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Pedestrian-level wind conditions in the space underneath lift-up buildings

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ABSTRACT

Lift-up buildings are advantageous in improving the wind circulation in a congested and compact city. However, the wind conditions in the void underneath a lift-up building, also known as the lift-up area, are vital for wind comfort of occupants of lift-up buildings. This study tested 28 lift-up buildings in a boundary layer wind tunnel to assess the influence of key design parameters; height and width of the main structure, and height, width, depth, and the shape of the central core on the wind conditions in the lift-up area. The results of the analyses show a significant influence of building height on the magnitude of wind speeds in the lift-up area while the width of the central core controls the area with low wind speeds. Tall buildings with short lift-up cores have small areas with acceptable pedestrian wind comfort, which can be increased by adopting corner modifications for the central core. The area of acceptable pedestrian wind comfort increases in oblique wind directions as the areas of high ($>3.5\,\mathrm{m\,s^{-1}}$) and low ($<1.5\,\mathrm{m\,s^{-1}}$) wind speeds are decreased. Finally, a non-linear second-order multivariable regression model is developed to predict pedestrian wind comfort in the lift-up area.

1. Introduction

The urban landscape of a high-density, compact city conserves land resources, reduces vehicular emissions, and adds economic vibrancy and vitality to the society using well-mixed land use, well-connected transport mediums, and well-facilitated social interactions (Betanzo, 2007). In addition, the urban landscape is one of the major factors that moulds the urban climate and consequently impacts the well-being of citizens (Tzoulas et al., 2007). Hong Kong, a high-density compact city in Southeast Asia, provides invaluable insight on how the urban landscape, urban climate, and citizens are mutually interconnected to influence each other. On the one hand, the compact city design of Hong Kong effectively uses about 250 square-kilometres of land to provide shelter for a population of 7 million (Ng et al., 2011). On the other hand, the compact city design severely affects the urban climate of Hong Kong and induces several adverse effects on the citizens. For example, a report of the Hong Kong Planning Department (HKPD, 2006) reveals about 40% decrease of the mean wind speed over a period of 10 years in the urban areas of Hong Kong. Ng et al. (2011) conjectured this reduction of wind speeds to the adverse effects of common building designs in Hong Kong, where the tall buildings are situated on bulky podium structures separated by very limited open spaces. Furthermore, Yim et al. (2009) demonstrated the negative impact of ‘wall-effect’ of similar height, closely-spaced tall buildings on the wind penetration into the city; and Tsang et al. (2012) revealed negative effects of podium structures on creating large areas with low wind speeds near the ground. The lack of air circulation in the urban areas is believed to be the origin of many wind-related issues of Hong Kong including causing outdoor thermal discomfort (Cheng et al., 2012), degrading air quality (Cheng and Lam, 1998), increasing the Urban Heat Island (UHI) effect (Giridharan et al., 2004), and creating favourable conditions for epidemics such as the outbreak of SARS (Severe Acute Respiratory Syndrome) in 2003 (Yu et al., 2004).

Given the importance of urban landscape and urban climate, the Hong Kong Government has stipulated several guidelines for buildings (HKBD, 2005, 2016), the pedestrian-level wind environment (HKPD, 2006), and greenery in urban areas (HKCEDD, 2010). A particular strategy promulgated in these guidelines is to enhance air circulation near the ground by increasing building permeability. An example is that

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the Sustainable Building Design Guidelines (HKBD, 2016) requires up to 1/3 of the vertically projected façade area to be permeable. To comply with these guidelines, designers are modifying conventional building designs and searching for novel building forms that are in harmonization with the urban landscape of Hong Kong.

The design of lift-up building, an uncommon building form in Hong Kong, can be a befitting building design for Hong Kong. For example, the lift-up building, which has an elevated main structure from the ground using columns, shear walls, a central core or a combination of them, can easily comply with the guidelines for building permeability while providing maximum space for wind to circulate through built-up areas. Moreover, the space underneath the elevated structure, hereafter referred to as the lift-up area, provides space for sitting and recreational activities for inhabitants and can be used for laying paths to access other areas in the neighbourhood. Fig. 1 shows two of the lift-up buildings in Hong Kong; the headquarters building of the Hongkong and Shanghai Banking Corporation in Central, and a campus building in the Polytechnic University of Hong Kong, Hung Hom.

Conventionally, the lift-up design is not recommended for buildings due to the accelerated wind flows often found in the lift-up area (Beranak, 1984; Gandemer, 1978; Melbourne and Joubert, 1971; Penwarden and Wise, 1975; Stathopoulos et al., 1992). The accelerated wind flows resulted from the ‘pressure-short-circuiting’ of the positive and negative pressures on the windward and the leeward side of the building produce unacceptable or even dangerous wind conditions for pedestrians. Several studies (Gandemer, 1978; Melbourne and Joubert, 1971; Penwarden and Wise, 1975; Stathopoulos et al., 1992) indicated that pedestrian wind discomfort in an opening underneath a building could be a serious problem if the main structure is tall or the ambient wind speed is high.

