Wind Engineering Joint Usage/Research Center
FY2022 Research Result Report

Research Field: Wind Hazard
Research Year: FY2022
Research Number: 22222002
Research Theme: Crosswind responses and aerodynamic damping of inclined high-rise buildings with large aspect ratio

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Budget [FY2022]: 600,000Yen

*There is no limitation of the number of pages of this report.
*Figures can be included to the report and they can also be colored.
*Submitted reports will be uploaded to the JURC Homepage.

1. Research Aim

With great improvement of current society, super-tall buildings with large aspect, featured with low natural frequency have been constructed in many cities around the world. As indicated in Fig. 1, high-rise buildings with super large aspect ratio as well as with quite basic squared sections has been constructed. With decrease of natural frequency, the concerning reduced design wind speed increases, which can approach and even become higher than the critical vortex lock-in wind speed in across-wind direction, and it might trigger the building fatigue or collapse more easily. Moreover, it is reported that the along-wind response can be enlarged once the vortex-induced resonance vibration happened in across-wind direction. Therefore, it's necessary to focus on the characters of both along- and across-wind responses of high-rise buildings with super large aspect ratio. Besides, some high-rise buildings are located in special terrains such like on the hill, as sketched in Fig. 2. In such a situation, the wind flow acts on the building with an inclination. Thus, the aim of this research is to investigate the effects of the inclinations on along- and across-wind responses of squared-section high-rise buildings with super large aspect ratios.

Fig. 1 High-rise buildings with super large aspect ratio

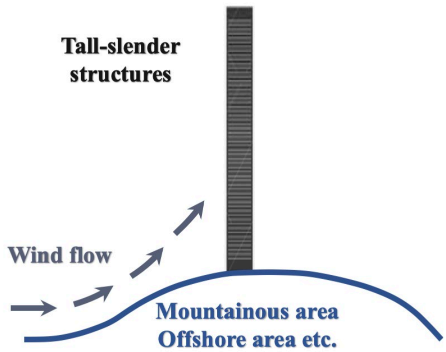
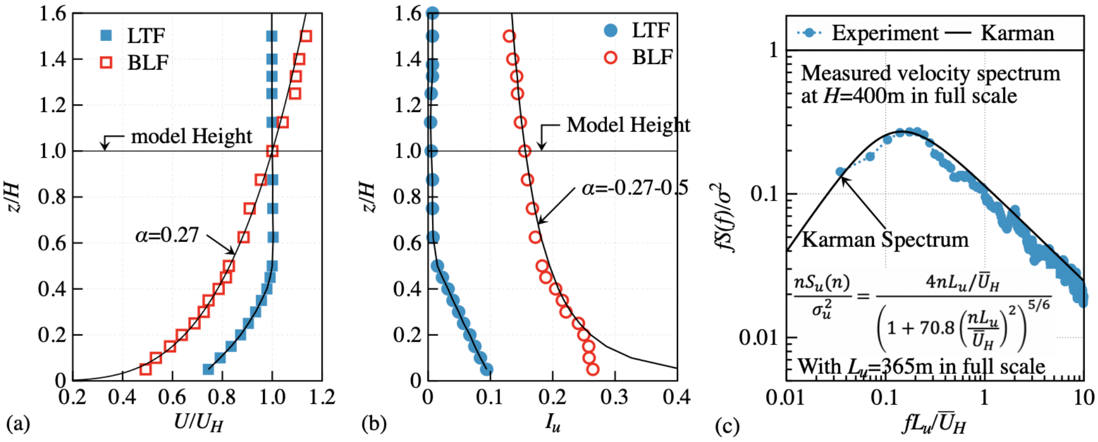


Fig. 2 Sketch of a vertical prism subjecting to pitching wind flow

2. Research Method

The wind tunnel tests on aeroelastic high-rise building models were carried in the large-scale boundary-layer wind tunnel of Tokyo Polytechnic University, whose test section is 3.0 m wide, 2.2 m high, and 19 m long. With respect to the approaching turbulent boundary layer flow, the low turbulent flow and urban flow were simulated. The mean wind speed and turbulence intensity are shown in Fig. 3 (a-b). The geometric scale was determined as the ratio of the turbulence integral scale in wind tunnel to that in natural wind, and it was 1/800. The power spectral density of the longitudinal wind speed at the model height in urban flow is shown as Fig. 3 (c), which matched Karman spectrum very well.



