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Evaluation of Pedestrian Wind Comfort near 'Lift-Up' Buildings with Different Aspect Ratios and Central Core Modifications

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Abstract

Owing to the void space at lower heights, lift-up buildings have high building permeability at ground level and subsequently improve the air circulation in congested urban areas. Despite this advantage, the lift-up design has been sparsely adopted for buildings in urban areas partly because of the lack of understanding of the combined effects of building dimensions and lift-up design on the surrounding pedestrian level wind (PLW) field. Therefore, this study aims to investigate the influence of lift-up buildings with different aspect ratios (height/width) on the surrounding PLW field and pedestrian wind comfort level. Five lift-up buildings with aspect ratios 4:1 to 0.5:1 were tested in a boundary layer wind tunnel and results were compared with those of five buildings with similar dimensions but without lift-up design. The results reveal a strong dependence of the maximal wind speed in lift-up areas with building height, which results subsequently a small area of acceptable wind conditions near tall and slender lift-up buildings. Lift-up designs adopted for short and wide buildings produce larger areas of pedestrian wind comfort. The central cores modified with corner modifications are effective in increasing the pedestrian wind comfort in the lift-up area of tall and slender buildings.

Keywords: Lift-up building, Building dimension, Corner modification, Pedestrian wind comfort, Wind tunnel test

1. Introduction

Wind has a stronger inter-dependence with air temperature than with any other weather factors. Winds largely originate from the temperature gradient between different geographical zones, and wind speed is one of the factors that control indoor and outdoor thermal comfort. On the one hand, Fanger (1972) estimated that the indoor cooling rate of the human body is proportional to $U^{0.5}$, where U is the wind speed in a laminar boundary layer. If the boundary layer is turbulent, which is a common condition in an outdoor environment, then the cooling rate would be approximately proportional to U (Bottema, 1993). Based on this principle, ancient wind catchers such as *Badgir* in Iran and *Manghu* in India, are designed to facilitate the air circulation inside a home to maintain an acceptable indoor temperature while the outside is hot and humid (Krautheim et al., 2014). On the other hand, a lack of air circulation can significantly increase the 'feel-like' temperature, as demonstrated by Cheng and Ng (2012) from field measurements. They reveal that a drop in wind speed from 1 m s^{-1} to 0.3 m s^{-1} is equal to an increase in ambient temperature by 2 ^{o}C on a hot summer day in Hong Kong. In addition, a weak air circulation near the ground causes several wind-related issues in Hong Kong including the degradation of air quality (Cheng and Lam, 1998), increase of the urban heat island effect (Giridharan et al., 2004), and the creation of favourable conditions for spreading airborne pathogens such as the SARS (Severe Acute Respiratory Syndrome) virus (Yu et al., 2004).

The compact arrangement of bulky and tall buildings with small separation distances has been identified as the main reason for weak air circulation in the urban areas of Hong Kong (Yim et al., 2009; Ng, 2009; Tsang et al., 2011). As a solution for the weak air circulation, researchers have proposed to maintain an appropriate level of building permeability at the ground level (Ng et al., 2011) and that is further enforced by building regulations stipulated by the Hong Kong government (HKBD, 2011). Furthermore, the Air Ventilation Assessment

(AVA), a mandatory test for all major government and semi-government development projects, requires that a minimum wind speed of 1.5 m s^{-1} be maintained at the pedestrian level (~ 1.75 to 2 m above ground) to achieve acceptable outdoor thermal comfort on a hot, humid summer day in Hong Kong (Ng et al., 2004). The findings of previous research and the stipulated regulations demand a novel building form that has sufficient building permeability at lower heights to allow air to circulate with minimal obstruction.

'Lift-up' building designs, which are uncommon in Hong Kong, may be a fitting solution to the lack of air circulation in urban areas. In a lift-up design, a void is created in the lower part of a building by elevating the main structure off the ground using columns, shear walls, a central core, or a combination of these. The void, also called the lift-up area, allows air to circulate with a minimal obstruction where a building with impenetrable lower floors does not allow. Furthermore, this void provides space to create sitting or recreation areas for inhabitants of the building. Paths can also be laid in the void for accessing other areas in the surrounding of the building. Despite these advantages, the number of studies on lift-up building designs and the surrounding wind environment is sparse in the literature. Xia et al., (2015) have conducted a series of wind tunnel tests to investigate the PLW fields near an isolated building, an array of buildings, and buildings with podium structures with and without lift-up designs. The wind tunnel test results show a reduction of areas where wind speeds are reduced to less than 1.5 m s^{-1} near the lift-up buildings and thus helpful to achieve outdoor thermal comfort even under weak ambient wind conditions common in Hong Kong. Tse et al., (2017) have tested a number of lift-up buildings in a boundary layer wind tunnel to evaluate how changing the dimensions of the lift-up core influences the pedestrian level wind (PLW) field. This study has confirmed that tall lift-up cores noticeably increase the wind speeds near and within a lift-up area thus, height of the lift-up core is identified as the most significant design parameter for lift-up designs. Du et al., (2017) have employed

Computation Fluid Dynamic (CFD) simulations to assess pedestrian comfort near the lift-up buildings with ‘U’, ‘L’, ‘□’, and ‘-’ plan shapes under three incident wind directions: 0^{o}, 45^{o}, and 90^{o}. They have concluded that lift-up buildings produce better pedestrian wind comfort than non-lift-up buildings, particularly in cases where the wind approaches from an oblique direction.

Despite its effect in enhancing air circulation at the ground level, the conventional lift-up design is not recommended by wind engineers due to unacceptable or unsafe wind conditions found inside the lift-up area (Melbourne and Joubert, 1971; Penwarden, and Wise, 1975; Gandemar, 1975; Beranek, 1984; Stathopoulos et al., 1992). The unacceptable or unsafe wind conditions are attributed to the accelerated wind flow in the lift-up area, which connects the positive pressure on the windward side of the building and the negative pressure on its leeward side (Stathopoulos et al., 1992). The accelerated wind flow contains high wind speeds and can cause discomfort or even danger for pedestrians, particularly if ambient wind speeds are high (Kim, 2014). However, in terms of outdoor thermal comfort and dispersing air pollution, the accelerated wind flow may be more of a benefit than a danger for Hong Kong, especially if ambient wind speeds are low (Ng, 2009).

Although lift-up designs may be presumed appropriate for Hong Kong, the lack of knowledge on (1) designing the lift-up core, (2) its influence on the surrounding wind conditions, and (3) the most suitable type of building (i.e., tall-slender, intermediate, or short-wide) for lift-up designs, makes it difficult for the lift-up concept to be incorporated into building designs. The designing of lift-up core and its effects on the surrounding wind conditions have been addressed properly by the authors of this paper previously (Tse et al., 2017), which provides an invaluable insight on designing central cores and determining their influence on the wind conditions near and within the lift-up area. However, the type of buildings, for which the lift-up design is more suitable, has yet to be investigated systematically, even though the literature has indicated that this type of building has very large implications on the wind conditions in the lift-up area. For example, Wu (1994) estimates that the increase of the maximal normalised wind speed in a passage ($K_{Through}$) underneath a building of height (H) is $0.65*H^{0.24}$. This relationship indicates a possibility to expose pedestrian to a wind flow that has a magnitude approximately double the ambient wind speed measured at the pedestrian level, in a passage underneath a 100-metre building.

High-speed winds that flow through a lift-up area can possibly be reduced if an architecturally modified lift-up core design similar to the design of a tall building is adopted. As indicated by several researchers (Stathopoulos, 1985; Uematsu et al., 1992; Jamieson et al., 1992), modified corners such as chamfered, rounded, and cut corners are effective in reducing the areas of high wind speeds near tall buildings. According to Stathopoulos (1985), by chamfering the corners of a building, the size of the corner streams with high wind speeds can be reduced significantly, thus improving the wind conditions at the pedestrian level to an acceptable level. Results from Uematsu et al. (1992) have demonstrated a superior performance of rounded corners on reducing the area and magnitude of high wind speeds near a 93-metre building, particularly at 0^{o} wind incidence angle. Results of these studies postulate that corner modifications can be applied to a lift-up core to control the volume and the speed of wind flows found in a lift-up area. The current study, therefore, aims to investigate PLW conditions near lift-up buildings with different aspect ratios (height/width) and to assess the effectiveness of a number of corner modifications in achieving pedestrian wind comfort in lift-up areas.

The experimental setup of this study is introduced in Section 2: the specifications to the wind tunnel test, including approaching wind conditions, dimensions of the building models, and details of measurement technique are explained. Section 3 demonstrates the wind speed distributions in the PLW fields around lift-up buildings with different aspect ratios.

