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Characteristics of pedestrian-level wind around super-tall buildings with various configurations

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ABSTRACT

Super-tall buildings with unconventional configurations have been constructed all over the world, because of the social demand for more iconic buildings, better aerodynamic performance and/or for architectural aesthetic reasons. The aerodynamic characteristics of various super-tall building configurations have been studied by Tamura et al. (2010, 2011). However, there is also a need to study pedestrian-level winds around super-tall buildings with various unconventional configurations. These have not been studied well, although pedestrian-level winds around tall buildings with conventional rectangular-plan up to 200 m high have been studied intensively. In this study, a series of wind-tunnel tests were carried out to investigate pedestrian-level winds around 40 super-tall building models with various configurations, including basic models, tapered models, corner-modified models, opening models, helical models, tilted models, composite models, triangular models, and polygonal models, corresponding to the cases in Tamura et al. (2010, 2011). The results of these tests have led to comprehensive discussions on pedestrian-level-wind characteristics of various super-tall building configurations under the condition of “same height and same volume”. It was found that super-tall buildings (400 m in this study) provide much higher speed-up ratios at the pedestrian level than 200 m-high buildings. The projected building widths, especially in the lower part, were found to significantly affect pedestrian-level winds.

1. Introduction

Tall and super-tall buildings may cause uncomfortable or unsafe pedestrian-level wind conditions. Since the 1960s, pedestrian wind environments have attracted significant attention (Lawson, 1978; Melbourne, 1978; Beranek, 1984). Studies have focused on pedestrian wind environments around traditional symmetric tall buildings like square- and rectangular-plan buildings. Wind tunnel tests (Wiren, 1975; Stathopoulos and Storms, 1986; Stathopoulos and Wu, 1995; Yamada et al., 1996; Tsang et al., 2012; Bady et al., 2011), CFD simulations (Blocken et al., 2007, 2008; Blocken, 2014) and full-scale measurements (Murakami et al., 1979); Dye, 1980); Letchford and Isaacs, 1992); Visser and Cleijne, 1994) have been applied in relevant studies. For instance, Kamei and Maruta (1979) examined the effects of heights of square-plan buildings on pedestrian-level wind speed distribution. They found that speed-up area and maximum wind speed increase with increasing aspect ratio. Blocken and Carmeliet (2004) suggested that there are two pressure systems for rectangular buildings that determine the flow pattern. Stathopoulos (1985) concluded that 45-degree-chamfered corners of a tall square building improve wind conditions at pedestrian level by significantly reducing the size of the strong wind area in the corner stream. Uematsu et al. (1992) studied the effects of corner shapes of tall buildings on the pedestrian-level wind environment, and concluded that even a slight change of corner shape may greatly improve the pedestrian wind environment. Stathopoulos et al. (1992), Sasaki et al. (1997) and Visser et al. (2000) developed knowledge-based expert systems for preliminary evaluation of wind environments around buildings.

Recently, more and more tall and super-tall buildings with unconventional configurations have been constructed worldwide, such as Turning Torso (2005), Burj Khalifa (2010), and Shanghai Tower (2016). Past studies on pedestrian-level winds might be insufficient to assess the environmental conditions for urban areas with unconventionally shaped tall and super-tall buildings. Therefore, a series of wind-tunnel tests were carried out to investigate the characteristics of pedestrian-level winds around 40 super-tall building models with various configurations such as square plan, rectangular plan, elliptical plan, polygonal plan, corner modifications, tilted angle, taper, setbacks,

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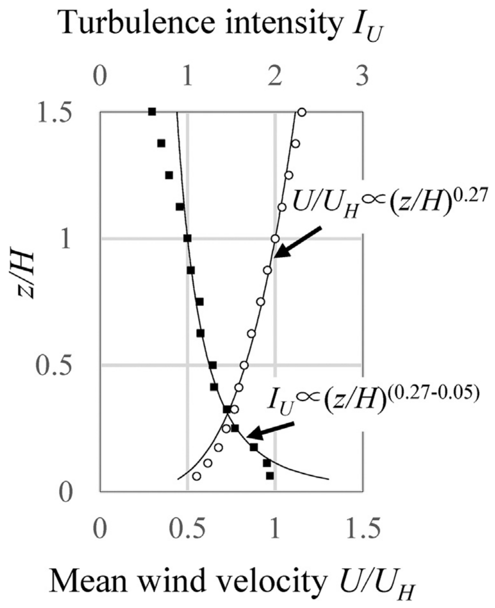

Fig. 1. Approaching wind conditions.

twist angle, openings and so on. The aerodynamic characteristics of these models were studied by Tamura et al. (2010, 2011). This research aimed to comprehensively investigate pedestrian-level wind characteristics around super-tall building models with various configurations and to examine the effects of some important parameters such as corner modifications, twist angle of helical models, number of sides of building plan, projected width, etc., on speed-up ratio and speed-up area.

