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Cross ventilation with small openings: Measurements in a multi-zone test building

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ABSTRACT

Designing for wind driven cross ventilation is challenging due to the dynamic characteristics of wind. While numerous studies have used wind tunnels and computational fluid dynamics to study cross ventilation, few have utilized a full scale experimental approach. Thus, this paper provides measurements of wind properties, façade pressures, airflow rates through small window openings, and tracer gas concentrations for a multi-zone test building located in Austin, TX. This experimental data connects outdoor and indoor environments and demonstrates the dynamic nature of wind driven cross ventilation flow. Several interesting observations were made: (1) cross ventilation rate can be correlated to the velocity component of the approaching wind that is normal to the inlet openings; (2) obstructions that are far upwind of a building (e.g., kilometers) can have significant impacts on cross ventilation flows; (3) wind pressures on building façades are highly dynamic that a steady state assumption may not be appropriate; and (4) locations of openings that are leeward have a small impact on the overall flow rate, but significantly impact a building's internal flow distribution. This paper provides the summary of the collected data, while the detailed dataset is available upon request.

1. Introduction

Energy efficient buildings have been the goal for many architects, building engineers, and policy makers. While adding energy generation onsite, such as photo-voltaic panels, can substantially decrease a building's power draw from the electrical grid, reducing building energy consumption is also important, and in most cases, a more affordable solution [1]. One approach to reducing building energy consumption is to minimize the amount of energy required for ventilation by designing buildings with wind-driven cross ventilation. Engineers today are embracing cross ventilation designs used by many cultures for millennia. However, with the size, complex geometry, and density of buildings in today's urban society, wind driven cross ventilation presents a challenging design problem. A primitive community could easily use prevailing wind due to simplistic dwelling designs and the lack of modern man-made landscapes. Compared to these pioneers, designers today must acquire more than just typical weather data to incorporate cross-ventilation, especially at crowded urban locations where wind flow patterns are complex. While these challenges are immense, current literatures does provide a few details and tools to help cross-ventilation designs.

One tool used by researchers in attempts to simulate complex wind driven flows is computational fluid dynamics (CFD). Some researchers have used Large Eddy Simulation (LES) to successfully simulate wind and its predicted interaction between outdoor and indoor airflow [2–4]. Unfortunately, LES has proven to be too resource costly for designers [5], and others have attempted to improve and simplify turbulence models for an affordable solution [6,7]. Besides CFD simulations, various wind tunnel based studies have also revealed useful information related to cross ventilation. For example, Ohba et al. [8] showed that cross-ventilation flow in a rectangular building model was dominated by outdoor eddies, while others showed that determining discharge coefficients in an orifice equation could be a better approach for predicting the flow [9–11]. A more recent study in a wind tunnel by Ji et al. [12] found that cross ventilation is largely dependent on fluctuating wind directions. While these CFD and wind tunnel studies have furthered the understanding of cross ventilation, most of them lack full scale data for validation. Additionally, tested building types have mostly been limited to single zone buildings with large openings. Since many buildings are multi-zone with relatively small openings, the practical usages of this knowledge remain limited.

While many researchers have focused on the dynamic nature of wind-driven flow, Etheridge [13] showed that the mean flow rate should be sufficient for ventilation design in most cases, and perhaps instantaneous changes in flow, often generated by wind turbulence,

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can be neglected. This seems to contradict the findings by Ohba and others, who suggest that dynamic outdoor wind characteristics translate to indoor flow conditions. The reason behind this difference could be the sizes of opening used in these studies. One can argue that in the case of a building with relatively small openings (e.g. windows), the dynamic characteristics of wind might have less of an impact due to the momentum and direction of the wind not transferring indoors through the small openings. Nevertheless, the question of whether or not the unsteady nature of wind is important to cross ventilation can be partially answered by a full scale experimental study. Unfortunately, full scale data for wind driven cross ventilation are scarce. Some of applicable full scale experimental results were summarized by Zhai et al. [14], but the data provided were not comprehensive to cross ventilation. There are also full scale experimental studies related to structural engineering, such as Smith et al. [15], who measured façade pressures as well as internal pressures in a full scale test building to validate the ASNI/ASCE-88 [16] standard on structural wind loads. While their study focused on the impact of wind on structural integrity, a subset of data that included internal pressures with 2% wall porosity (the ratio of the opening-to-wall areas, assuming windows and doors were open) could be used for validating ventilation and air quality studies, as done by Chang and Meroney [17].

