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

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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...
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 (Berna-nak, 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 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 cloud 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 m²) 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 s⁻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.ofwinhongkong.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.
corners (Zhang et al., 2017). The design parameters of the central core were tested parameter tested in this study, thus kept as a constant value of 20 m. A

\[
fig. 2. \text{Profiles of (a) normalised mean wind speed and (b) turbulence intensity at the centre of the turntable.}
\]

building model tested in this study (Fig. 2(a)). The profile of turbulence intensity as shown in Fig. 2(b) had a proper variation with height and had the magnitude about 5% at the 0.6 m height. The more details about approaching wind profile including the simulation technique, flow properties, and flow consistency can be found from Tse et al. (2016).

There were 28 buildings with unique sets of dimensions of the main structure and the central core tested in this study. The height (H) and width (W) of the main structure varied from 45 m to 120 m and from 30 m to 90 m (in full-scale) having the Height-to-Width ratio (H/W) ranging from 0.5 to 4. The depth of the main structure (D) was not a parameter tested in this study, thus kept as a constant value of 20 m. A central core was adopted to elevate the main structure from the ground as shown in Fig. 3(a) because the central core design induced minimum disturbance to the wind conditions in the lift-up area (Tse et al., 2017; Zhang et al., 2017). The design parameters of the central core were tested by varying its height (h) from 3 m to 9 m and width (w) and depth (d) changing in the ranges of 9 m–21 m, and 6 m - 14 m, respectively (Fig. 3(b)). The combinations of w and d are to represent different plan areas of the central core (w × d), which is expressed as a percentage with respect to the plan area of the building (W × D). The tested central cores had the percentage of plan area (AP) ranging from 9% to 49% in this study. In addition, the basic design of the rectangular shaped central core (Rt) was modified using chamfered (Ch), recessed (Rc), and rounded (Rd) corners as shown in Fig. 3(c). The three corner modifications were defined by changing the length, a, inwardly from the lowest value of \(a = 0\) for rectangular corners and the maximum value of \(a = 2.25\) m for recessed corners. Each modification was extended to 2.25 m length (i.e., length \(\tau\)) from any corner of the central core. All buildings were tested for a wind flow that approached perpendicular to the width of buildings (0° wind incidence angle) and some of the buildings were subjected to oblique wind flows that approached at 15°, 30°, and 45°. Table 1 shows the dimensions of the main structure and the central core, the shape of the central core, and wind incidence angles that were used for each building. For the wind tunnel tests, all buildings were fabricated using Balsa wood in a geometric scale of 1:200.

Two types of omnidirectional wind sensors namely the Irwin sensors and Kanomax®1560, were installed over an area of 1.2 × 1.8 m² to measure the wind speed at the pedestrian level. A total of 186 Irwin sensors were installed in the far-field of the building as shown in Fig. 4(a) with the minimum separation distances of 0.075 m and 0.1 m in the longitudinal (x), and lateral (y) directions, respectively. These separation distances satisfied the longitudinal and lateral minimum spacing of 0.019 m and 0.0064 m as proposed by Wu and Stathopoulos (1994) to minimize the interference effect of neighbouring sensors on wind speed measurements. The Irwin sensors used for this study were fabricated in a geometric scale of 1:200 and had a 0.01 m long protruding tube to represent a 2 m measurement height in field conditions. The mean wind speed at the pedestrian level \(W_0\) was calculated by using the square-root-of-pressure-difference \(\sqrt{\Delta P}\) between two holes on the Irwin sensors as proposed by Irwin (1981).

\[
\overline{W} = a + \beta \sqrt{\Delta P}
\]

In Equation (1), two constants, \(a\) and \(\beta\), are estimated from the calibration of Irwin sensors with respect to known wind speeds. For this study, the values of \(a\) and \(\beta\) were found to be 0.15 and 1.72, respectively.

