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Keynote Paper

Effects of configurations of super-tall buildings on aerodynamic and wind-environmental characteristics

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ABSTRACT

Recent super-tall building design has been released from the spell of compulsory symmetric shape design, and free-style design is becoming increasingly popular. This is mainly due to architects' and structural designers' challenging demands for novel and unconventional expressions. A series of wind tunnel tests have been carried out to determine aerodynamic performance and pedestrian-level wind characteristics of many super-tall buildings with various configurations: square plan, rectangular plan, elliptic plan, tilted, tapered, inverse tapered, with setbacks, helical, openings and so on. Dynamic wind-induced response analyses of these models have also been conducted. The results of these tests have led to comprehensive discussions on the aerodynamic and pedestrian level wind characteristics of various tall building configurations.

1. INTRODUCTION

The trend of Manhattanization requires the attention of wind engineering researchers, particularly the increasing preference for free-style building shapes, as seen in Burj Khalifa, Shanghai Tower, and so on. To avoid excessive seismic-induced torsional vibrations due to eccentricity, super-tall buildings have been traditionally designed to be symmetric rectangular, triangular or circular in plan. However, freewheeling building shapes have advantages not only in architectural design reflecting architects' challenging spirits for new forms but also in structural design reducing wind loads. Development of analytical and vibration control techniques has greatly contributed to this trend. In particular, cross-wind response, which is a major factor in safety and habitability of tall buildings, is greatly suppressed.

The authors' group has conducted wind tunnel experiments on super-tall buildings

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with unconventional configurations to investigate the aerodynamic response and pedestrian level wind characteristics. Their findings provide the structural designer with comprehensive wind tunnel test data that can be used in preliminary design, and can be helpful in evaluating the most effective structural shape in wind-resistant design for tall buildings with various aerodynamic modifications. The characteristics of pedestrian-level wind are significantly affected by some important parameters such as corner modifications, twist angle of helical models, number of sides of building plan, etc.

2. WIND TUNNEL EXPERIMENTS

2.1 Approaching flow conditions

Wind tunnel experiments were performed in a closed-circuit-type boundary-layer wind tunnel whose working section is 1.8m high by 2.0m wide. The approaching turbulent boundary layer flow had a power-law index of 0.27, representing an urban area.