Pedestrian wind comfort near lift-up buildings is also evaluated in Section 3 according to a set of wind comfort criteria developed based on the prevailing wind conditions in Hong Kong. The second half of Section 3 presents the wind speed distributions and a comparison of pedestrian wind comfort levels in lift-up areas that have lift-up cores without corner modifications. The effectiveness of corner modification is also evaluated in the second half of Section 3 by comparing the PLW wind conditions in modified and basic lift-up designs (i.e. lift-up cores without corner modifications). A number of concluding remarks are stated in Section 4.

2. Experimental Setup

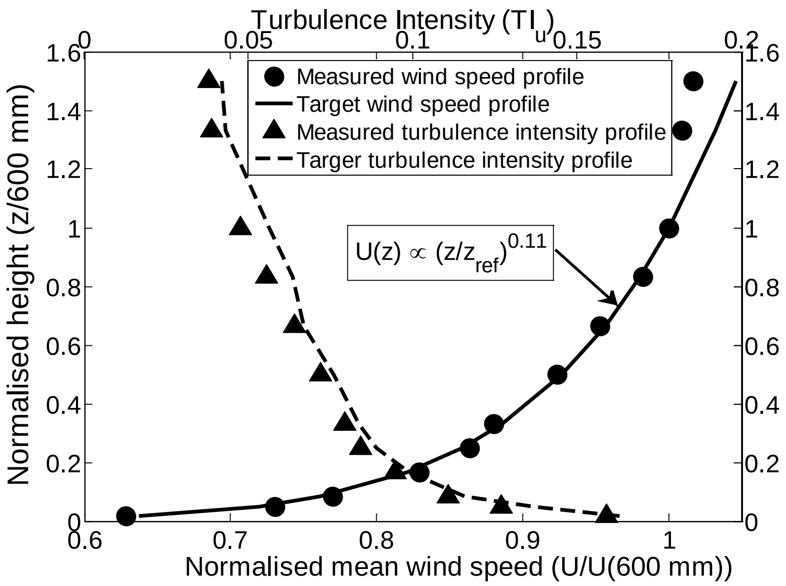


Figure 1. Normalised mean wind speed and turbulence intensity profiles at the centre of the turntable

All wind tunnel tests described in this study were conducted in the CLP Power Wind/Wave Tunnel Facility (WWTF) at the Hong Kong University of Science and Technology. The boundary layer wind tunnel (BLWT) of the WWTF is of a closed return type with two parallel test sections named the high-speed and low-speed sections according to their operational wind speed ranges. The low-speed section, whose test section's dimensions are 5 m × 4 m (width × height) was selected to conduct wind tunnel tests in this study under the test section's maximal operating wind speed of 10 m s^{-1}. The roughness elements and spires were arranged systematically in the development section of the low-speed section to simulate an atmospheric boundary layer (ABL) wind flow, as shown in Figure 1. The mean wind profile in Figure 1 is normalised with respect to the mean wind speed measured at a height of 600 mm at the centre of the turntable. The mean wind speed there was about 7.35 m s^{-1} and was part of a wind profile that followed the power-law wind profile model with an exponent of 0.11. The Reynolds number (*Re*) calculated based on width of the building, 150 mm, is 7.35×10^4 (> $Re_{critical}$ =5×10^4), thus flow conditions are independent from the Reynolds number. Moreover, the turbulence intensity profile displayed a proper vertical decay as in an ABL wind flow, and measured turbulence intensity at the normalised height of 600 mm was about 4.76 %.

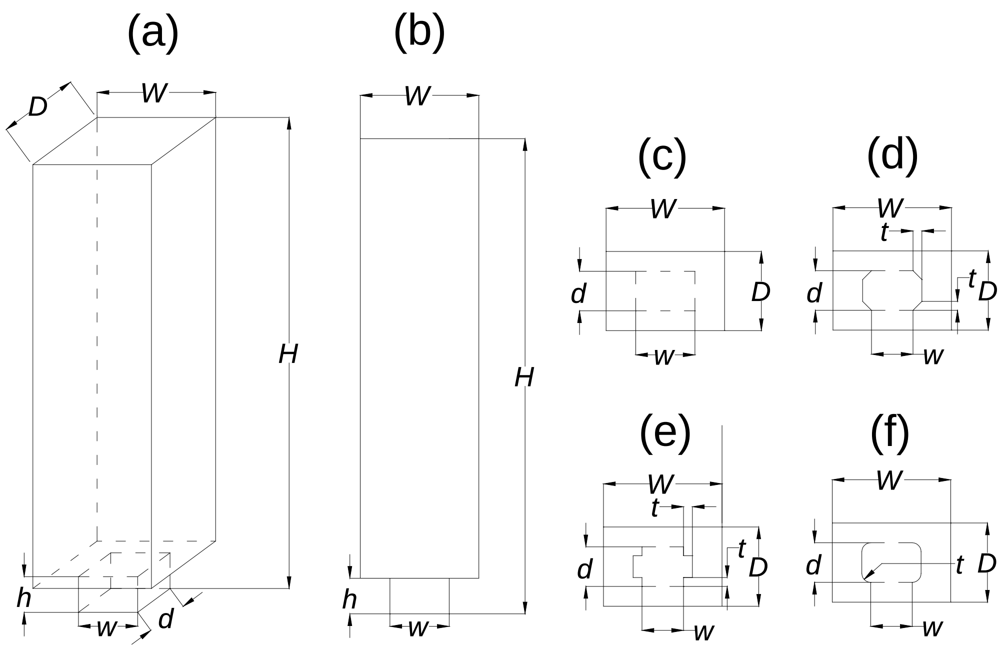
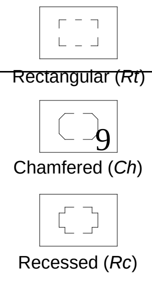


Figure 2. Schematic diagrams of a 'lift-up' building (a) 3-D view, (b) front view, and (c) rectangular central core (*Rt*), (d) chamfered central core (*Ch*), (e) recessed central

core (*Rc*), and (f) rounded central core (*Ro*) (corner modifications are applied over a length, *t* = 2.25 m)

Figure 2 shows the schematic diagrams of the lift-up buildings tested in this study. All buildings have a central core to elevate the main structure from the ground. The central core design is preferred over columns or shear wall designs because a central core induces a minimal disturbance to the wind conditions in a lift-up area (Tse et al., 2017), of which the evaluation is the main objective of this study. The central core has a constant height (*h*) of 6 m, and a depth (*d*) of 10 m, but different widths (*w*) to maintain a constant plan area of 25% of the total plan area of a building. The basic central core with a rectangular shape (*Rt*) (Figure 2(c)) was modified using three corner modifications; chamfered (*Ch*), rounded (*Ro*), and recessed (*Rc*) as shown in Figures 2 (d)-(f). Each modification was applied to all corners and extended a 2.25 m distance on each side. Table 1 shows the dimensions of the buildings, central cores and corner modifications used in this study. The height of the buildings (*H*) varied from 120 m to 45 m and the width (*W*) spanned from 30 m to 90 m, covering a range of aspect ratios (*H*/*W*) from 4:1 to 0.5:1. Depth (*D*) of the buildings was not a main design parameter of this study, thus it was kept at a constant value of 20 m. In addition, five buildings with similar dimensions to the 'lift-up' buildings but without a central core were selected as the control buildings (CB) for this study. All buildings were scaled by a factor of 1/200 (a linear scale of 1:200) and were made of balsa wood for the wind tunnel tests.

Table 1. Full-scale dimensions of the selected buildings

Control building	Building dimensions (m)			Aspect ratio	Lift-up building	Lift-up dimensions (m)			Shapes of central core
	Height (*H*)	Width (*W*)	Depth (*D*)	(*H*/*W*)		Height (*h*)	Width (*w*)	Depth (*d*)	
CB1	120	30	20	4:1	M1	6	15	10	

CB2	60	30	20	2:1	M2	6	15	10	
CB3	45	30	20	1.5:1	M3	6	15	10	
CB4	45	60	20	0.75:1	M4	6	30	10	
CB5	45	90	20	0.5:1	M5	6	45	10	

Mean wind speeds at the pedestrian level were measured by using two types of omnidirectional wind speed sensors: Irwin sensor, and Kanomax thermal anemometer (Kanomax1560). The Irwin sensors used for this study were fabricated according to a linear scale of 1:200 with a 10 mm protruding tube. The protruding tube was to measure the mean wind speed at the height of 10 mm in model scale or a 2 m height in full scale according to the linear scale of 1:200. The mean wind speed (U) was calculated from Irwin sensor measurements according to the method proposed by Irwin (1981) as expressed in equation (1).

$$U = \alpha + \beta\sqrt{\Delta P}$$

(1)

In equation (1), $\sqrt{\Delta P}$ is the square root of the pressure difference between two holes on an Irwin sensor, and α, and β are constants, which are determined by calibrating Irwin sensors with respect to instantaneous wind speeds (u) measured by a hot-wire anemometer. In the present study, α and β were estimated to be 0.15 and 1.72, respectively.