$$\frac{nS_u(n)}{\sigma_u^2} = \frac{4nL_u/\bar{U}_H}{\left(1+70.8\left(\frac{nL_u}{\bar{U}_H}\right)^2\right)^{5/6}}$$

Fig. 1 Simulated sub-urban and urban flow in boundary layer wind tunnel:
(a) Mean wind speed; (b) turbulence intensity; (b) PSD of longitudinal wind speed under urban flow

The prototype size of a full-scale high-rise building are height of H =400m (aspect ratio λ=16), width of D =25m, natural frequency of around 0.125Hz, structural mass ratio of $M/\rho B^2 H$=150, structural damping of 0.5, and linear sway modes of vibration. The geometric scale, frequency scale and velocity scale of the wind tunnel test are set as 1/800, 80 and 1/10, respectively. According to above requirement of dynamic similarity, the scaled models are designed, and are made of curable resin and fabricated by the 3-D print technique. By adjusting wall thickness of the test model, the mass similarity is achieved.

In order to simulate the dynamic properties such as natural frequency and structural damping, the scaled model is installed to the gimbal system shown in Fig. 4(a). As shown in Fig. 4(b), the stiffness is provided by coil springs, and structural damping is offered by the oil damper. To determine the natural frequency and structural damping of the test model, free vibration test of non-wind condition is performed and the measured free decay response is filtered within (1±0.3)f_s by a band-pass filter to eliminate influence of the noise on the free decay responses, as shown in Fig. 5. The natural frequency and structural damping of the scaled model are estimated based on the free decay response before and after the rocking model wind tunnel test. Dynamic properties of the test model are summarized in Table 1.

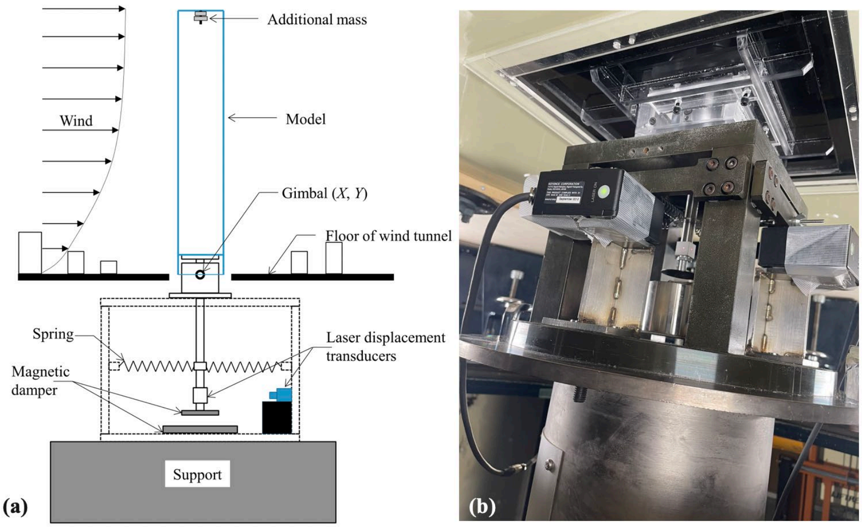


Fig. 2 Equipment of the rocking vibration model tests:
(a) Sketch of rocking vibration model test (Kim et al., 2016); (b) Basement of the equipment