However, a general lack of full scale experimental data for cross ventilation is evident among the published literature, and perhaps for good reasons. Measurements in real weather conditions with real buildings require large efforts and resources and often tend to yield large measurement errors. In this paper, despite the difficulties, a series of detailed measurements were collected from a full-scale test house located in Austin, TX, including external wind conditions, indoor tracer gas concentrations, ventilation flow rates through openings, and façade pressures. These measurements captured real wind driven cross ventilation flows in a residential building that are difficult to reproduce in a wind tunnel or a CFD simulation model. The goal of this paper is to discuss several observations from the experimental dataset, as well as to share the data with the academic community as an experimental validation tool. Due to the extent of the experimental dataset, only a selected subset of processed data is presented in this paper. The complete experimental dataset is available to researchers by contacting the authors.

2. Experimental methods

The following sections present the experimental setup and instrumentation used, as well as a discussion on the quality of the data collected in a real building. Some challenges associated with conducting full scale experiments are also discussed.

2.1. Building and site description

A test house located at the University of Texas at Austin was used for full scale cross ventilation experiments. The south and east sides of the test house are unobstructed for approximately 200 m, while the west and south sides are unobstructed for only 50 and 15 m, respectively, as shown in Fig. 1. The vegetation surrounding the building consists of weeds, which were periodically mowed during the test period so that the maximum height did not exceed 1 m. There is a minor obstruction on the west side (a 1.5 m high stack of metal frame), but it is far enough away to not affect the incoming prevailing wind from the south. Notable larger structures, including the intersection of two large highways with multiple overpasses approximately 15 m high, are located approximately 2 km south-southwest of the house. The downtown city center of the City of Austin, with a high density of high-rise buildings, is approximately 10 km south.

The test house is a double-wide manufactured home with three bedrooms and two bathrooms. The dimensions of the house are 13.2 m long along the north-south side, 8.3 m wide, and 3.5 m tall with a 20° pitched roof. The house is elevated by a 0.8 m high crawl space. The volume of the house, excluding walls and mechanical rooms, is 250 m^3. Since the house is aligned to the site, but not the absolute direction (approximately 5° to the west), a relative coordinate system aligned to the house orientation was used, with the line perpendicular to the north façade deemed as 0° instead of due north. All experiments were conducted with prevailing south winds, with the average wind direction within five degrees from 180° (i.e., facing the southern wall). This ensured a relatively consistent wind direction and profile throughout the experiments. Three different windows were used as cross ventilation openings for the study, enabling combinations of two and three-opening test scenarios for the experiments. A graphical representation of the openings and sensor locations is shown in Fig. 2. The openings are

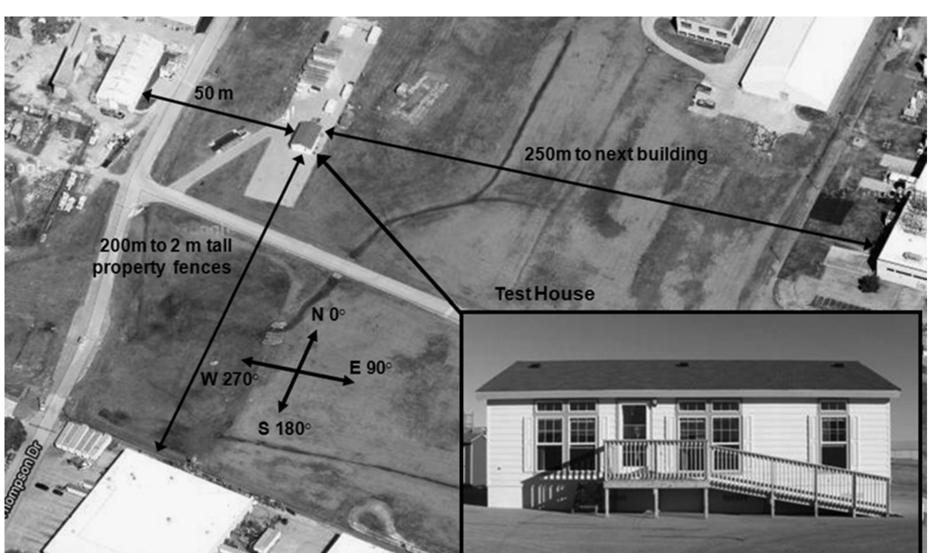

Fig. 1. Photo of the test house and satellite image of the experimental site with the distance to obstructions and coordinate systems labeled.