The Kanomax1560 anemometer system is a multi-channel thermal anemometer system, which has multiple wind speed sensors and a data acquisition unit. The wind speed sensor is a spherical thermistor-type omnidirectional sensor, which measures the resultant mean wind speed at a sampling frequency of 10 Hz. Each sensor has a temperature compensator unit to correct any effects from room temperature fluctuations on the measurements and is precalibrated with its own individual calibration curve. Its convenience in operating, and the ability to measure low wind speeds are the advantages of the Kanomax anemometer system being used in pedestrian-level wind tunnel tests.

There were 186 Irwin sensors and 34 Kanomax sensors arranged systematically around a ‘lift-up’ building as shown in Figure 3. Altogether the wind speed sensors of the two types covered an area spanning 375 mm in the upstream direction, 1425 mm in the downstream direction, and 600 mm in the lateral directions from the centre of the building model. The minimal separation distances of Irwin sensors were 75 mm in the longitudinal direction and 100 mm in the lateral direction, satisfying the minimal separation distances proposed by Wu and Stathopoulos (1994). Kanomax sensors had a minimal spacing of 30 mm in both the longitudinal and lateral directions. The wind speed measurements were recorded for 135 seconds at a sampling rate of 400 Hz for the Irwin sensors and 10 Hz for the Kanomax anemometers. With an assumed velocity ratio of 1/7, the sampling time period of the wind tunnel tests is equal to a one-hour of measurement period in field conditions.

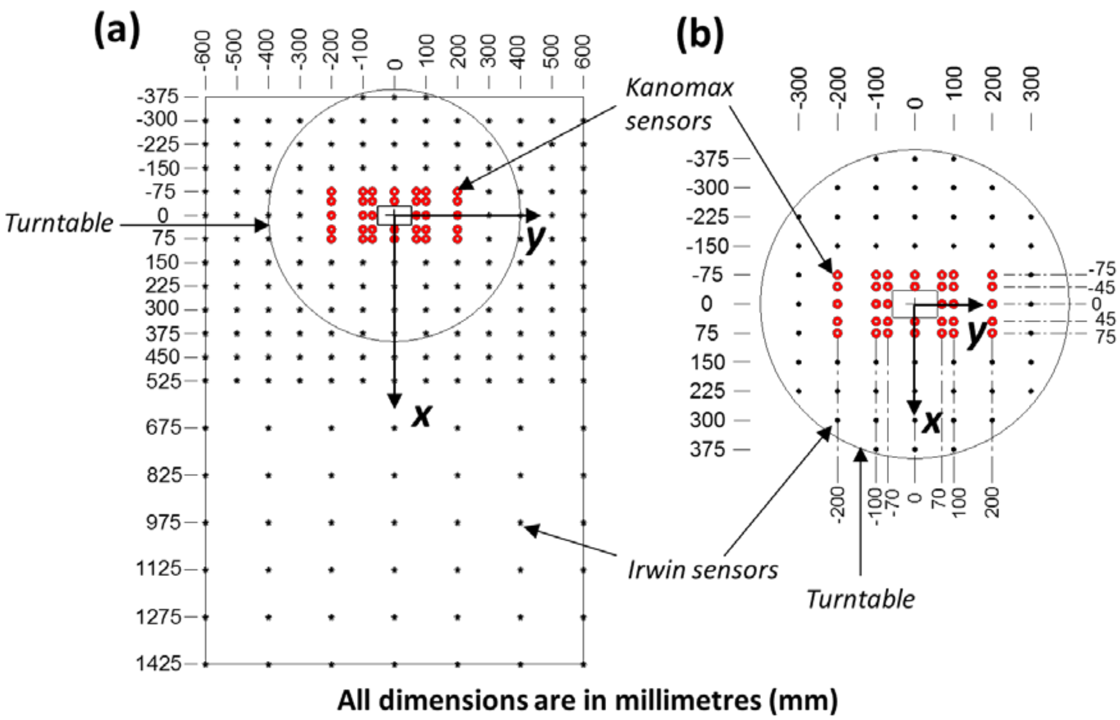


Figure 3. The sensor arrangement (a) in the whole measurement area, and (b) within the turntable

3. Result and discussion

3.1.Maximal wind speed in the 'lift-up' area

Before conducting a detailed analysis, the notion that the maximal wind speeds in the 'lift-up' area may have a similar relationship with building height, as proposed by Wu (1994), needs to be investigated. For comparisons with similar data from four previous studies (Melbourne and Joubert, 1971; Gandemer, 1975; Penwarden and Wise, 1975), the maximal wind speeds at the pedestrian level in the 'lift-up' area are normalised using equation (2):

$$K = \frac{\overline{U}_{10mm,x,y}}{\overline{U}_{ambient}} \qquad (2)$$

where, $\overline{U}_{10mm,x,y}$ is the mean wind speed at the 10 mm height measured at location (x, y), and $\overline{U}_{ambient}$ is the mean wind speed at the same location but without the building.

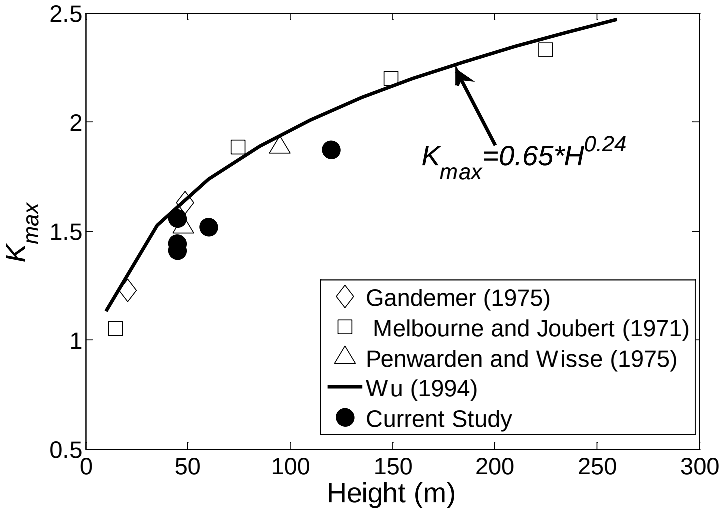


Figure 4. Variation of the maximal normalised mean wind speed in the open space underneath the building (K_{max}) with building height

Figure 4 shows the comparison of the normalised maximal wind speed (K_{max}) found in the lift-up area of buildings M1-M5 with similar data of the four previous studies. The K_{max} values of lift-up buildings deviate moderately from the predictions of $K_{max} = 0.65*H^{0.24}$ with smaller magnitudes than the corresponding values of the previous studies, which tested buildings with a passage underneath them. Despite having smaller values, a steady increase in K_{max} values with building height suggests that tall lift-up buildings have a trend of generating accelerated wind flows in lift-up areas similar to a passage underneath a tall building does. Smaller K_{max} values of the lift-up buildings may be attributed to the difference in designs of a lift-up area and a passage underneath a building, where the latter can be considered as an orifice that channels wind flow from the windward side of the building to the leeward side. A lift-up area, however, is opened to the ambience on the lateral sides by allowing some winds to leak from the lift-up area, thus producing a wind flow that is not as intense as in a passage underneath a building. Compared with the notable increase with building height, the K_{max} value increases slightly with building width (W). The limited wind tunnel test results, however, restrain the possibility of further investigating the increase of K_{max} with building width and proposing a new relationship between the K_{max} value and lift-up building height.

3.2.Proposed pedestrian wind comfort criteria

Several researchers have proposed a number of pedestrian wind comfort criteria based on mechanical and thermal effects of winds (Davenport, 1972; Gandemer, 1975, 1978; Isyumov and Davenport, 1975, 1978; Lawson, 1975; Hunt et al., 1976; Melbourne 1978). Any pedestrian wind comfort criteria has threshold wind speeds in the form of mean, gust or a combination of both defined based on physical or mental acceptability in performing specific types of pedestrians' activities in assigned areas, in combination with allowable frequencies of occurrence or an exceedance within a certain duration of time (Koss, 2006). By considering prevailing wind conditions in Hong Kong, a novel pedestrian wind comfort criteria has been proposed for this study as shown in Table 2.

Table 2. Proposed pedestrian wind comfort criteria

Wind Speed (m s^{-1})	K_{200}	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

It is noteworthy that the proposed pedestrian wind comfort criteria are based on mean wind speeds and an assumed a 50% probability of exceedance. The minimal threshold mean wind speed of 1.6 m s^{-1} is in accordance with generally accepted minimal wind speed for outdoor thermal comfort on a hot humid summer day in Hong Kong (Cheng et al., 2012). The maximal threshold wind speed of 5 m s^{-1} is based on the recommendation of Penwarden (1973) as an acceptable wind speed in a town. An intermediate wind speed, 3.5 m s^{-1}, marks the beginning of wind discomfort felt by pedestrians as the wind disturbs hair, causes clothes to flap and makes it difficult to read newspapers (Penwarden, 1973).