A total number of 34 Kanomax sensors were installed in the near-field and within the lift-up area of a building as shown in Fig. 4(b). The grid resolution of Kanomax sensors was finer than that of the Irwin sensors with the minimum separation distance of 0.03 m in both longitudinal and lateral directions. The synchronized measurements of mean wind speed were recorded for a period of 135 s by Kanomax sensors and Irwin sensors at the frequencies of 10 Hz and 400 Hz, respectively. It was found that the measurement period of 135 s was sufficient for calculating mean wind speeds using data from Kanomax and Irwin sensors.
3. Results

3.1. Evaluation of wind conditions in a lift-up area

The wind conditions in the lift-up area are evaluated using normalised mean wind speed ratio \( K \) as defined in Equation (2).

\[
K = \frac{\bar{U}_{x,y,0.01m}}{\bar{U}_{200m,\alpha=0.15}}
\]  (2)

In Equation (2), \( \bar{U}_{x,y,0.01m} \) is the mean wind speed measured at the 0.01 m height at a location \((x, y)\) near the building and \( \bar{U}_{200m,\alpha=0.15} \) is the mean wind speed at 200 m height in a wind profile that follows a power-law model with an exponent \( \alpha \) of 0.15. The magnitude of \( \bar{U}_{200m,\alpha=0.15} \) is representative of the long-term data of wind speed of Hong Kong and is advantageous in establishing pedestrian wind comfort criteria for Hong Kong (Zhang et al., 2017).

Zhang et al. (2017) first proposed the pedestrian wind comfort criteria shown in Table 2 by considering the prevailing wind conditions in Hong Kong. For example, the minimum threshold wind speed of 1.6 m s\(^{-1}\) is in accordance with the recommendation of Cheng et al. (2012) to maintain outdoor thermal comfort on a hot, humid, summer day in Hong Kong. The maximum threshold wind speed of 5 m s\(^{-1}\) is the

### Table 2

Details of the 28 buildings.

| Building | Building (m) | Lift-up core (m) | Wind incidence angles |
|----------|--------------|------------------|-----------------------|
|          | Height \((H)\) | Width \((W)\) | Depth \((D)\) | Height \((h)\) | Width \((w)\) | Depth \((d)\) | Corner Shape |
| M1-A1-Rt | 120 | 30 | 20 | 3 | 9 | 6 | Rectangular | 0° |
| M1-A2-Rt | 120 | 30 | 20 | 6 | 9 | 6 | Rectangular | 0°, 15°, 30°, 45° |
| M1-A3-Rt | 120 | 30 | 20 | 9 | 9 | 6 | Rectangular | 0° |
| M1-B1-Rt | 120 | 30 | 20 | 3 | 15 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M1-B2-Rt | 120 | 30 | 20 | 6 | 15 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M1-B2-Ch | 120 | 30 | 20 | 6 | 15 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M1-B2-Rc | 120 | 30 | 20 | 6 | 15 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M1-B2-Rd | 120 | 30 | 20 | 6 | 15 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M1-B3-Rt | 120 | 30 | 20 | 9 | 15 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M1-C1-Rt | 120 | 30 | 20 | 3 | 21 | 14 | Rectangular | 0° |
| M1-C2-Rt | 120 | 30 | 20 | 6 | 21 | 14 | Rectangular | 0°, 15°, 30°, 45° |
| M1-C3-Rt | 120 | 30 | 20 | 6 | 21 | 14 | Rectangular | 0° |
| M2-B2-Rt | 60 | 30 | 20 | 6 | 15 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M2-B2-Ch | 60 | 30 | 20 | 6 | 15 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M2-B2-Rc | 60 | 30 | 20 | 6 | 15 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M2-B2-Rd | 60 | 30 | 20 | 6 | 15 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M3-B2-Rt | 45 | 30 | 20 | 6 | 15 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M3-B2-Ch | 45 | 30 | 20 | 6 | 15 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M3-B2-Rc | 45 | 30 | 20 | 6 | 15 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M3-B2-Rd | 45 | 30 | 20 | 6 | 15 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M4-B2-Rt | 45 | 60 | 20 | 6 | 30 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M4-B2-Ch | 45 | 60 | 20 | 6 | 30 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M4-B2-Rc | 45 | 60 | 20 | 6 | 30 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M4-B2-Rd | 45 | 60 | 20 | 6 | 30 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M5-B2-Rt | 45 | 90 | 20 | 6 | 45 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M5-B2-Ch | 45 | 90 | 20 | 6 | 45 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M5-B2-Rc | 45 | 90 | 20 | 6 | 45 | 10 | Rectangular | 0°, 15°, 30°, 45° |
| M5-B2-Rd | 45 | 90 | 20 | 6 | 45 | 10 | Rectangular | 0°, 15°, 30°, 45° |

Fig. 4. The sensor arrangement (a) in the whole measurement area, and (b) within the turntable.
Table 2
Pedestrian wind comfort criteria.