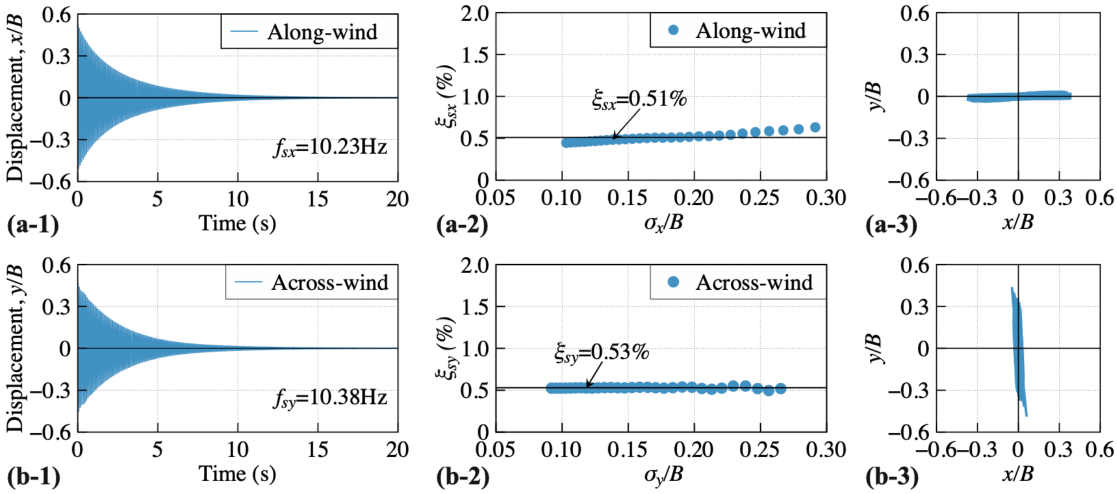


Fig. 3 Free-vibration tests on rocking model high-rise building models with aspect ratio 16
(a-1) Free vibration decay of the along-wind direction; (a-2) Structural damping ratio of the along-wind direction; (a-3) Phase-plane trajectory; (b-1) Free vibration decay of the across-wind direction; (b-2) Structural damping ratio of the across-wind direction; (b-3) Phase-plane trajectory.

Table 1 Parameters of aeroelastic model of squared high-rise buildings with aspect ratio 16

building	Prototype	Rocking vibration model(Straight)
Geometrical size	25×25×400 (m^3)	31.2×31.2×500(mm^3)
Moment of inertia I_x, I_y ($kg \cdot m^2$)	3.16×10^{12}	0.0096
Mass ratio $I_{x,y}/(\rho B^2H^3)$	64.81	61.54
Structural frequency f_{sx}, f_{sy} (Hz)	0.1	10.40, 10.42
Structural damping ratio ξ_{sx}, ξ_{sy} (%)	0.5, 0.5	0.47, 0.51

To investigate the effects of the building inclination, three inclined models were designed and made with the inclination 5°, 10°, and 15°. It is worthy to know that all models have similar dynamic properties, and their volumes are totally the same. Fig. 6 shows the straight and 5° inclined rocking vibration models installed in low turbulent flow and urban flow.

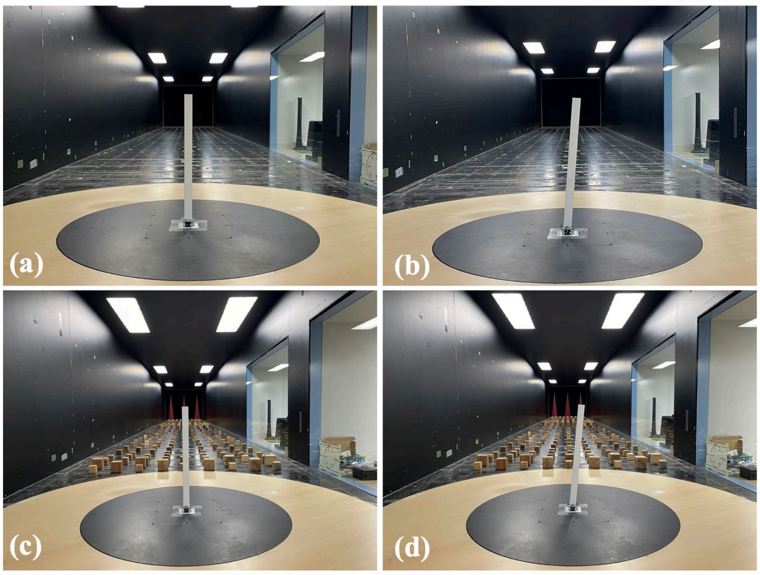


Fig. 6 Experimental model installed in the wind tunnel in low turbulent flow and urban flow:
(a) LTF_Straight ($\beta = 0°$); (b) LTF_Sideward Inclined model ($\beta_s = 5°$);
(c) BLF_Straight ($\beta = 0°$); (d) BLF_Inclined ($\beta_s = 5°$).