The K_{200} values listed in Table 2 are the ratio between threshold wind speeds and mean wind speed measured at a height of 200 m at the meteorological station at Waglan Island (U_{200}) and is estimated from long-term wind measurements, which are also accepted as the representative wind conditions of Hong Kong, to be about 5-6 m s^{-1}, with a probability of exceedance of 50% (Hitchcock et al., 2003). By considering U_{200} is 5 m s^{-1}, then the K_{200} values of 0.3 and 0.7 m s^{-1} mark the limits of low wind speed (LWS), which cause outdoor thermal discomfort, and high wind speed (HWS), with which pedestrians may feel annoyance from the wind. K_{200} values that fall between 0.3 and 0.7, therefore, indicate acceptable wind conditions in Hong Kong, while a K_{200} value exceeds 1 is unacceptable and should be prevented from occurring at any location near a building.

Although the K_{200} ratio is convenient in interpreting wind conditions near buildings, the calculation of the K_{200} ratio is not straightforward because of the differences between the mean wind profile measured at Waglan Island and the simulated mean wind profile for wind tunnel tests in this study. More specifically, the mean wind profile at the Waglan Island follows the power-law wind profile model with an exponent (a) equal to 0.15, which corresponds to sea and open terrain conditions (HKPD, 2005), while the wind profile simulated for this study has a power-law exponent of 0.11. Therefore, the calculation of K_{200} requires a conversion of wind speeds between the two wind profiles as shown in Equation (3).

$$\left.\begin{aligned}
K_{200} &= \left(\frac{\overline{U}_{2m}}{\overline{U}_{200m,\alpha=0.15}}\right) \\
K_{200} &= \left(\frac{\overline{U}_{2m}}{\overline{U}_{2m,ambient}}\right)_{a=0.11} \cdot \left(\frac{\overline{U}_{2m}}{\overline{U}_{200m}}\right)_{a=0.15} \\
K_{200} &= \left(\frac{\overline{U}_{2m}}{\overline{U}_{2m,ambient}}\right)_{a=0.11} \cdot \frac{\overline{U}_{500}\left(\frac{2}{500}\right)^{0.15}}{\overline{U}_{500}\left(\frac{200}{500}\right)^{0.15}} \\
K_{200} &= \left(\frac{\overline{U}_{2m}}{\overline{U}_{2m,ambient}}\right)_{a=0.11} \cdot \left(\frac{2}{200}\right)^{0.15} \\
K_{200} &= \left(\frac{\overline{U}_{2m}}{\overline{U}_{2m,ambient}}\right)_{a=0.11} \times 0.5012 \\
K_{200} &= K \times 0.5012
\end{aligned}\right\} \tag{3}$$

In Equation (3), $\overline{U}_{500}$ is the mean wind speed measured at a height of 500 m, which is considered as the gradient height in Hong Kong. It should be noted that similar wind speed conversions were employed by Gandemar (1975), and Blocken and Pearson (2009) if the two wind profiles in wind tunnel tests and field conditions were different from each other.

3.3. General flow features in the surrounding PLW field of lift-up buildings

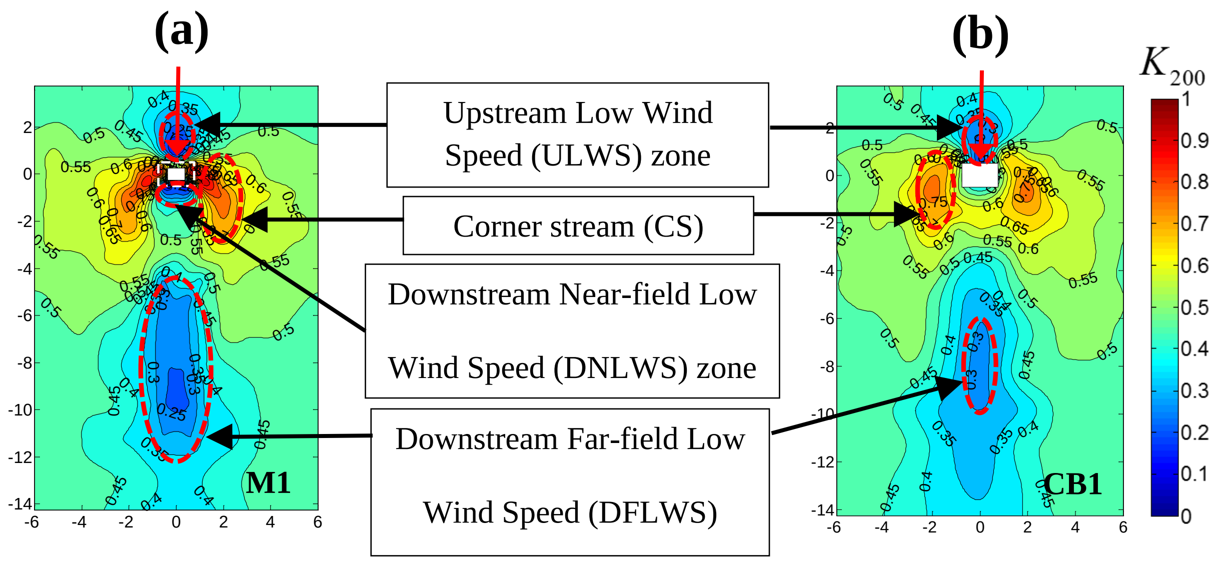


Figure 5. Distribution of K_{200} value near (a) a lift-up building (M1) and (b) a control building (CB1)

Figure 5 shows the distribution of K_{200} values in the PLW fields near the lift-up building (M1) and the control building (CB1). The red arrow shown in the upstream edge of each figure points in the direction of the approaching wind and all the distances are normalised with respect to the constant building depth (*D*) of 20 m. Clearly, the two PLW fields are similar in that they have several common flow features with LWS and HWS. More specifically, there are three LWS zones: the Upstream Low Wind Speed (ULWS) zone, Downstream Near-field Low Wind Speed (DNLWS) zone and Downstream Far-field Low Wind Speed (DFLWS) zone, and an HWS zone: the Corner Stream (CS) on the lateral sides of the buildings. Some of these flow features may not appear in the PLW fields of both the lift-up and control buildings, for example, compared with a prominent DNLWS zone that can be identified near building M1, the DNLWS zone is outright absent for CB1. The magnitude and area of these flow features also vary considerably for the lift-up and control buildings. For example, the K_{200} values in the ULWS zone of M1 are significantly lower than those of

CB1, while the areas of the CS zone and the UFLWS zone of M1 are larger than those of CB1.

Figure 6 demonstrates how the PLW field varies with heights and widths of the lift-up buildings and corresponding control buildings. The overall variations of the PLW fields such as changes in the locations of common flow features are similar near both lift-up and control buildings. For instance, the distance between the building centre and the UFLWS zone decreases with building height, and the width of the ULWS zone increases with building width for both lift-up and control buildings. However, the properties of the common flow features exhibit distinct differences in variations of area and magnitude near the lift-up buildings and control buildings. An example is that the DNLWS zones of the lift-up buildings swell rapidly with building width and have small K_{200} values, while the area of the DNLWS zone of the control buildings increases at a lower rate. HWS in the corner streams of the lift-up buildings reduces slowly with building height but with the increase of building width the CS zones of the lift-up buildings grow and stretch to a longer distance (e.g. M4 and M5) compared with those of the corresponding control buildings.