| Wind Speed (m s⁻¹) | K | Remarks              |
|-------------------|---|----------------------|
| <1.6              | <0.3| Low wind speed (LWS) |
| 1.6–3.5           | 0.3–0.7| Acceptable wind speeds |
| 3.5–5             | 0.7–1| High wind speed (HWS) |
| >5                | >1  | Unacceptable wind speeds |

The maximum allowable wind speed in cities recommended by Penwarden and wise (1975). The wind speed of 3.5 m s⁻¹ demarcates the beginning of wind discomfort felt by pedestrians due to flapping of clothes, disturbance of hair, etc. The K values in Table 2 are calculated by taking U_{200m,a=0.15} = 5–6 m s⁻¹ according to the long-term measurements of mean hourly wind speed recorded at the anemometer station at Waglan island, Hong Kong.

Fig. 5 shows how the wind condition in a lift-up area varies with the design of the central core. The three lift-up areas shown in Fig. 5 are an integrated part of the same lift-up building, which has dimensions of 120 m in height, 30 m in width, and 20 m in depth. The three central cores have the same width (w) and depth (d) of 15 m and 10 m, respectively. The height of the central core varies from 3 m for building M1-B1-Rt to 6 m for buildings M1-B2-Rt and M1-B2-Rc. The central core of building M1-B2-Rc is modified by adopting the recessed corners. It is evident from Fig. 5 that the wind conditions in the lift-up area are strongly dependent on height and design of the central core. An example is that the magnitude and the area of HWS are decreased with the increase of height of the central core from 3 m to 6 m for buildings M1-B1-Rt and M1-B2-Rt. The recessed corners further reduce the area of HWS in the lift-up area of building M1-B2-Rc while its maximum K value remains unchanged. Moreover, the area of LWS on the leeward side of the central core is noticeably reduced for building M1-B2-Rc whereas the other two buildings have comparable LWS areas, which are wider than the width of the rectangular shaped central cores.

The following subsections discuss in detail the wind conditions in the lift-up areas of the 28 buildings by highlighting the magnitude of maximum wind speed, areas of HWS, LWS and pedestrian wind comfort, and the relationships between the wind conditions and the dimensions of buildings, the design of central core, and wind incidence angle.

3.2. Maximum K value (K_{max}) in lift-up area

Fig. 6 shows the maximum K value (K_{max}) observed in the lift-up areas of the 28 buildings. The blue dashed line points out the lower bound K value of 0.7 for the beginning of wind discomfort felt by pedestrians and the red dashed line (K = 1) indicates the unacceptable wind condition, which should be avoided from occurring at any location in a lift-up area. According to Fig. 6, the K_{max} values of the three buildings, M1-A1-Rt, M1-B1-Rt, and M1-C1-Rt are higher than 1 with the highest K_{max} value of 1.11 recorded for M1-B1-Rt. The large K_{max} values of these three buildings probably relate to two common features; the largest building height (H = 120 m) and the shortest central core (h = 3 m). In fact, the magnitude of K_{max} shows a strong dependency on the heights of both the building and the central core as the K_{max} value noticeably declines with the decrease of the building's height and/or increase of the central core's height. For example, the K_{max} value decreases from 1.01 to 0.90 with the increase of height of the central core from 3 m to 9 m for buildings M1-A1-Rt and M1-A3-Rt. The magnitude of K_{max} further reduces from 0.96 to about 0.80 as the height of the building decreases from 120 m to 45 m for buildings M1-B2-Rt and M3-B2-Rt. The lowest K_{max} value of 0.72 is recorded for the two buildings M4-B2-Rt, and M4-B2-Ch; both are 45 m in height and one building adopts recessed corners for the central core. In general, the corner modifications have a minimum impact on reducing the K_{max} value compared with noticeable reductions observed for the dimensions of the central core.