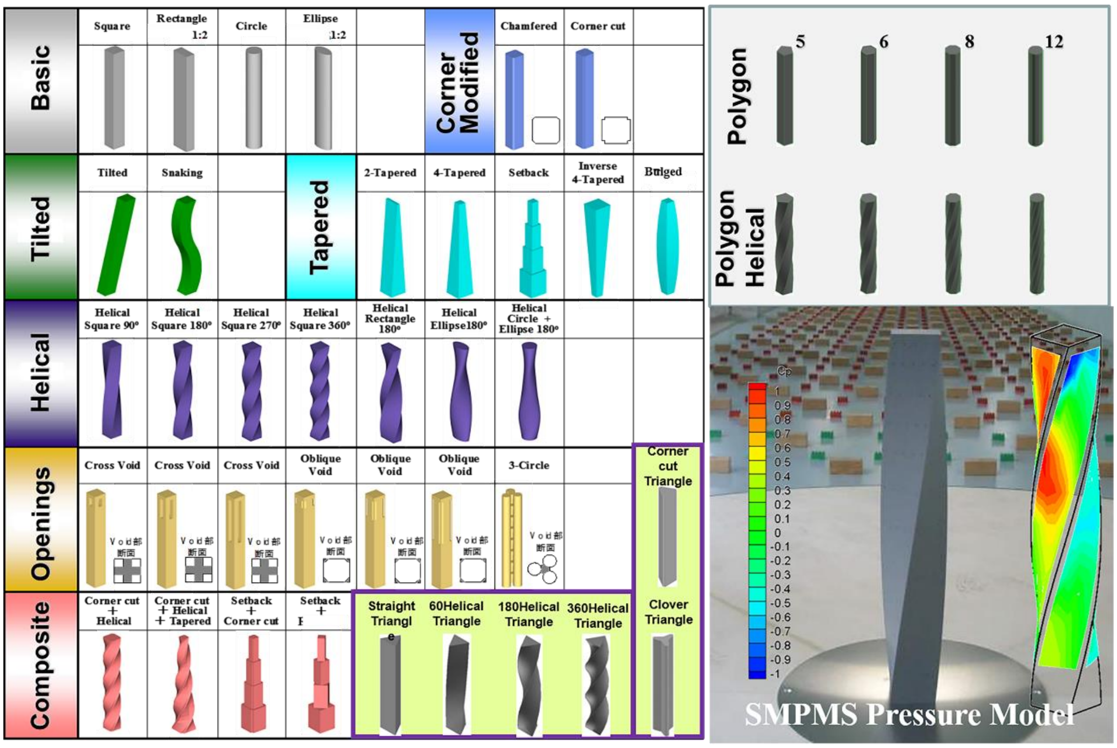
Dynamic wind forces were measured by a 6-component high-frequency force balance supporting light-weight and stiff models. The measured wind forces and aerodynamic moments are normalized by $q_H BH$ and $q_H BH^2$ to get wind force coefficients and moment coefficients, respectively. Here, q_H is the velocity pressure at model height H, and B is commonly set at the width of the Square Model. Thus, the models' force and moment coefficients can be directly compared. Wind pressure measurements were conducted on 28 models. They were determined from the results of aerodynamic force measurements and for relatively realistic building shapes in the current era. For details of wind tunnel tests and aerodynamic characteristics of super-tall building models, refer to Tamura et al. (2010), Tanaka et al. (2013) and Kim et al. (2015)

Pedestrian-level wind measurements were conducted on 40 models with various configurations and 11 square type models with different heights but a constant width (B=50m≡B_0). To make the measurements more accurate, thermistor anemometers were set 5mm above the wind tunnel floor (2.5m above ground in full scale), a little bit higher than an average human being's height. Anemometers were distributed over an area of 792mm×792mm, which is almost 8 times the square model's side, and the pitch between two sensors was a minimum of 2cm in the inner area. For details of wind tunnel tests to determine pedestrian-level winds around super-tall building models, refer to Xu. et al. (2017).

2.2 Models of super-tall building with various configurations

The super-tall building models used for the experiments are shown in **Table 1**. The height H and volume V of each building model are generally set at H = 400m and V = 10^6m^3. The width B of the square model is 50m and the aspect ratio H/B is 8. The geometric scale of the wind tunnel models is set at 1/1,000 for pressure and force measurement, and 1/500 for pedestrian level wind measurements. They were grouped as nine types of models and denoted as Basic, Tapered, Corner Modified, Opening, Helical, Tilted, Composite, Triangular, and Polygonal.

Table 1 Configurations of 40 super-tall building models



3. AERODYNAMIC CHARACTERISTICS

3.1. Overturning moment coefficients

The maximum along-wind o.t.m. coefficient $|\overline{C_{MD}}|_{max}$ and crosswind o.t.m. coefficient $|\overline{C_{ML}}|_{max}$ of Circular and Dodecagon models show very small values, and those of the Rectangular model, the Triangular and Elliptic models are larger than those of the Square model because of their larger widths. The maximum mean along-wind o.t.m. coefficients $|\overline{C_{MD}}|_{max}$ of the 4-Tapered model and the Setback model, whose sectional area decreases with height, are relatively small. The maximum mean crosswind o.t.m. coefficients $|\overline{C_{ML}}|_{max}$ of the Corner Cut and Corner Chamfered models are small. The maximum mean crosswind o.t.m. coefficients of the Helical Square and the Cross Opening h/H=11/24 models whose opening size is the largest are also small. Conversely, the models whose along-wind and crosswind o.t.m. coefficients are larger than those of the Square model are the 2-Tapered, the 180° Helical Rectangular, the Tilted models, and the Inversely 4-Tapered model. The maximum mean o.t.m. coefficients $|\overline{C_{MD}}|_{max}$ and $|\overline{C_{ML}}|_{max}$ of the Helical Square models and Helical Triangular models tend to decrease with increase in twist angle. The aerodynamic characteristics of the composite models with multiple modifications are superior to those of the models with single modification (Tanaka et al. 2013). The mean o.t.m. coefficients of Polygon models tend to become smaller with increase in the number of sides (Kim et al. 2015).

