) indoor air velocity should not exceed 0.2 m/s (ASHRAE, 2010); (2) Indoor operative temperature should be within the acceptable range based on the chart 'Acceptable operative temperature ranges for naturally conditioned spaces' in ASHRAE standard 55-2010 (ASHRAE, 2010); and (3) air change rate requires to be 6–8 exchanges per hour (ASHRAE, 2013).

Design parameter	**Variables**
Building segmentation	Every 5, 10, 15, and 20 floors
Cavity depth	1 m (3 ft) and 3 m (10 ft)
Opening size / location	30 (1 ft), 60 (2 ft), and 90 (3 ft) cm / Every floor, 2, and 4 floors

Table 1: Design parameters and variables defined for simulations.

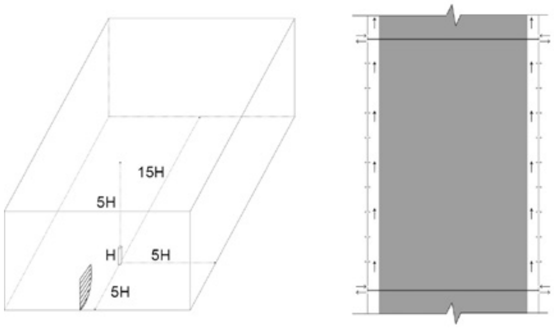

Figure 2: A tall office building with DSFs in the CFD domain (left) (Source: Franke et al., 2004) and a part of the whole building section (right).

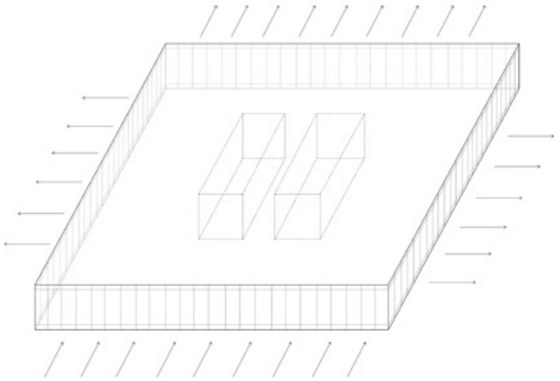

Figure 3: A typical floor plan and the wind direction with positive and negative pressure.

Results

The CFD simulation is currently being conducted to obtain the valuable results and key findings. Thus, at this point, the expected results from the CFD simulation and the wind tunnel test are discussed in this section. In order to assess the DSF configurations, indoor air velocity, indoor temperature, airflow rate, and air change rate will be calculated under two different climatic conditions in the CFD simulation. These values will be visualized through the contour plots at 1.2 m (4 ft) and 1.8 m (6 ft) (i.e., occupied zone, Montazeri [2018]) above the floor to determine the acceptability of thermal comfort and natural ventilation based on the requirements established in the ASHRAE standards. In terms of the feasibility of natural ventilation in tall office buildings with DSFs, the number of natural ventilation hours throughout the year in two cities will be predicted by comparing the airflow and temperature distribution with the weather data of the two cities. In other words, the thermal acceptability in each floor with respect to air velocity and indoor operative temperature will be investigated based on the natural ventilation requirements (i.e., ASHRAE, 2010) depending on the climatic conditions of each city throughout the year. Lastly, the expected results mentioned above will enable to draw the most proper DSF configuration for each climatic condition.

Conclusions

Based on the expected results mentioned above, the conclusions will address several important issues in the area of DSFs, natural ventilation, and tall office buildings: (1) the potential of DSF applications in the climatic conditions in which a large number of tall office buildings are located, (2) the viability of natural ventilation in tall office buildings by means of DSFs, and (3) the maximum number of natural ventilation hours throughout the year in Chicago and Shanghai. The proper DSF configurations will lead to a better understanding of how DSFs should be designed for different climate conditions in which DSFs have not been commonly applied, other than temperate climates. The integrated framework including the consideration of climatic and design parameters will provide a performance-based design assessment tool for early design stage in which iterative and rapid design decisions are made. Further insight on the airflow behavior depending on outdoor conditions will enable to maximize the number of hours when natural ventilation is applicable and simultaneously indoor thermal comfort is maintained. Therefore, the expected results will prove that the occupants in naturally ventilated tall office buildings with DSFs can experience thermal comfort without the use of mechanical systems.

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