Fig. 7 shows the variation in K_{max} in the lift-up area and in the passage underneath a building with heights of the building and central core. The filled markers show the K_{max} values in the lift-up area in this study and the open markers indicate K_{max} values in the passage underneath a building observed in several previous studies of Gandemer (1978),...
Melbourne and Joubert (1971), Penwarden and Wise (1975) and in the lift-up area of a 53.5 m tall building (Xia et al., 2017). For comparison, the $K_{\text{max}}$ value is calculated as $U_{\text{max}}/U_{\text{ambient}}$, where $U_{\text{max}}$ is the maximum wind speed at the pedestrian level in the lift-up area or the passage underneath the building and $U_{\text{ambient}}$ is the wind speed at the pedestrian level in the absence of the building. As it can be seen from Fig. 7, the $K_{\text{max}}$ value in lift-up areas increases with building height but are noticeably smaller than the $K_{\text{max}}$ values in the passage underneath similar height buildings tested in previous studies. The $K_{\text{max}}$ values in the lift-up areas in this study and study done by Xia et al. (2017) significantly deviate from the relationship of $K_{\text{max}} = 0.65 \times h^{0.63}$ proposed by Wu and Stathopoulos (1994). The small $K_{\text{max}}$ values in the lift-up area are indicative of less intense wind flows that are probably a result of some wind leaked from the lift-up area to the surrounding through the opened lateral sides. Moreover, the small $K_{\text{max}}$ values are suggestive of lesser wind danger in the lift-up area compared with that in the passage underneath a building. Compared with building height, the $K_{\text{max}}$ value does not show a strong dependence on width of the building ($W$). For example, the three lift-up buildings with the same height (45 m) and different widths (30 m, 60 m, 90 m) have comparable $K_{\text{max}}$ values in the lift-up area. Fig. 7 shows a gradual decrease of the $K_{\text{max}}$ value with height of the central core, $h$, for the 120 m tall buildings with the central core with the plan area of 150 m$^2$. The variation in $K_{\text{max}}$ with $h$ can be approximated using the relationship of $K_{\text{max}} = 2.21 \times h^{0.07}$ for the data shown in Fig. 7. Further analysis of the variation in $K_{\text{max}}$ with height of the central core is hindered by the limited experimental data available in this study.

### 3.3. Area with low wind speeds (LWS)

Fig. 8 shows the percentage area of low wind speed ($A_{\text{P,LWS}}$), which is the ratio between areas with the $K$ value less than 0.3 and the effective plan area of the building (i.e., plan area of the building without the central core), in the lift-up area of 28 buildings. The number above each bar indicates the absolute area of LWS within the lift-up area. The area is selected for the analysis of LWS because of a large area with LWS can affect the thermal comfort of many people than the magnitude of wind speed. Among all test cases, buildings M1-C1-Rt, M1-C2-Rt, and M1-C3-Rt have large $A_{\text{P,LWS}}$ values about 46%-63% while buildings M1-A1-Rt, M1-A2-Rt, and M1-A3-Rt record small $A_{\text{P,LWS}}$ values about 3%-7%. Interestingly, both sets of buildings have similar main structures with dimensions of $120 \times 30 \times 20$ m but have different plan areas for the central core. More specifically, buildings M1-C1-Rt, M1-C2-Rt, and M1-C3-Rt have the central core with larger plan area ($A_P = 49\%$) compared with smaller central cores ($A_P = 9\%$) of buildings M1-A1-Rt, M1-A2-Rt, and M1-A3-Rt. The large $A_{\text{P,LWS}}$ values reported for buildings with large central cores postulate a probable influence of the plan area of the central core on creating large areas with LWS in the lift-up area. Conversely, the $A_{\text{P,LWS}}$ value decreases with width of the main structure as it can be seen for the 45 m tall buildings with different widths (buildings M3-, M4-, and M5-). For these buildings, the $A_{\text{P,LWS}}$ value steadily decreases from 32% to 16% as the width of the building increases from 30 m to 90 m. The modified central cores with corner modifications effectively reduce the $A_{\text{P,LWS}}$ of slender buildings (M1- and M2-) but have no notable reduction for short and wide buildings (e.g. buildings M4- and M5-). Among the three corner modifications, the recessed and rounded corners are more effective in reducing the area with LWS in the lift-up area with a slender central core. For instance, a 60% reduction in the $A_{\text{P,LWS}}$ value is found for buildings M1-B2-Rc and M1-B2-Rd compared with building M1-B2-Rt with a rectangular shaped central core. In contrast, the corner modifications are ineffective for short and wide central cores as it can be seen from buildings M5-B2-Rc and M5-B2-Rd,
which have 5–6% larger $AP_{LWS}$ values than that of building M5-B2-Rt. The less effective of corner modifications in short and wide central cores is largely attributed to the fact that corner modifications are applied on a short length compared to the width of the central core. For example, corner modifications are applied only over 20% of the widths of the central core of buildings M5-B2 while the corner modifications span over 60% of the widths of the central core of buildings M1-B2. The smaller length of corner modifications compared to width of the central core cannot induce a considerable influence on the wind conditions in the lift-up area (Zhang et al., 2017).