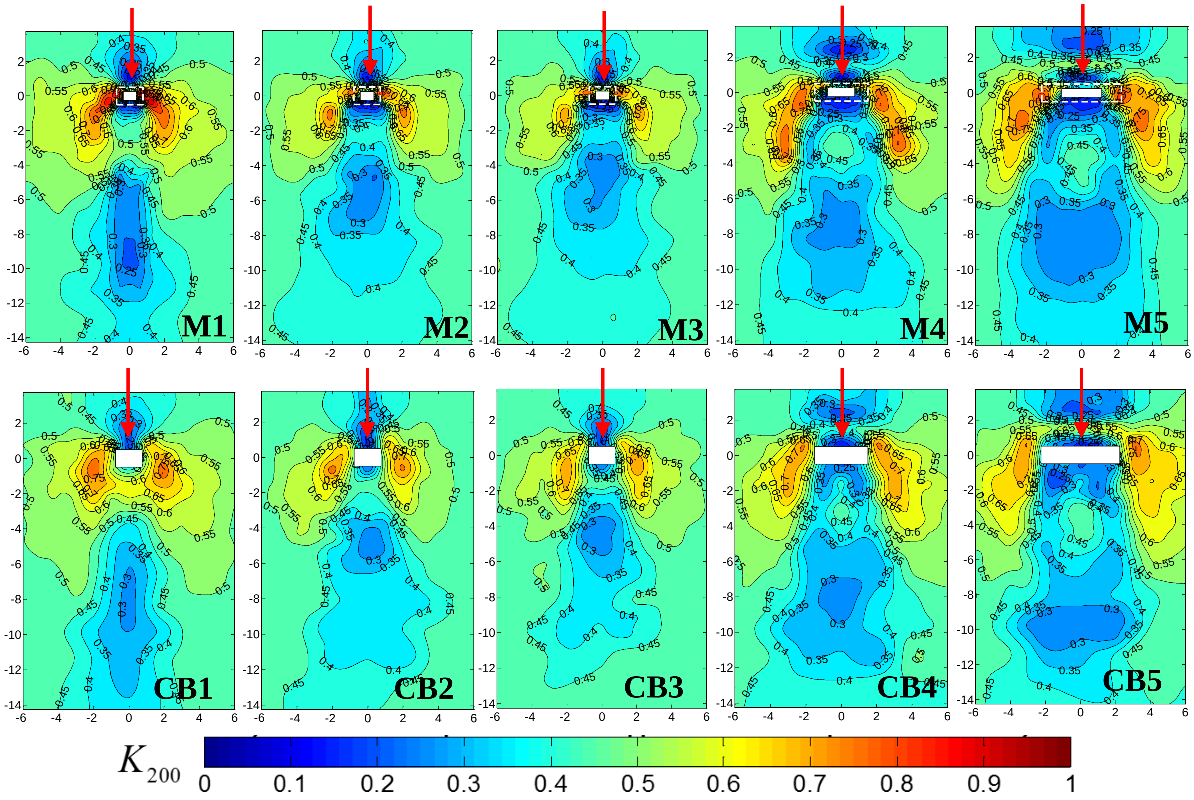


Figure 6. Distribution of K_{200} value near the five lift-up building (M1-M5) and the corresponding control buildings (CB1-CB5)

3.3.1. Areas with high wind speeds (HWS)

The variation of HWS zone with the dimensions of lift-up and control buildings is estimated by defining the area average of high wind speed ($\overline{K}_{HWS}$) as in Equation (4).

$$\overline{K}_{HWS} = \frac{\sum_{K_{200}=0.7}^{1} [A_{(K_{200},K_{200}+0.05)} \times K_{200(K_{200},K_{200}+0.05)}]}{A_{HWS}}$$

(4)

In Equation (4), K_{200} is the contour level when the mean wind speed ratio is larger than 0.7; A_{HWS} is the total area of the HWS zones and $A_{(K_{200}+K_{200}+0.05)}$ is the area within the contour lines K_{200} and K_{200}+0.05.

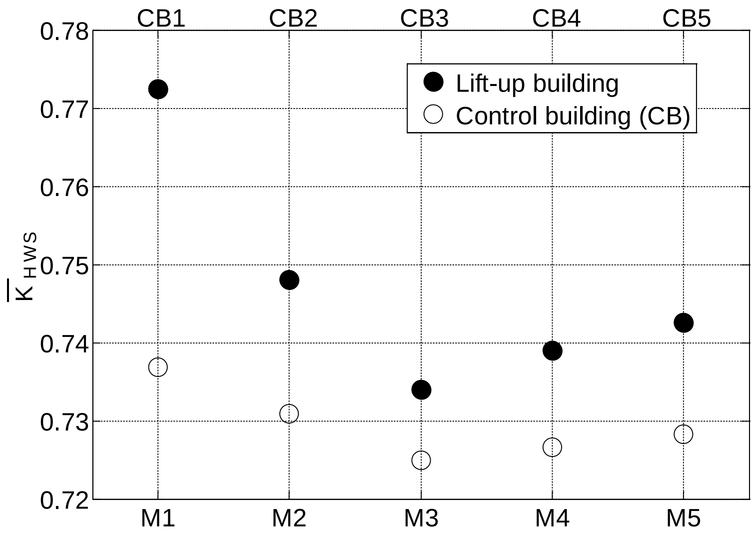


Figure 7. Area average of high wind speed ($\overline{K}_{HWS}$) of the 5 lift-up buildings and the corresponding control buildings and (b) area percentage of high wind speeds

Figure 7 shows the effect of building dimensions on the HWS zones near the lift-up and control buildings. The $\overline{K}_{HWS}$ values of lift-up buildings are higher than the corresponding control buildings may be due to the combined effect of high K_{200} values and large CS zones of the lift-up buildings. Tse et al., (2017) have revealed that the large CS zones of lift-up buildings are a combination of two sets of CS zones of the main structure and central core. The difference in $\overline{K}_{HWS}$ values between the lift-up buildings and control buildings is at its maximum for the tall and slender buildings (M1 and CB1), for which the difference is of about 5% and for the widest buildings (M5 and CB5), the difference is moderate about 2% but becomes its minimum for the intermediate buildings such as M3 and CB3. The rapid drop in $\overline{K}_{HWS}$ values with building height compared with a moderate increase of $\overline{K}_{HWS}$ values with building width postulates a greater influence of building height on creating HWS zones near lift-up buildings.

Since the $\overline{K}_{HWS}$ values represent the combined effects of the magnitude and area of HWS zones, Figure 7 does not distinguish how lift-up building dimensions influence the HWS zone by altering area of HWS and wind speed. Therefore, Figure 8 is plotted to demonstrate the variations of areas of HWS for the 5 lift-up buildings and their complementary control buildings. The percentage area (*AP*) of HWS, which is defined as a ratio between the areas of HWS to the total measurement area (1.2 × 1.425 m^2), decreases with building height such that the *AP* values of M3 and CB3 are similar. Despite having slight differences in $\overline{K}_{HWS}$ values, buildings M3 and CB3 have the difference in *AP* of about 0.06, whereas the *AP* difference between M1 and CB1 is 1.06, which also have a considerable difference in $\overline{K}_{HWS}$ values, as shown in Figure 7. The comparison of *AP* differences together with the difference in $\overline{K}_{HWS}$ values of buildings depicts a more prominent influence of building height on the magnitude of HWS than on the areas of HWS. Larger HWS areas of short and wide lift-up buildings may be the principal contributor of high $\overline{K}_{HWS}$ values of buildings M4 and M5 as observed in Figure 7. In fact, a short and wide lift-up building can generate an area of HWS twice the size of the HWS area of a building without lift-up design, as evident from buildings M5 (*AP* = 4.29) and CB5 (*AP* = 2.28). A less significant influence of building width on the magnitude of HWS is further validated by Figure 4, which shows approximately the same K_{max} values for lift-up buildings M4 and M5, which have the same height but different widths.

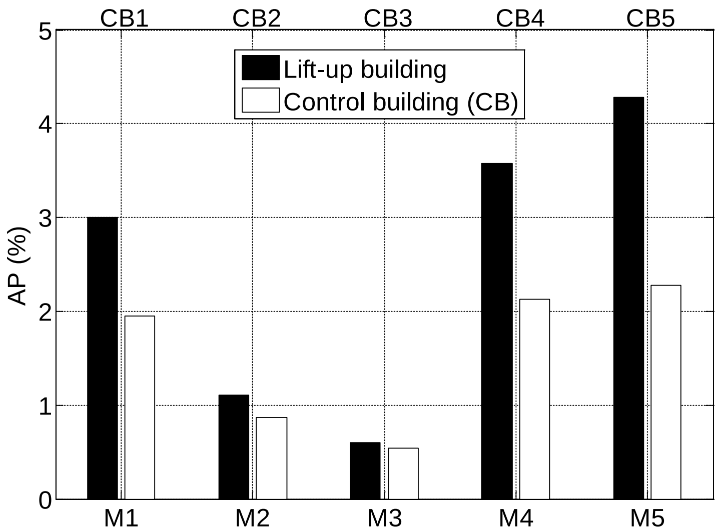


Figure 8. Area percentage (*AP*) of high wind speed (HWS) of the 5 lift-up buildings and the corresponding control buildings

3.3.2. Areas with low wind speeds

Similar to the analysis of HWS, the LWS zones are scrutinised separately according to their locations in the upstream and downstream directions of a building. Since the LWS zone far downstream, i.e., the DFLWS zone, of the tested lift-up and control buildings displays minimum variations with building dimensions (see Figure 6), the following analysis only focuses on discerning the variations of the LWS zone in the downstream near-field (the DNLWS zone) of the buildings. Figure 8 shows the variation of $\overline{K}_{LWS}$ value, which is calculated according to Equation (5), for the lift-up and control buildings.

$$\overline{K}_{LWS} = \frac{\sum_{K_{200}=0}^{0.3} [A_{(\mathrm{K}_{200},\mathrm{K}_{200}+0.05)} \times K_{200(\mathrm{K}_{200},\mathrm{K}_{200}+0.05)}]}{A_{LWS}}$$

(5)

In Equation (5), K_{200} is the contour level when the mean wind speed ratio is smaller than 0.3; A_{LWS} is the total area of the LWS zones either in the upstream or downstream area of a building and $A_{(K_{200}+K_{200}+0.05)}$ is the area within the contour lines K_{200} and K_{200}+0.05.