The maximum fluctuating along-wind o.t.m. coefficients $C_{MD}'{}_{max}$ of the Corner Chamfered, Corner Cut, 4-Tapered and Setback models are smaller than those of the Square model. The maximum fluctuating crosswind o.t.m. coefficients $C_{ML}'{}_{max}$ of the 4-

Tapered, Setback, Helical Square, and Cross Opening 11/24 models show relatively small values. These trends are the same as those of the maximum mean o.t.m. coefficients. And, the effect of twist angle of the Helical Square models, the effects of opening size for the two types of Opening models, and the composite effects on the maximum fluctuating o.t.m. coefficients are also significant (Tanaka et al. 2013). The fluctuating o.t.m. coefficients tend to decrease with increase in the number of sides of Polygon models (Kim et al. 2015).

3.2 Power spectral densities of crosswind overturning moment coefficients

The sharp peak observed for the Square model from the power spectra of crosswind o.t.m. coefficients is reduced dramatically by shape modifications such as corner cut, tapered, setback, and helical, implying the reduced effects of periodic vortex shedding on aerodynamic forces and responses. The spectral peak value of the 180^o Helical is almost 5% that of the Square model. Incidentally, the reduced frequency showing the spectral peak of the Square model corresponds closely to 500-year recurrence wind speed in Tokyo. The square roots of spectral peak values of crosswind o.t.m. coefficients for the corner cut, tapered, setback, helical square (θ=180^o~360^o), and cross opening (h/H=11/24) models are almost one third or one fourth that of the square model, showing advantages for safety design. And the values for the corner cut & 4-tapered & 360^o helical square and setback & 45^o rotate models are almost one tenth that of the square model, so it can be said that the Composite type models are very efficient for reducing aerodynamic forces (Tanaka et al. 2013).

Tamura et al. (2010) pointed out that local peak pressure coefficients for complicated shape models tend to become higher than those for the Square model. For example, the largest negative peak wind pressure coefficient is –2.50 for the Square model, but –2.61 for the 90^o Helical square model and –2.91 for the 180^o Helical square model. So more careful design is required for claddings and components of super-tall buildings with unconventional configurations.

3.3 Effect of number of sides of straight and helical polygon models

The overturning and torsional moment coefficients decrease with increasing number of sides, and the degree of decrease becomes small when the number of sides is larger than 5. For the straight and helical models, the differences in overturning and torsional moments also become small when the number of sides is larger than 5. The spectral values for 1-year-return-period design wind speed of the straight Pentagon, Hexagon, Octagon and Dodecagon models show similar values, showing much smaller values than those of the straight triangle and square models. The largest spectral values were found for the straight square model for both safety and habitability level (Tanaka et al. 2013).

4. PEDESTRIAN-LEVEL WIND CHARACTERISTICS

4.1 Maximum speed-up ratio R_{max}

The maximum speed-up ratios of the models range from 1.9 to 2.3, and the differences among building configurations are not significant. The maximum speed-up ratio R_{max} of Rectangular, Elliptic, Tapered Square, Helical, Tilted, and Triangular models are higher than the value of 2.0 for the Square model. On the other hand, Circular, Octagon and Dodecagon models show lower values. (Xu et al. 2017)

4.2 Integrated normalized speed-up area $A^*_{R\text{-}int}$

The integrated normalized speed-up area $A^*_{R\text{-}int}$ is defined as the average of normalized speed-up areas for all directions:

$$A^*_{R-\mathrm{int}} = \frac{\sum_{\theta_j=1}^{N} A^*_{R,\theta_j}}{N} \quad (1)$$

where N is the number of tested wind directions.