### 3.4. Area with acceptable wind speeds

Fig. 9 shows the percentage of area underneath the building with pedestrian wind comfort ($AP_{com}$), which is defined as the areas with the magnitude of $K$ value lying between 0.3 and 0.7 to the effective plan area of the corresponding building. The number above each bar shows the absolute size of area with pedestrian wind comfort in the lift-up areas. The $AP_{com}$ values of the buildings show distinct variations with dimensions of the building and the central core, and the type of the corner modifications adopted for the central core. For instance, the $AP_{com}$ value rises from 32.8% to 62.6% as the height of the central core increases from 3 m to 9 m in buildings M1-A1-Rt and M1-A3-Rt. In fact, the shortest central cores have the most adverse effect on the pedestrian wind comfort in the lift-up areas as depicted by buildings M1-A1-Rt, M1-B1-Rt, and M1-C1-Rt, which have the shortest lift-up cores ($h = 3$ m) and the smallest $AP_{com}$ values of 32.8%, 35%, and 35.8% compared with the rest of the buildings. Conversely, building height has an inversely proportional relationship with the $AP_{com}$ value such that the decrease of building height tends to increase the $AP_{com}$ value. Between heights of the building and the central core, the former has a slightly larger influence on the $AP_{com}$ value as it can be seen from the $AP_{com}$ values of buildings M1-B2-Rt, M1-B3-Rt, and M2-B2-Rt. The $AP_{com}$ value increases about 12.7% with the increase of the height of the central core from 6 m to 9 m for buildings M1-B2-Rt and M1-B3-Rt while the increment of $AP_{com}$ is about 17.6% for the decrease of building height from 120 m to 60 m for buildings M1-B2-Rt and M2-B3-Rt.

The dependency of $AP_{com}$ value on widths of the building and the central core is rather complex as both widths influence the wind conditions in the lift-up area. For example, the $AP_{com}$ value rises from 58.5% for building M3-B2-Rt to 69.9% for building M4-B2-Rt as building width increases from 30 m to 60 m and width of central core changes from 15 m to 30 m. A further increase of widths of the building and the central core reduces the $AP_{com}$ value as it can be seen for building M5-B2-Rt, whose $AP_{com}$ value of 55.5% depicts a 20% reduction with respect to that of building M4-B2-Rt. The aspect ratio of a building ($H/W$) is a better indicator to describe the variation in the $AP_{com}$ value across the test cases than the dimensions of a lift-up building. For instance, the buildings with the aspect ratio less than 0.5 or greater than 2 have smaller $AP_{com}$ values than the rest of the buildings. In other words, tall and slender buildings ($H/W > 2$) and short and wide buildings ($H/W < 0.5$) are not advantageous in creating large areas with pedestrian wind comfort whereas buildings with the aspect ratio between 0.5 and 2 are more favourable in creating wind comfort for pedestrian in the lift-up area.

The corner modifications are more effective in increasing the $AP_{com}$ value of tall and slender buildings than those of short and wide buildings. For example, the $AP_{com}$ value of building M1-B2-Rt is increased from 35% to 58% after adopting recessed corners for building M1-B2-Rc while both buildings M5-B2-Rt and M5-B2-Rc have similar $AP_{com}$ values. The relatively smaller length of the corner modifications is the reason for the insignificant influence on the wind conditions in the lift-up areas with wide central cores. If the corner modifications are applied over a sufficient length, then recessed corners are more effective in increasing the area with pedestrian wind comfort in the lift-up area than other two corner modifications. The effectiveness of recessed corners relies on the ability of significantly minimising the area with LWS and moderate reducing the magnitude of HWS (Zhang et al., 2017).