Figure 9 displays the area average of low wind speed in the upstream near-field ($\overline{K}_{ULWS}$) and downstream near-field ($\overline{K}_{DNLWS}$) of buildings. Across the test cases, the control buildings have larger $\overline{K}_{LWS}$ values than the corresponding lift-up buildings, thus indicating a less severe problem of LWS near the control buildings. Particularly, the tall and slender control building CB1 reported a 5.5% higher $\overline{K}_{ULWS}$ value (Figure 7(a)) and a zero $\overline{K}_{DNLWS}$ value compared with the lift-up building M1 (Figure 7(b)). The outright absence of the DNLWS zone in building CB1 (see Figure 5) may be attributed to the strong horseshoe vortex of CB1 that wraps firmly around the base of the building, preventing the formation of an LWS zone attached to the building's leeward side. It is noteworthy that, compared to the slight differences of $\overline{K}_{ULWS}$ values about 2-10%, the difference of $\overline{K}_{DNLWS}$ values is significant and is about 13%-23% (excluding M1 and CB1), therefore indicating a possible problem of having larger areas or smaller wind speeds or both on the leeward side of a lift-up building.

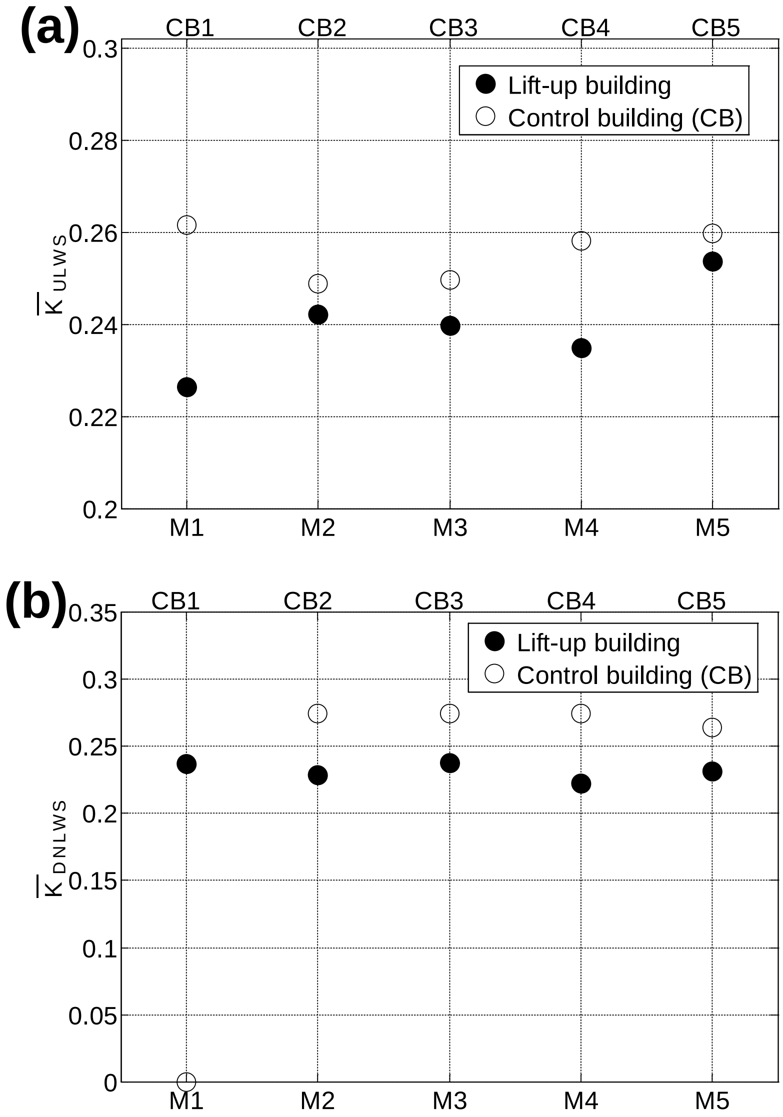


Figure 9. Area average of low wind speed ratios in (a) upstream ($\overline{K}_{ULWS}$) (b) downstream near-field ($\overline{K}_{DNLWS}$) of the 5 lift-up buildings and the corresponding control buildings

Figure 10 shows the area percentage (*AP*) of LWS zones in the upstream direction and the downstream near-field of the lift-up and control buildings. According to Figure 10(a), the control buildings have larger areas of LWS in the upstream direction than their corresponding lift-up buildings. The results shown in Figures 9(a) and 10(a) postulate that the ULWS zones of the lift-up buildings are comparable in size but smaller in K_{200} values than those of the control buildings. Smaller K_{200} values of the lift-up buildings indicate a possible effect of the leakage of downwash flow through the lift-up area that consequently weakens the reverse flow generally found in front of buildings (Hosker, 1985). Figure 6 also verifies the postulation of smaller K_{200} in the ULWS zone of the lift-up buildings, for example, despite 15% smaller in area, the lift-up building M5 is only 2.3% smaller in the $\overline{K}_{ULWS}$ value compared with the corresponding control building CB5. Smaller $\overline{K}_{DNLWS}$ values of the lift-up buildings also relate to the less intensive downwash flow, which subsequently creates a horseshoe vortex that is too weak to wrap firmly around the building base allowing an LWS zone to form and attach itself to the building's leeward side. Owing to the strong horseshoe vortex of the control buildings CB1-CB3, they either do not have the DNLWS zone or their DNLWS zones are extremely small with AP = 0~0.06 compared with fairly large areas (e.g. AP=0.42~0.80) of the DNLWS zones of the lift-up buildings. The results of the current study are tally with the results of the previous study (Tse et al., 2017), in which larger DNLWS zones were found near 120 m tall lift-up buildings with different sizes of central cores compared with a 120 m tall building without lift-up design. However, the control buildings CB4 and CB5, whose aspect ratios are less than 1, have 9% and 22% larger AP values in the DNLWS zones compared with their corresponding lift-up buildings M4 and M5, despite the lower calculated $\overline{K}_{DNLWS}$ for the lift-up buildings. Smaller areas of the DNLWS zones of the short and wide lift-up buildings (H/W < 1) may be caused by the expansion of the DNLWS zone to the lateral sides of the wide central cores, and are subsequently exclude from the AP calculation rather than an actual reduction of the LWS area (Tse et al., 2017). On the other hand, wide central cores, which induce large wind blockage, produce considerably small K_{200} values on the leeward side of the short and wide lift-up buildings and result in $\overline{K}_{DNLWS}$ values smaller than those of the control buildings.

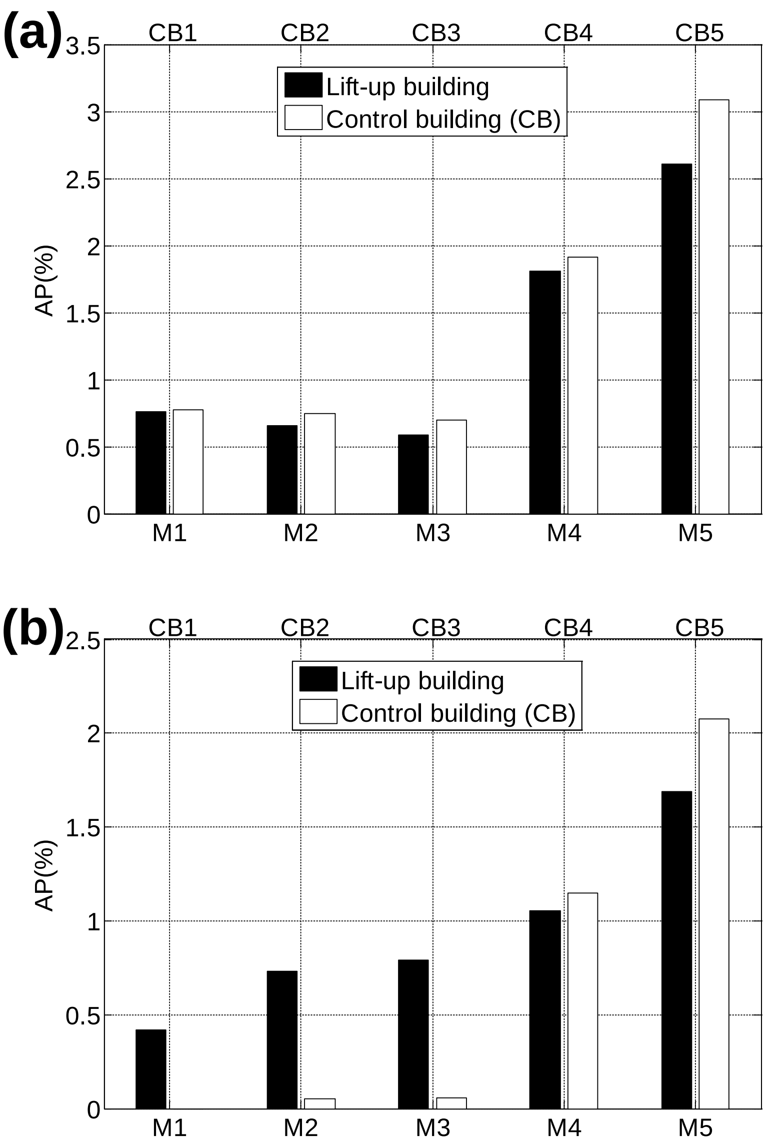


Figure 10. Area percentage (*AP*) of LWS zones in (a) upstream (b) downstream near-field of the 5 lift-up buildings and the corresponding control buildings