Conversely, under low ambient wind speeds similar to that in Hong Kong, the lift-up design could be advantageous to improve the urban wind environment. For example, Xia et al. (2017) demonstrated significant reductions in areas with low wind speeds near isolated buildings, an array of buildings, and tall buildings with podium structures after they were modified with the lift-up design. Although their study indicated high wind gust speeds in the lift-up area, Xia et al. (2017) predicted less severe pedestrian wind discomfort owing to the low ambient wind speeds in Hong Kong. Du et al. (2017a) evaluated buildings with four shapes of ‘—’, ‘□’, ‘L’ and ‘U’, and with and without the lift-up design using Computational Fluid Dynamics (CFD) simulation technique. Their study reveals better pedestrian wind comfort in the surrounding of the lift-up buildings, in particular, when the buildings are subjected to oblique wind flows. Later Du et al. (2017b, c) employed wind tunnel tests and field measurements to assess pedestrian wind comfort and outdoor thermal comfort near the lift-up buildings in the Hong Kong Polytechnic University. They found better air circulation within the lift-up areas and concluded that the wind speeds are adequate to achieve outdoor thermal comfort on a hot, humid, sunny, summer day in Hong Kong. Most importantly, Du et al. (2017a, b, c) reported that the wind speeds in the lift-up areas are less than 3.6 m s^{-1} and predicted no wind danger in summer or no strong clod stresses in winter. Liu et al. (2017) modelled a 53.5 m tall lift-up building using the Detached Eddy Simulation (DES) technique and their results, calculated according to the ambient wind speeds in Hong Kong, show that the wind gust speeds in the lift-up area are about 5–6.4 m s^{-1}. A series of wind tunnel tests done by Tse et al. (2017) and Zhang et al. (2017) aimed to investigate the influence of dimensions of the main structure and design of the central core on the pedestrian wind comfort near isolated lift-up buildings. Tse et al. (2017) revealed significant influence of height of the central core on creating large areas with the pedestrian wind comfort near lift-up buildings and concluded that height of the central core is the most influential parameter in designing the central core. Zhang et al. (2017) discovered large areas with high wind speeds (mean wind speeds larger than 3.5 m s^{-1}) in the lift-up areas of tall and slender buildings and proposed to modify the central core adopting chamfered, rounded, and recessed corners to improve pedestrian wind comfort in the lift-up areas.

A probable drawback of the previous studies is the lack of details on the combined effect of key design parameters of a lift-up building on the pedestrian-level wind (PLW) field. In particular, the knowledge on the PLW field in lift-up areas has paramount of importance as the lift-up areas are frequently populated in daytime (see. Fig. 1). The lack of knowledge is attributed to the smaller number of studies done on the lift-up buildings, the limited number of buildings tested in these studies, and measurements of wind speed were sparsely taken in the lift-up area. To avoid these limitations, this study assesses 28 lift-up buildings with different heights and widths and various designs of the central core in a boundary layer wind tunnel (see Section 2) to comprehensively investigate the wind conditions in the lift-up area. In addition, several lift-up buildings are tested for 4 wind incidence angles to estimate the influence of approaching wind direction on the PLW field in the lift-up area. The measured wind speeds in the lift-up areas are analysed for estimating pedestrian wind comfort according to the criteria proposed by Zhang et al. (2017) (see Section 3). Furthermore, a nonlinear second-order multiple-variable regression model is developed to predict the combined effect of key design parameters on the wind conditions in the lift-up area (see Section 4). The findings of this study are summarised (see Section 5 and Section 6) for engineering applications and future research.

2. Experimental setup

The wind tunnel tests described in this study were carried out in the boundary layer wind tunnel (BLWT) at the CLP Power Wind/Wave Tunnel Facility (WWTF) at the Hong Kong University of Science and Technology (HKUST). All building models were tested in the largest test section (4×5 m^2) of the BLWT under a maximum wind speed of 10 m s^{-1} at 1 m height. An atmospheric boundary layer (ABL) wind flow was simulated using systematically arranged roughness blocks in the development section. The simulated ABL wind flow followed the power-law type wind profile with an exponent of 0.11 and had a mean wind speed of about 7.59 m $^{-1}$ at 0.6 m height, which is the height of the tallest

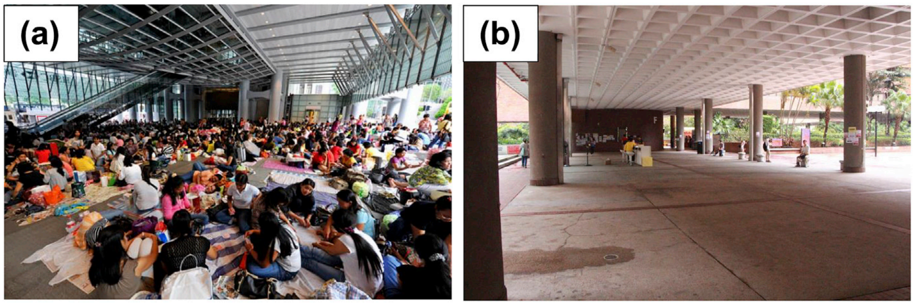

Fig. 1. (a) People are lounging in the lift-up area of the headquarters of Hongkong and Shanghai Banking Corporation in Central, Hong Kong (source: www.ofwsinhongkong.wordpress.com), (b) The lift-up areas provide space for seating and access to other areas in the Hong Kong Polytechnic University, Hung Hom, Hong Kong.