3. Research Result

In this section, the effects of windward, backward and sideward inclination on wind-induced responses are examined in subsection 3.1 ~ 3.3, respectively. The sideward inclination has been shown in Fig. 6(b&d). Fig. 7 illustrates the windward and backward inclination.

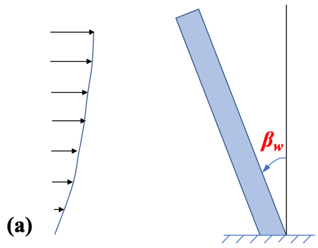


Fig. 7 Illustration of the windward and backward inclinations: (a) windward; (b) backward.

3.1 Effects of windward inclination on responses of tall-slender buildings

Fig. 8 and Fig.9 show the along- and across-wind responses of the high-rise building models with windward inclination $\beta_w = 5°$, $10°$ and $15°$ under low turbulent flow and boundary layer flow, where $\beta_w = 0°$ indicates a straight model without inclination.

In low turbulence flow shown in Fig.8, the along-wind mean responses of the four models with different inclinations are almost the same at each wind speed. While the along-wind and the across-wind fluctuating displacement response of the straight model are significantly larger than those of inclined models, when the wind speed is larger than the vortex-resonance wind speed. And the across-wind fluctuating displacement responses of the straight model increases with the wind speed. While those of the inclined models reach to the maximum when the wind speed is close to the vortex-resonance wind speed. Overall speaking, the across-wind fluctuating responses decrease with the windward inclination increases.

In boundary layer flow shown in Fig. 9, when wind speed is small, the windward inclination has no effects on the along-wind and across-wind displacement responses. While when the wind speed is larger than vortex resonance wind speed, the across-wind fluctuating responses decrease with the windward inclination increases.

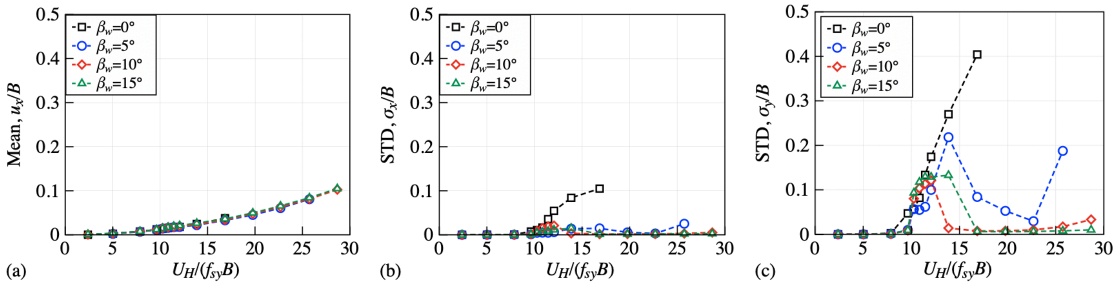


Fig. 8 Effects of the windward inclination on wind-induced responses under low-turbulent flow:
(a) Along-wind mean responses; (b) Along-wind fluctuating responses;
(c) Across-wind fluctuating responses.

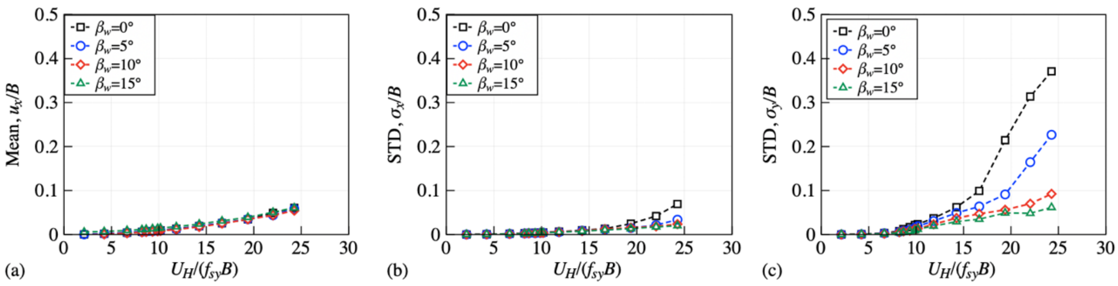


Fig. 9 Effects of the windward inclination on wind-induced responses under boundary layer flow:
(a) Along-wind mean responses; (b) Along-wind fluctuating responses;
(c) Across-wind fluctuating responses.