### 3.5. Variations in wind conditions with wind incidence angle

Among the 28 lift-up buildings, 12 buildings are selected and tested for three additional wind incidence angles, 15°, 30°, and 45°. The 12 buildings are sufficient to represent the variation in wind conditions with dimensions of the building ($H$ and $W$) and the central core ($h$, $w$, and $d$) under wind flows that approach in oblique wind directions. Fig. 10(a) shows the variation in the maximum $K$ value ($K_{max}$) and the percentage area of HWS ($AP_{HWS}$) with wind incidence angle for the 12 lift-up buildings. The $K_{max}$ value has a steady decreasing trend about 0.055 for every 10° increment of wind incidence angle, $\theta$. As a result, the $K_{max}$ value of some buildings is reduced more than 40% causing the magnitude of $K_{max}$ smaller than 0.7 and no area of HWS at large wind incidence angle such as 45° (e.g., buildings M2-B2-Rt and M3-B2-Rt). However, the
$K_{\text{max}}$ values of tall and slender buildings (e.g. M1-B2-Rt) and short and wider buildings (e.g. M5-B2-Rt) are larger than 0.7 at 45° wind incidence angle indicating that possible HWS conditions exist in the lift-up area. The area of HWS can be further reduced by adopting the corner modifications for the central core, in particular, the rounded corners (Rd) that are highly effective in preventing the occurrence of HWS if the wind incidence angle is larger than 15°.

Fig. 10(b) shows a steady decrease of the percentage area of LWS ($AP_{\text{LWS}}$) with wind incidence angle up to 30°. In particular, the tall and slender buildings M1-B1-Rt and M1-B2-Rt show a 60%–70% reduction in the $AP_{\text{LWS}}$ value at 30° while the short and wide building M5-B2-Rt has the maximum reduction of 16% in the $AP_{\text{LWS}}$ value at 15°. In contrast to its best performance against HWS, the rounded corners are the worst corner modification in reducing the area of LWS. The most effective corner modification in reducing the area of LWS in oblique wind directions is the recessed corners, which creating no area of LWS for building M1-B2-Rc at 45°. Compared to the notable variation in $AP_{\text{LWS}}$, the $K_{\text{min}}$ value of the 12 buildings remains constant about 0.18 with minor deviations in the range of $K_{\text{min}} = -0.04$.

Fig. 11 shows the variation in the percentage area of pedestrian wind comfort ($AP_{\text{com}}$) in the modified lift-up areas with wind incidence angle. In general, corner modifications increase the $AP_{\text{com}}$ value about 7%–40% as the wind incidence angle changed from 0° to 45°. Particularly, recessed corners have better performance in increasing the area with pedestrian wind comfort than other corner modifications at all wind incidence angles. For instance, the $AP_{\text{com}}$ value of building M1-B2-Rc is 7% and 2% higher than those of M1-B2-Rd and M1-B2-Ch for the wind that approaches at 30°. The ability of recessed corners to significantly reduce the area of LWS as shown in Fig. 12(c) is the reason for the large $AP_{\text{com}}$ value recorded for building M1-B2-Rc. The chamfered corners reduce the area of LWS similar to the recessed corners (see Fig. 12 (b)) creating the $AP_{\text{com}}$ value of building M1-B2-Ch comparable with that of building M1-B2-Rc. The large area of LWS in the lift-up area with the rounded corners (Fig. 12 (d)) is the main reason for slightly higher $AP_{\text{com}}$ values of building M1-B2-Rd than those of building M1-B2-Rt.

\[ K_{\text{max}} = 0.0005 \theta + 0.9074 \]
\[ R^2 = 0.8946 \]

Fig. 10. (a) Variation in $K_{\text{max}}$ and the percentage area of high wind speed ($AP_{\text{HWS}}$) with wind incidence angle, and (b) Variation in $K_{\text{min}}$ and the percentage area of low wind speed ($AP_{\text{LWS}}$) with wind incidence angle.

Fig. 11. Variation in the percentage area of pedestrian wind comfort ($AP_{\text{com}}$) with wind incidence angle.
4. Combined effects of key design parameters

As it can be seen from the previous subsections, the design parameters of the main structure and the central core differently influence pedestrian wind comfort in the lift-up area. Although this study separately analysed the effects of individual design parameters, both the main structure and the central core concurrently modify pedestrian wind comfort in the lift-up area. The combined effect of the main structure and the central core on the pedestrian wind comfort can be investigated by using the multivariable regression analysis by taking the design parameters as independent variables (or predictors) and the area with pedestrian wind comfort in the lift-up area as the dependent variable. Wen et al. (2017) successfully adopted the multivariable regression analysis to predict the rate of air change in a street canyon formed by buildings with an arcade design and later Juan et al. (2017) employed that multivariable regression model to optimise the arcade design.