3.4.Pedestrian wind comfort in lift-up area

The distribution of K_{200} values in lift-up areas with rectangular shaped central cores (*Rt*) are shown in Figure 11. Since in a previous study, Tse et al. (2017) have identified central core height and its plan area as the most influential design parameters for a lift-up design, both parameters are kept constant to minimise the effects of central core dimensions on wind conditions in a lift-up area. Therefore, the variations of K_{200} value in Figure 11 strongly relate to height and width of the relevant lift-up building with some effects of the central cores, which are considered as a constant for all the tested lift-up buildings. For example, the lift-up area of building M1, which is the tallest lift-up building tested in this study, has the maximal K_{200} value of 0.95, thus indicating possible wind discomfort for pedestrians in the lift-up area. However, the maximal K_{200} value drops from 0.95 to 0.75 as building height decreases from 120 m (building M1) to 45 m (building M3), indicating a reduced level of pedestrian wind discomfort in lift-up areas of buildings with the aspect ratio less than 2. The maximal K_{200} value further reduces to 0.7 in building M4 before that value increases to 0.8 in building M5, suggesting the given dimensions of the central core (h = 6 m, and A = 25%) are the most suitable for a lift-up building with similar dimensions to building M4. This opinion is further validated by the data shown in Figure 12, where the $AP_{effective}$ value, which is the percentage area with acceptable wind conditions (i.e. $0.3 < K_{200} > 0.7$), is maximal for Building M4 ($AP_{effective}$=0.70). Two lowest $AP_{effective}$ values: 0.46 and 0.58, are calculated for Buildings M1, M2 and M5, of which M1 and M5 are the most slender and the widest buildings among the tested 5 lift-up buildings. Therefore, the $AP_{effective}$ values in Figure 12 suggest that the use of central core design would be beneficial for buildings with aspect ratio $0.33 < H/W < 1.25$ to create the maximal area with the pedestrian wind comfort in lift-up areas.

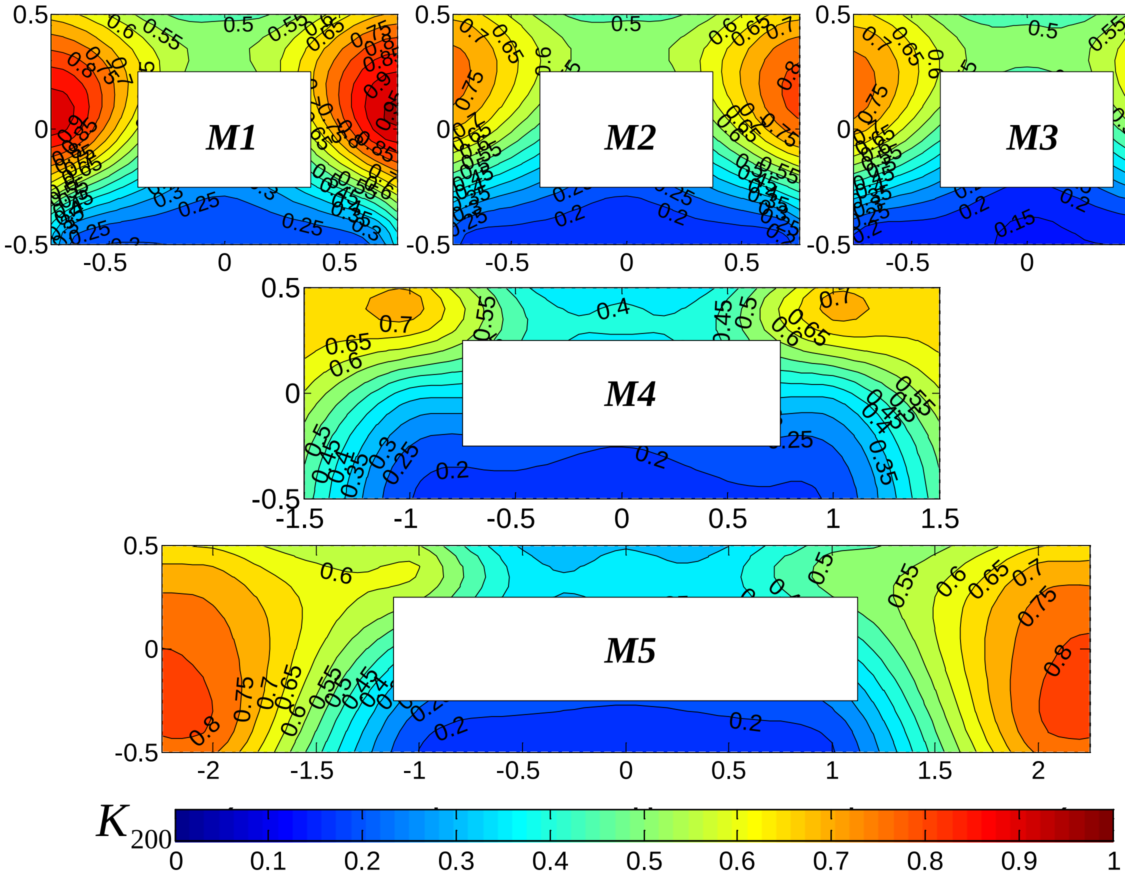


Figure 11. Distribution of K_{200} values in the lift-up area of the 5 lift-up buildings.

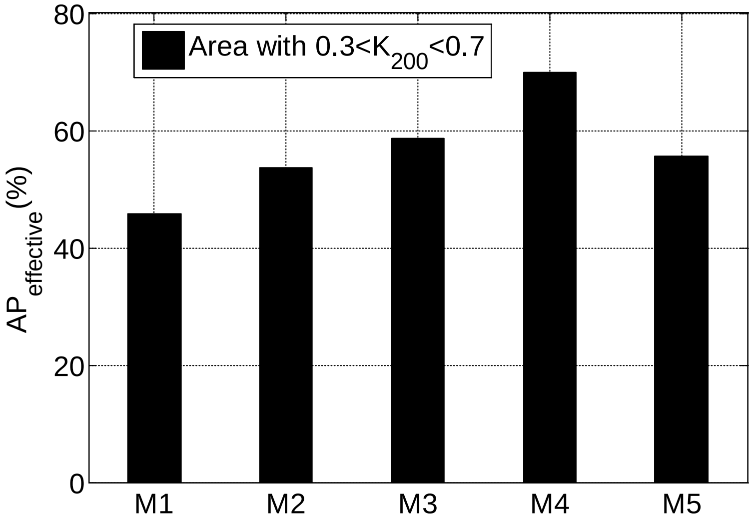


Figure 12. The effective percentage area ($AP_{effective}$) in lift-up areas with rectangular central cores of the 5 lift-up buildings

3.5.Pedestrian wind comfort in Lift-up areas with modified central cores

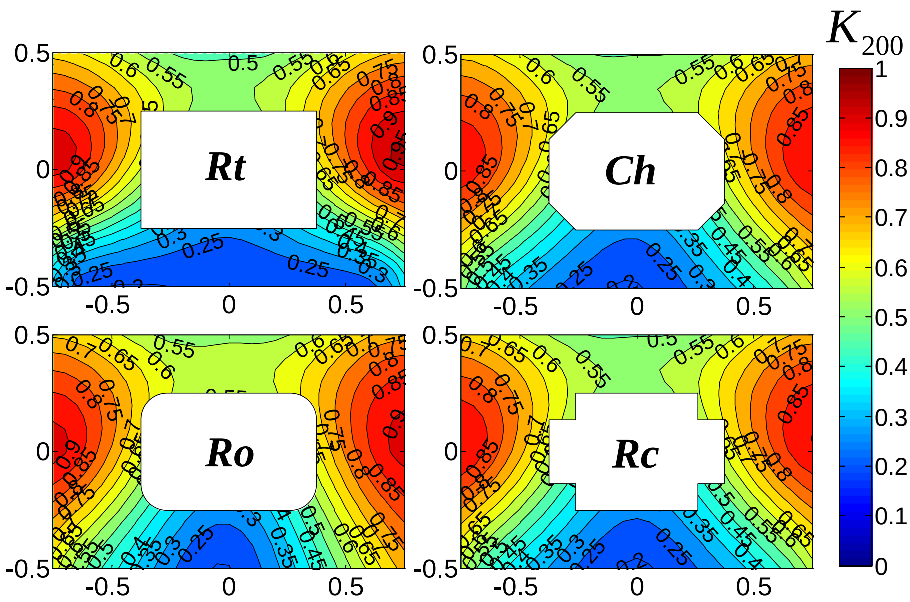


Figure 13. Distribution of K_{200} values in the lift-up area of building M1 with the basic rectangular shaped central core (*Rt*) and the central core modified with chamfered corners (*Ch*), rounded corners (*Ro*), and recessed corners (*Rc*)

As evident from Figure 12, building M1 has the lowest pedestrian wind comfort among the five tested lift-up buildings, and the wind conditions may even be unacceptable, as the maximal K_{200} value is close to 1. To improve the wind conditions in the lift-up area of building M1, as well as to investigate any further increase of pedestrian wind comfort in the lift-up area of other buildings, three types of corner modifications, chamfered (*Ch*), recessed (*Rc*), and rounded (*Ro*) have been added to the basic rectangular shaped central core (*Rt*).