Elliptic, Circular, Inversely 4-Tapered, Bulged, Corner Chamfered, Corner Cut, 180° Helical Elliptic, Corner Cut + 360° Helical, and Polygon Models show better results than the Square model, and the Circular model shows the smallest integrated normalized speed-up areas $A^*_{1.3\text{-}int}$. The results demonstrate the efficiency of corner modifications in improving pedestrian-level wind quality.

However, Rectangular, 2-Tapered, 4-Tapered, Setback, 180° Helical, Setback + 45° Rotation, Triangular, Corner Cut Triangular, and 180° Helical Triangular models show worse results than the Square model, and the Triangular model shows the worst. These worse building configurations commonly have larger projected widths near the bottom part of the building. 4-Tapered and Inversely 4-Tapered models are typical contrasts. The latter, with a smaller projected width, shows the better result (Xu et al. 2017).

4.3 Effects of number of sides of polygon models

The integrated normalized speed-up areas $A^*_{1.3\text{-}int}$, $A^*_{1.5\text{-}int}$, and $A^*_{1.7\text{-}int}$ clearly decrease with the number of sides N_S for Polygon models including Triangular, Square, and Circular models ($N_S = \infty$). In particular, the integrated normalized speed-up areas significantly decrease from N_S = 3 to 5, keeping almost constant up to N_S = 8, then gradually decease to the Circular model. In practice, the number of sides N_S = 5 (Pentagon model) seems to be enough to improve pedestrian-level wind conditions (Xu et al. 2017).

4.4 Speed up ratio and speed up area for models with different heights and constant width

For models with different heights (H = 50m - 600m) and constant width (B = 50m ≡ B_0) in boundary layer flow, the characteristic of pedestrian level wind is mainly affected by height. The maximum speed-up ratio R_{max} seems to have a limitation with increasing height, and increasing the building's height will not affect the maximum speed-up ratio when it exceeds 400m (H/B = 8). The integrated normalized speed-up area $A^*_{R\text{-}int}$ presents a geometric logarithm increase with height, showing a convergent tendency. The effects of height on pedestrian level wind for models with relatively low altitude is obvious, while it will become smaller and smaller with constant increase in height.

5. CONCLUDING REMARKS

Based on comprehensive experimental studies on aerodynamic characteristics of super-tall building models and pedestrian-level wind characteristics around them, the following results are obtained (Tamura et al. 2010, Tanaka et al. 2013, Kim et al. 2015, Xu et al. 2017).

- Efficiency of corner modifications, setback, tapered, helical and so on in reducing aerodynamic force components was clarified under the conditions of the same height and volume.
- The increase in twist angle of helical models show better aerodynamic characteristics, but 180° seems to be enough.
- Polygon models with five or more sides show excellent aerodynamic performance, and increase in the number of sides tends to give better aerodynamic characteristics.
- The aerodynamic performance of triangular models including a clover type is not good.
- The maximum speed-up ratios R_{max} of pedestrian-level winds are almost 2.1 for 400m-class super-tall buildings, while those of 200m-class tall buildings are 1.5 according to past studies.
- Corner modifications, i.e. almost 10% corner chamfered and corner cut, provide an approximately 30% reduction of integrated normalized speed-up area $A^*_{1.3\text{-}int}$ for all cases tested in this study.
- The normalized integrated speed-up area A^*_R clearly decreases with the number of sides N_S of Polygon models, including Triangular, Square and Circular models. In particular, significant reduction is observed from N_S = 3 to 5, and the Pentagon model with N_S = 5 seems to be enough to improve the pedestrian-level wind environment.
- The effects of height on the pedestrian level wind for square type models (B=50m≡B_0) with the relatively low altitude is obvious, while it will become smaller and smaller with constant increase in height.

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