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Aerodynamic characteristics of tall building models with various unconventional configurations

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Biography

Yukio Tamura is a Professor of School of Architecture & Wind Engineering, Tokyo Polytechnic University, Japan. He is serving as the President of International Association for Wind Engineering. His research areas include wind-resistant design of buildings and structures, vibration control, modal identification, and so on.

Abstract

Tall buildings have been traditionally designed to be symmetric rectangular, triangular or circular in plan, in order to avoid excessive seismic-induced torsional vibrations due to eccentricity, especially in seismic prone regions like Japan. However, recent tall building design has been released from the spell of compulsory symmetric shape design, and free-style design is increasing. This is mainly due to architects' and structural designers' challenging demands for novel and unconventional expressions. Another important aspect is that rather complicated sectional shapes are basically good with regard to aerodynamic properties for crosswind excitations which are a key issue in tall-building wind-resistant design. A series of wind tunnel tests have been carried out to determine wind forces and wind pressures acting on tall building models with various configurations: square plan, with corner cut, with setbacks, helical and so on.

The results have led to comprehensive understanding of the aerodynamic characteristics of various tall building configurations.

Keywords: Tall building, Unconventional configurations, Aerodynamics characteristics, Response analyses

Introduction

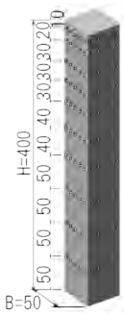
Tall buildings have been traditionally designed to be symmetric rectangular, triangular or circular in plan, to avoid excessive seismic-induced torsional vibrations due to eccentricity. However, recent tall building design has been released from the spell of compulsory symmetric shape design, and free-style design is increasing. This is mainly due to architects' and structural designers' challenging demands for novel and unconventional expressions. Development of computer aided analytical techniques and of vibration control techniques using auxiliary devices has also contributed to this trend. Another important aspect is that rather complicated sectional shapes are basically good with regard to aerodynamic properties for crosswind responses, which is a key issue in tall-building wind-resistant design. For example, changes of corner configurations and variations of sectional shape with height, called aerodynamic modification, make vortex formation and/or vortex shedding weak and/or random, which could improve the wind-resistant performance of tall buildings. The effectiveness of aerodynamic modification to reduce wind loads has been widely reported, and aerodynamic modifications thought to be effective can be classified as modifications of sectional shape (horizontally) such as polygon or Y-type (Hayashida et al., 1992), corner modification (Miyashita et al., 1993; Amano, 1995; Kawai, 1998), modifications of building shape (vertically) such as taper (Cooper et al, 1997; Kim et al., 2008; Kim and Kanda, 2010a, 2010b) or setback (Kim and Kanda, 2010a, 2010b), and introduction of openings (Miyashita et al., 1993). Although there are some reports on cross comparisons between different aerodynamic modifications using a limited number of aerodynamic modifications, almost none have comprehensively investigated the aerodynamic characteristics of various types of tall buildings with different configurations.

To investigate the relationships among structural properties, aerodynamic modifications and aerodynamic force characteristics, aerodynamic force measurements and wind pressure measurements were conducted on models with various aerodynamics modifications, and related response analyses were also conducted. This paper discusses the results of aerodynamic force measurements and wind pressure measurements for models that showed effective wind-resistant performance.

Experimental conditions

Although aerodynamic force measurements were carried out on 31 tall building models and wind pressure measurements were carried out on 9 models (Tamura et al., 2010), only those shown in Table 1 will be discussed. These models include: Square, Corner Cut, 4-Tapered, Setback, and two Helical Models. The full-scale height and the total volume of each building model are commonly set at H = 400m (80 stories) and 1,000,000m^3, respectively. The width B of the Square Model is 50m and the aspect ratio H/B is 8.

Table1. Test models (unit: mm, length scale: 1/1000)

Case	Square	Corner Cut	4-Tapered	Setback	90° Helical	180° Helical
Configuration						

Wind tunnel experiments were performed in a closed-circuit-type boundary-layer wind tunnel whose working section was 1.8m high by 2.0m wide. Figure 1 shows the condition of the approaching turbulent boundary layer flow with a power-law index of 0.27, representing an urban area. The mean wind speed and turbulence intensity at the top of the model were about U_H =7.0m/s and I_{UH} = 10%, respectively. Dynamic wind forces were measured by a 6-component high-frequency force balance. Wind direction α was changed from 0°, normal to a wall surface of a model, to 45° or 180° every 5° depending upon the building configuration. The measured wind forces and aerodynamic moments were normalized by $q_H BH^2$ to get wind force coefficients and moment coefficients. Figure 2 shows the definitions of wind forces, moments, and the coordinate system employed in this study. The Reynolds number based on the mean wind speed at the roof height U_H and the width of the Square Model B is $Re = 2.6\times10^4$.

The approaching flow and coordinate system for wind pressure measurement were the same as for the aerodynamic force measurement, except for the wind speed at a model height of 11.8m/s. The sampling frequency was 1kHz with a low-pass filter of 500Hz. The total number of data was 32,768. The fluctuating wind pressures were revised considering the transfer function of the vinyl tube. The wind pressure coefficients C_p were obtained by normalizing the fluctuating pressures p by the velocity pressure q_H at model height. And the level wind force coefficients, C_{fD} for along-wind, C_{fL} for crosswind and C_{mT} for torsional moment, were derived by integrating the wind pressure coefficients C_p using the building width of the Square Model B (B^2 for torsional moment) regardless of building shape.