In this study, a multivariable regression model is developed based on the data of 28 lift-up buildings. The key design parameters of $H$, $W$, $h$, $w$, $d$, $t$, and $a$ are employed as the predictors to estimate the percentage area with pedestrian wind comfort ($AP_{com}$) in the lift-up area. The key design parameters are converted to a set of dimensionless parameters and among them $H/h$, $h/w$, $W/d$, and $v_1/v_2$, where $v_1 = t/w$, and $v_2 = a/t$ are subsequently selected as predictors from the correlation analysis. A non-linear second-order regression model with the correlation coefficient ($R^2$) of 0.9094 is established using the multivariable regression analysis as shown in Equation (3).

$$AP_{com} = \left[ \begin{array}{l}
-0.103 \times \left( \frac{W}{d} \right)^2 - 11.66 \times \left( \frac{W}{d} \right) + 0.273 \times \left( \frac{W}{d} \right) \\
+0.760 \times \left( \frac{W}{d} \right) + 6.243 \times \left( \frac{W}{d} \right) - 42.574 \times \left( \frac{W}{d} \right)^2 \\
+4.751 \times \left( \frac{W}{d} \right) + 287.233 \times \left( \frac{W}{d} \right) + 163.212 \times \left( \frac{W}{d} \right) \\
-1.4 \times \left( \frac{W}{d} \right)^2 + 12.996 \times \left( \frac{W}{d} \right) + 17.436 \times \left( \frac{W}{d} \right) \\
+8.234 \times \left( \frac{W}{d} \right)^2 - 169.358 \times \left( \frac{W}{d} \right) - 61.605
\end{array} \right]^{1/2}
$$

The multivariable regression model as shown in Equation (3) is valid for the design parameters $H$, $W$, $h$, $w$, and $d$, in the ranges of 45–120 m, 30–90 m, 3–9 m, 9–45 m, and 6–14 m, respectively. The design parameters of corner modifications, $t$ and $a$, are in the range of 0–2.25 m and for the rectangular shaped central cores, $v_1/v_2$ is taken as 0 considering the numerical stability of the model. The square root of the regression model avoids negative $AP_{com}$ values resulting from the combinations of unrealistic values of the design parameters (e.g. the combination of $H/h = 40$ and $h/w = 1$).

Fig. 13 shows how the value of $AP_{com}$ varies with the two predictors $H/h$ and $h/w$ in the ranges of 7.5–40, and 0.13–1, respectively. The two other predictors $W/d$ and $v_1/v_2$ are taken as 5 and 0 to construct the response surface of $AP_{com}$. The response surface varies with the combination of $H/h$ and $h/w$ and has large (or small) $AP_{com}$ values at different ranges of the two predictors. The maxima of $AP_{com}$ is found when the value of $H/h$ is close to 7.5 and the value of $h/w$ reaches 1 and a secondary peak is observed for the $H/h \approx 27$ and $h/w \approx 0.14$. The $AP_{com}$ value reaches below 20% when the $H/h$ and $h/w$ are larger than 20 and 0.4, respectively. In other words, a lift-up building with a rectangular central core and $W/d = 5$ should satisfy the conditions $H/h < 20$ and $h/w < 0.4$ to create pedestrian wind comfort over an area that covers at least 20% of the effective lift-up area.

Fig. 14 shows two different patterns of the variation in $AP_{com}$ with $H/h$ and $h/w$ for a building with $W/d = 5$ and $v_1/v_2 = 0$. The $AP_{com}$ value initially increases with $H/h$ and reaches its maxima of 80% at $H/h = 15$ before it rapidly declines with the further increase of $H/h$. The $AP_{com}$ value decreases approximately linearly with the increase of $h/w$ as shown in Fig. 14(b). The relationship between $AP_{com}$ and $h/w$ suggests adopting a short and wide central core for the building to create a large area with pedestrian wind comfort.

5. Discussion

The current study comprehensively analysed the wind conditions in the lift-up areas of 28 buildings and developed a non-linear second-order multivariable regression model to predict the area with pedestrian wind comfort in the lift-up area based on the key design parameters of a lift-up building. There are few limitations of the current study necessary to be considered when interpreting and applying the findings of this study in engineering applications.