Figure 13 shows the distribution of K_{200} values in the lift-up area of building M4, which has a central core modified with three corner modifications. The chamfered and recessed corners lower the maximal K_{200} value from 0.95 to 0.85 while the rounded corners reduce it by only 0.05. However, no corner modification is able to reduce the area of HWS significantly or change the location where the maximal K_{200} occurs. The most noticeable flow modification is found on the leeward side of the central cores, where the size of the LWS zone is significantly reduced for modified central cores. The LWS zone behind the basic central core (*Rt*) is the largest in the area and spans beyond the width of the core, but the area gradually shrinks for chamfered (*Ch*) to recessed (*Rc*) corners until the LWS zone has its smallest area for the rounded corners (*Ro*).

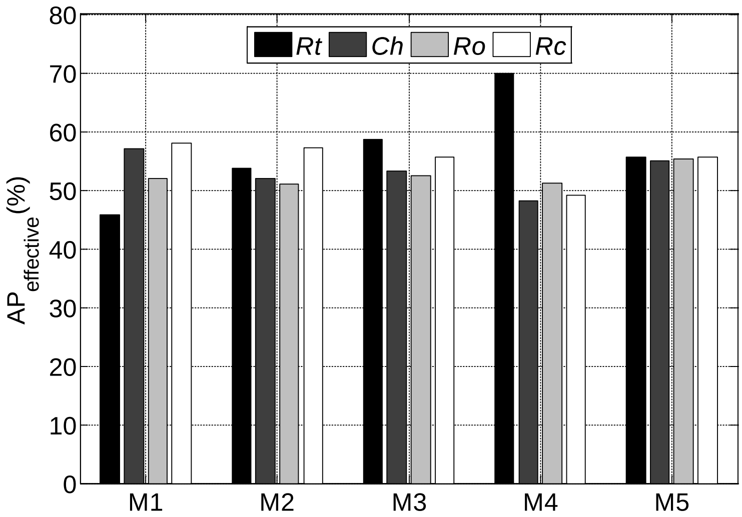


Figure 14. The effective percentage area ($AP_{effective}$) in lift-up area of the 5 lift-up buildings with the basic rectangular shaped central core (*Rt*) and the central core modified with chamfered corners (*Ch*), rounded corners (*Ro*), and recessed corners (*Rc*)

The effectiveness of the modified corners in achieving pedestrian wind comfort is evaluated using $AP_{effective}$ values of the lift-up areas with different central cores as shown in Figure 14. The reduced area of the LWS zone on the leeward side of the central core and the decrease of maximal wind speed lead recessed corners (*Rc)* to have the largest improvement in the $AP_{effective}$ value of Building M1. With the recessed corners, the lift-up area of Building M1 covers an area of $AP_{effective}$ = 58% with acceptable wind conditions, which is a 26% increment of the area compared to the basic core, *Rt.* However, with the decrease of building height, the effectiveness of corner modification diminishes such that only the central core modified with recessed corners has a larger $AP_{effective}$ value (57.23%) than the basic core, *Rt*, in Building M2 ($AP_{effective}$=53.71%). With further decrease of building height, no corner modification becomes effective for Building M3 but produces 5%-10% smaller $AP_{effective}$ values than by the basic core. The modified central cores lead to 15%-31% smaller $AP_{effective}$ values in Building M4, which records the largest $AP_{effective}$ of 0.70 compared with the basic central core, *Rt*. There is no notable effect of corner modifications in the lift-up area of the widest building, M5, as shown by similar $AP_{effective}$ values recorded for all four central core designs. Approximately the same $AP_{effective}$ values of the four central cores of the widest lift-up building M5 may relate to the fact that corner modifications are applied on a short length compared to the width of the centre core. More specifically, three corner modifications are applied only a 4.5-m length (i.e., $2t$ = 4.5 m) out of the core width of 90 m, thus this small size of corner modification is unable to induce significant effects on the wind conditions in the lift-up area of building M5. Stathopoulos (1985) reported similar results for chamfered corners, that no significant reduction of the area of strong wind was observed if the chamfered width was smaller than 85% of the building width.

4. Concluding Remarks

The influence of the building aspect ratio (*H*/*W*) on pedestrian wind comfort near a lift-up building was evaluated in a boundary layer wind tunnel by testing five lift-up buildings with *H/W* ratio ranging from 4:1 to 0.5:1. All lift-up buildings had a central core with a constant core height of 6 m (full scale) and a plan area of 25% of the plan area of a building. The pedestrian wind comfort was evaluated by proposing new criteria based on the prevailing wind conditions in Hong Kong and the results were compared with the PLW fields of the five control buildings, which had similar building dimensions as the five lift-up buildings but had no central core. Further improvements of pedestrian wind comfort in the lift-up area were investigated by modifying the central core using chamfered, recessed, and rounded corners. Based on the results of this study, the following concluding remarks can be stated:

1. The K_{max} value in a lift-up area increases with building height but The K_{max} value of a lift-up building is smaller than the corresponding value in a passage underneath the same building. Smaller K_{max} values, thus the deviation from the relationship with building height (K_{max}= 0. 65*$H^{0.24}$) as proposed by Wu (1994), may be attributed to some winds leak from the lateral side of the lift-up area to the surrounding environment. Similar K_{max} values of the lift-up buildings with different widths indicate a less significant influence of building width on the maximal wind speed in the lift-up area. Therefore, HWS in the lift-up areas is a concern of importance when adopting the lift-up design for a tall and slender building than for a short and wide building.
2. Tall and slender lift-up buildings have large HWSs that are concentrated in a small area near the buildings. A large HWS is attributed to the two pairs of corner streams created by the main structure and the central core of a lift-up building. Short and wide lift-up buildings create CS zones that stretch farther than their corresponding control buildings. Therefore, except tall and slender lift-up buildings that cause pedestrian wind discomfort (K_{200}>0.7) due to wind speeds, short and wide lift-up buildings are favourable in improving the air circulation in built-up areas.
3. The low wind speeds in the upstream part of a lift-up building are a result of the weakened downwash flow due to some flows having leaked through the lift-up. In the downstream direction, the DNLWS zone is larger in area for tall and slender lift-up buildings but smaller in area for short and wide lift-up buildings compared with the corresponding control buildings. By considering the detrimental effects of LWS zones

on air pollution dispersion and outdoor thermal comfort, a lift-up design cannot be recommended for tall and slender buildings.

4. The K_{200} value in the lift-up area is maximal for the tallest building and decreases with building height before it increases with building width. Owing to the large HWS zone, the tallest lift-up buildings have the smallest area of pedestrian wind comfort, whereas the largest area of pedestrian wind comfort is found for the building with the aspect ratio 0.75:1, which has the smallest HWS zone in the lift-up area. This suggests that large HWS zones may be a prominent factor in defining pedestrian wind comfort in a lift-up area.
5. Modified central cores with chamfered, rounded, and recessed corners effectively reduce the area of HWS but do not significantly decrease the maximal wind speed or alter the location where the maximal wind speed occurs. Rounded corners are the most effective in reducing the LWS zone on the leeward side of the central core while recessed corners moderately reduce areas with both HWS and LWS in the lift-up areas. Particularly, corner modifications are beneficial for tall and slender lift-up buildings in increasing the area of pedestrian wind comfort but are relatively incompetent for short and wide lift-up buildings ($H/W<0.5$) unless the corner modification extends to a larger portion of the core width. Therefore, it is advisable to adopt a corner modification, preferably recessed corners, for the central core of a tall and slender lift-up building to maximize the area with pedestrian wind comfort in the lift-up area.

While this study suggests adopting the lift-up design for buildings with aspect ratio $0.5<H/W<4$, a previous study of the authors (Tse et al., 2017) recommends to use a tall central core with a small plan area as the lift-up design. These two sets of design parameters, i.e., building and central core dimensions are, therefore, necessary to be combined systematically to determine the optimal lift-up design for a given building. As the next step, a novel design procedure is meant to be developed in a future study to determine the optimal lift-up design for a building with known dimensions.

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