3.2 Effects of backward inclination on responses of tall-slender buildings

Fig. 10 and Fig. 11 show the along- and across-wind responses of the high-rise building models with backward inclination $\beta_b = 5°$, 10° and 15° under low turbulent flow and boundary layer flow, where $\beta_b = 0°$ indicates a straight model without inclination.

It is shown in Fig. 10 that the backward inclination has very limited influence on the along-wind and across-wind displacement responses of high-rise buildings. While in boundary layer flow, the backward inclination has limited influence on the along-wind displacement responses, but the across-wind STD displacement responses decrease with the increase of the backward inclination.

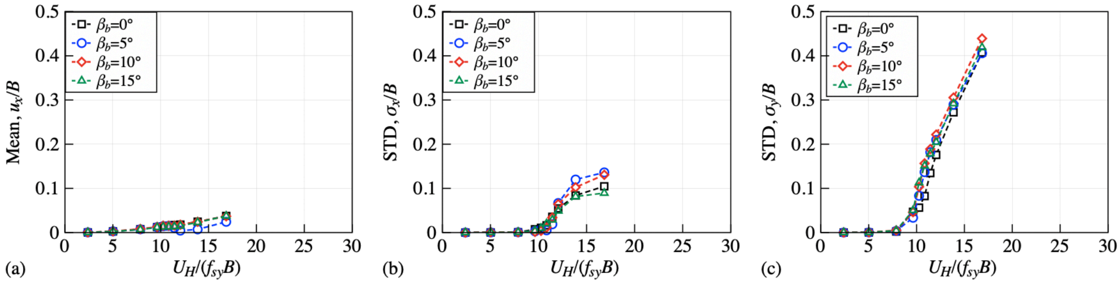


Fig. 10 Effects of the backward inclination on wind-induced responses under low-turbulent flow: (a) Along-wind mean responses; (b) Along-wind fluctuating responses; (c) Across-wind fluctuating responses.

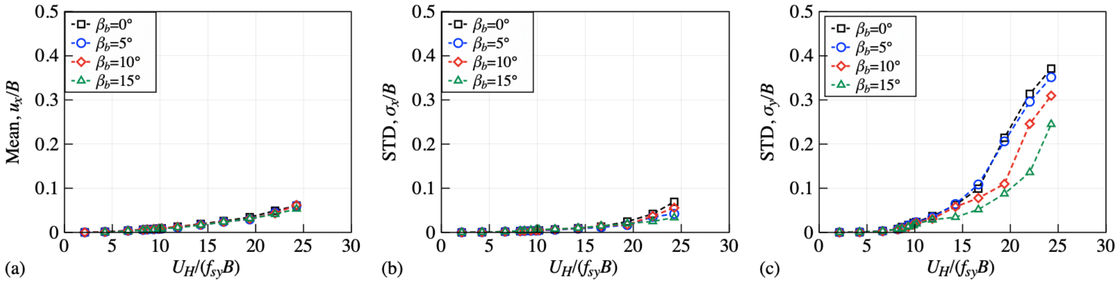


Fig. 11 Effects of the backward inclination on wind-induced responses under boundary layer flow: (a) Along-wind mean responses; (b) Along-wind fluctuating responses; (c) Across-wind fluctuating responses.

3.3 Effects of sideward inclination on responses of tall-slender buildings

Fig. 12 and Fig. 13 show the along- and across-wind responses of the high-rise building models with sideward inclination $\beta_b = 5°$, 10° and 15° under low turbulent flow and boundary layer flow, where $\beta_s = 0°$ indicates a straight model without inclination.

Similar to the effects of the backward inclination, Fig. 12 also indicates that the sideward inclination has very limited effect on the along-wind and across-wind displacement responses of high-rise buildings. While in boundary layer flow, the along-wind fluctuating displacement response and across-wind fluctuating response of straight model are slightly larger than those of the inclined model. The responses of three inclined models are quite similar to each other. Thus, it is concluded that the sideward inclination has less effects on the responses of tall-buildings.