2. Wind tunnel experiments

2.1. Approaching flow conditions and anemometers

The wind tunnel experiments were performed in an open-circuit-type boundary-layer wind tunnel with a working section 1.8 m high by 2.2 m wide. The blockage ratio of Square Model for the normal wind direction was 2%, and the blockage ratio of Elliptic was 3%, which was the maximum in all test models. The power-law exponent of the mean-wind-speed profile of approaching flow was 0.27, reproducing urban flow conditions as shown in Fig. 1. The geometrical scale was set at 1/500. The wind speed and turbulence intensity at the top of the model were U_H=7.0 m/s and I_{UH}=11.2%, respectively. Here, H is the height of building models.

To make the measurements more accurate, thermistor anemometers were set 5 mm above the wind tunnel floor (2.5 m above the ground in full-scale), a little bit higher than an average human being's height. Anemometers were distributed over an area of 792 mm×792 mm, which is almost 8 times the square model's side, and the pitch between two sensors was a minimum of 2 cm in the inner area (Fig. 2).

2.2. Models of super-tall building with various configurations

Forty super-tall building models with different configurations were studied. They were grouped as nine types of models and denoted as Basic, Tapered, Corner Modified, Opening, Helical, Tilted, Composite, Triangular, and Polygonal (shown in Table 1). These configurations are similar to those of Tamura et al., (2010, 2011) and Tanaka et al., (2012, 2013) for investigating aerodynamic characteristics of 400 m-high super-tall buildings, and the scale ratio was set to 1/500 in this study to simplify the wind speed measurement near the ground.

The Basic models included SQU, REC, ELL and CIR, as shown in Table 1(a). The side ratio of models REC and ELL was 1:2. The Reynolds number Re of model CIR in the wind tunnel experiments was Re=5.4×10^4, less than in the full-scale condition, which should be considered in applying the obtained results in practical designs.

The Tapered models included models 2TP-SQ, 4TP-SQ, SB-SQ, I4TP-SQ and BL-SQ, as shown in Table 1(b). The area ratio of the roof to the base floor for models 2TP-SQ, 4TP-SQ and SB-SQ was set at 1/6 and the taper ratio of model 4TP-SQ was set at 10%. Model I4TP-SQ had the inverse building shape of model 4TP-SQ. The area ratio of the roof or base floor to the largest middle floor of model BL-SQ was 1/3.

The Corner Modified models included Chamfered model CH-SQ and Cut model CC-SQ, with a modification length 0.1B, where B was the building width, as shown in Table 1(c).

The Opening models included three cross-opening models and three oblique-opening models with openings at the top-center and top-corner of the walls, respectively, as shown in Table 1(d). Three different opening heights h/H=2/24, h/H=5/24 and h/H=11/24 were investigated in the experiment, where H was building height.

The Helical models were with square, rectangular or elliptic plan. The twist angles β between the roof and the base floor were set at 90°, 180°, 270° or 360°, as shown in Table 1(e).

The Tilted models included model TL-SQ, where the roof was shifted 2B from the base floor, and model WI-SQ, where the floors at 0.25 H and 0.75 H were shifted 0.5B to the left and right side, respectively, as shown in Table 1(f).

The Composite models had configurations combining the primary configurations shown in Table 1(a)–(f), noted as 360H-CC-SQ, 4TP-360H-CC-SQ, SB-CC-SQ and SB-45R-SQ, shown in Table 1(g). The rotational angle of each setback layer in model SB-45R-SQ was 45°.

Triangular models included models TRI, 180H-TR and CC-TR, shown in Table 1(h). The cut length in model CC-TR was also set as 0.1B.

Eight Polygonal models, PEN, HEX, OCT, DOD, and their corresponding Helical models with twist angle 180°, shown in Table 1(i), were investigated.

The Square model was 400 m high and 50 m square in full-scale, i.e. its volume was 10^6 m^3. For comparative discussions, two conditions, the same height of 400 m and the same volume of 10^6 m^3 were set to all models, except the Opening models, whose outline dimensions were the same as those of the Square model, so the volumes were less than 10^6 m^3.

The definition of wind direction θ for various models is shown in Fig. 3. The wind direction interval in the tests was 22.5° for most models, but 20° for Triangular, Hexagon, and Dodecagon models, and 18° for Pentagon models.

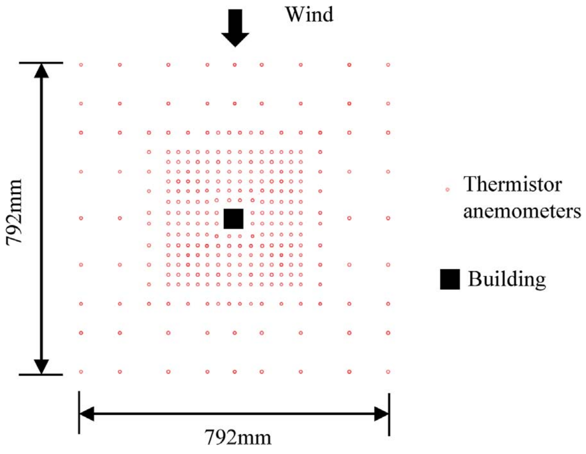

Fig. 2. Anemometer distribution.