- The current study adopted the central core design for the lift-up buildings because the central core induces minimum disturbance to the wind conditions in the lift-up area. However, other designs of lift-up buildings such as the use of peripheral columns (see Du et al., 2017(a)) or shear walls can alter the wind conditions in the lift-up area due to sheltering of peripheral building components. In such a case, the wind conditions in the lift-up area might be considerably different from the results presented in this study.
- This study modelled an empty lift-up area without replicating the installed furniture such as benches, or parked vehicles, or the users commonly found in lift-up areas. All these objects can increase turbulence intensity and can modify the wind conditions influencing wind comfort of people in the lift-up area. In addition, the ambient turbulence intensity of this study is lower than that commonly found in urban sites. The low ambient turbulence intensity may affect the wind conditions near lift-up buildings differently than by high turbulence intensity, for example, the latter is known to be modifying magnitudes and area of corner streams, building wake, and building far wake. Therefore, the effects of objects in the lift-up area and high turbulence intensity of urban wind flows on the wind conditions should be replicated for an accurate evaluation of pedestrian wind comfort.
- The multivariable regression model developed in this study is based on the wind tunnel test data of 28 lift-up buildings. The limited data avoid a comprehensive evaluation of the multivariable regression model, in particular, unrealistic values of design parameters. Therefore, it is advisable to employ an advanced evaluation technique
Fig. 12. Distribution of normalised mean wind speed ($K$) in the lift-up area with (a) rectangular central core ($Rt$), (b) chamfered corners ($Ch$), (c) rounded corners ($Rd$), and (d) recessed corners ($Rc$) of the building M1-B2 for the wind approach at 30°.

Fig. 13. Variation in $AP_{com}$ with two predictors $H/h$ and $h/w$ for a building with $W/d = 5$ and $V_1/V_2 = 0$. 

X. Zhang et al. Journal of Wind Engineering & Industrial Aerodynamics 179 (2018) 58–69
such as wind tunnel tests or CFD simulations to assess the design if the multivariable regression model predicts a negative $AP_{com}$ value. The multivariable regression model can be further improved by using more data obtained from CFD simulations (see Wen et al., 2017; Elshaer et al., 2017) and validating with respect to results of an advanced prediction tool such as the Artificial Neural Network (ANN) model (Elshaer et al., 2017).

6. Concluding remarks

This study investigated the influence of six key design parameters of a lift-up building including height ($H$) and width ($W$) of the main structure, and height ($h$), width ($w$), depth ($d$) and shape of the central core on the pedestrian wind comfort in the lift-up area. In addition, several buildings were tested for three wind directions (15°, 30°, and 45°) to quantify the variation in pedestrian wind comfort in the lift-up area with wind incidence angle. The key findings of this study are;

- The heights of the building and the central core ($H$ and $h$) have a significant influence on high wind speeds in lift-up areas as the magnitude of wind speeds rapidly increases with $H$ but slightly decreases with increase of $h$. In particular, short lift-up cores tend to generate accelerated wind flows with velocities higher than 5 m s$^{-1}$. The relationship between $H/h$ and $AP_{com}$ suggests limiting the $H/h$ ratio less than 30 for building with $W/d = 5$ to create an area larger than 50% of the effective lift-up area with pedestrian wind comfort.
- Compared with width of the building, the width of the central core has a greater effect on creating areas with low wind speeds. The wider central core can produce areas of LWS larger than 50% of the effective lift-up area causing thermal discomfort to the user of the lift-up area. A suitable width for the central core can be determined by limiting the ratio of $h/w$ less than 0.6 as indicated by the multivariable regression model developed in this study.
- Large magnitudes and areas of HWS and small areas with pedestrian wind comfort found for 0° wind incidence angle indicate that wind blowing perpendicular to building width is the critical for evaluating pedestrian wind comfort in the lift-up areas. The areas of HWS and LWS in lift-up areas become small or sometimes are entirely absent at large wind incidence angles from are diminished from. The magnitude of HWS linearly decreases with wind incidence angle but extremely low wind speeds remain unchanged in the lift-up areas even at large wind incidence angles. Overall, the area with pedestrian wind comfort steadily increases with the wind incidence angle.
- The corner modifications are advantageous in creating wind comfort for pedestrians under a perpendicular wind flow (0° wind incidence angle) than a wind flow that approaches in an oblique wind direction. The recessed corners are the most effective corner modification in increasing the area with pedestrian wind comfort in both perpendicular and oblique wind flows.
- The multivariable regression model developed in this study can be used to estimate the area with pedestrian wind comfort in the lift-up area based on preliminary building design. In addition, the multivariable regression model can be employed as an optimisation tool to select the most suitable dimensions for a lift-up building to maximise the area with pedestrian wind comfort in the lift-up area. As the next step, the multivariable regression model will be employed to optimise the design of lift-up building in a future study by taking the pedestrian wind comfort in the lift-up area as the objective of the optimisation process.

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