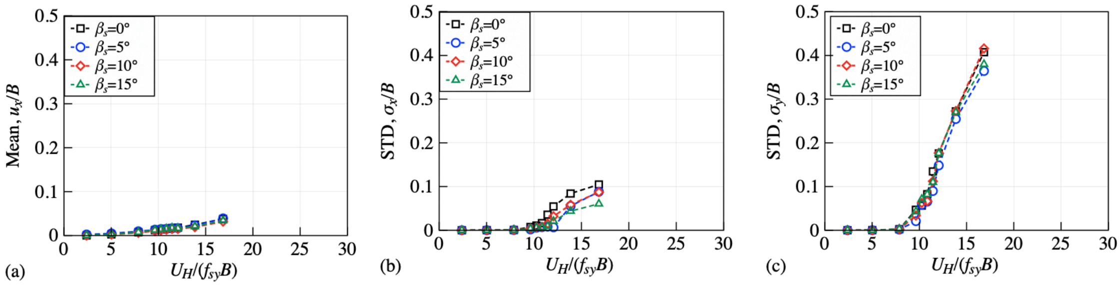


Fig. 12 Effects of the sideward inclination on wind-induced responses under low-turbulent flow: (a) Along-wind mean responses; (b) Along-wind fluctuating responses; (c) Across-wind fluctuating responses.

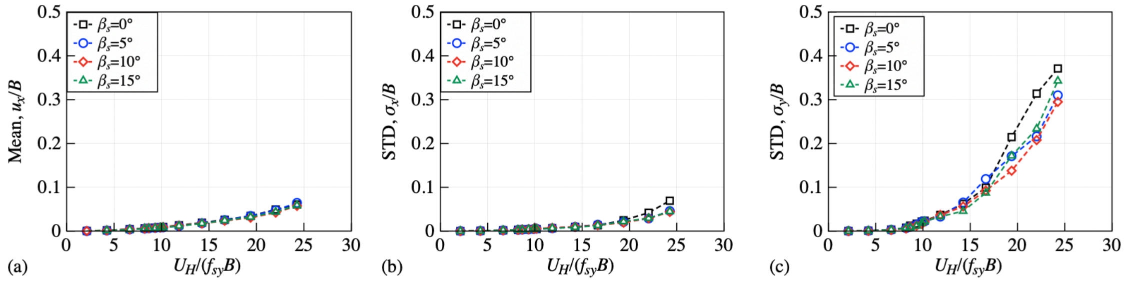


Fig. 13 Effects of the sideward inclination on wind-induced responses under boundary layer flow: (a) Along-wind mean responses; (b) Along-wind fluctuating responses; (c) Across-wind fluctuating responses.

As the summary, the windward, backward and sideward inclinations have limited influence on the along-wind responses in both of the low turbulence flow and boundary layer flow. For the across-wind displacement responses of the tall buildings, the windward inclination has significant influence in both the low turbulence flow and boundary layer flow, the sideward inclinations have limited influence in both the low turbulent flow and boundary layer flow, and the backward inclination has no influence in low turbulence flow but has significant influence in boundary layer flow.

4. Published Paper etc.

[Underline the representative researcher and collaborate researchers]

[Published papers]

1.

2.

[Presentations at academic societies]

1.

2.

[Published books]

1.

2.

[Other]

Intellectual property rights, Homepage etc.

5. Research Group

1. Representative Researcher

Qingshan, Yang

2. Collaborate Researchers

1. Yong Chul, Kim
2. Yukio, Tamura
3. Wenshan, Shan
4. Kunpeng, Guo

6. Abstract (half page)

Research Theme :Crosswind responses and aerodynamic damping of inclined high-rise buildings with large aspect ratio

Representative Researcher (Affiliation) : Qingshan, Yang (Chongqing University)

Summary・Figures

By wind tunnel tests on aeroelastic model of squared-section high-rise buildings with aspect ratio 16, the effects of the inclination on along- and across-wind response are investigated. It can be concluded that: the windward, backward and sideward inclinations have limited influence on the along-wind responses in both of the low turbulence flow and boundary layer flow. For the across-wind displacement responses of the tall buildings, the windward inclination has significant influence in both the low turbulence flow and boundary layer flow, the sideward inclinations have limited influence in both the low turbulent flow and boundary layer flow, and the backward inclination has no influence in low turbulence flow but has significant influence in boundary layer flow.