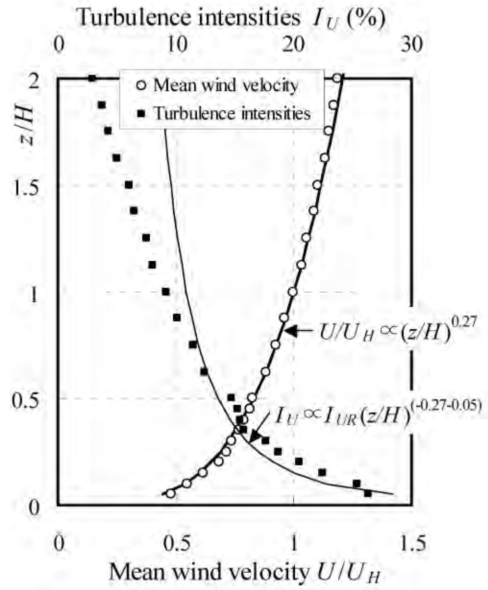


Figure 1. Approaching flow condition

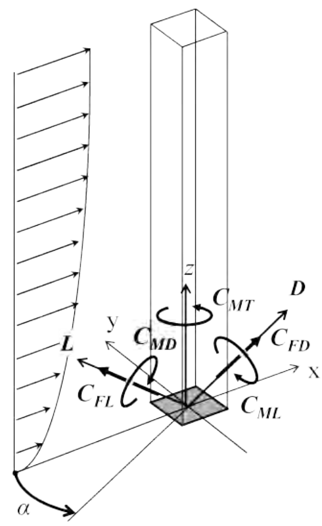
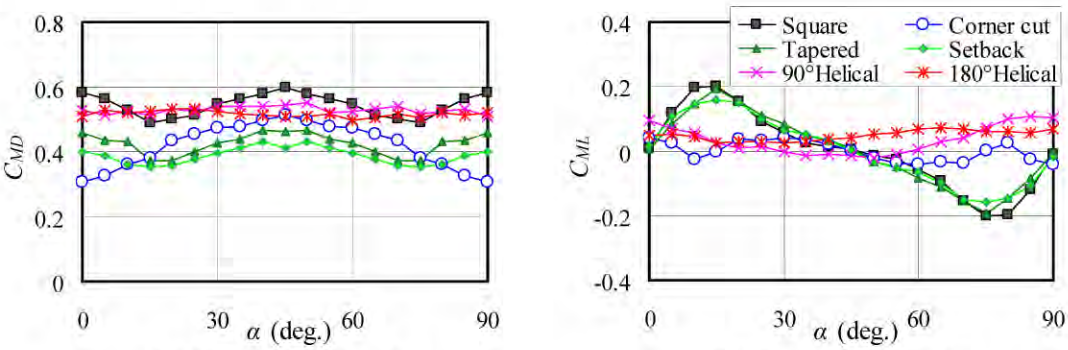


Figure 2. Coordinate system

Mean overturning moment coefficients

Figure 3 shows the variation of the mean overturning moment coefficients C_{MD}, C_{ML} with wind directions. C_{MD} is larger than C_{ML} for all cases, and the maximum value of $|C_M|_{max}$ is shown for the Square model with 0.60 at a wind direction of 45°. The minimum $|C_M|_{max}$ is shown for the Setback model with 0.43, showing 70% of that of the Square model (Figure 3(a)).

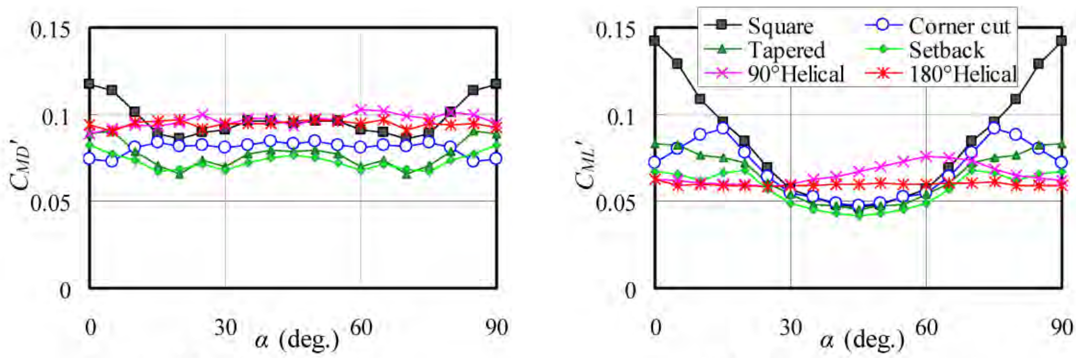


(a) Along-wind direction (b) Crosswind direction

Figure 3. Mean overturning moment coefficient.

Fluctuating overturning moment coefficients

Figure 4 shows the variation of the fluctuating overturning moment coefficients C_{MD}', C_{ML}' with wind directions. For the Square model and the Corner cut model, the crosswind component, C_{ML}', is larger than the along wind component, C_{MD}', but for the other models, the coefficients show the inverse trend. The maximum $C_{M}'_{max}$ is shown for the Square model with 0.142 for a wind direction of 0° (90°). The minimum $C_{M}'_{max}$ is shown for the Setback model with 0.082, being 60% of that of the Square model. The mean and fluctuating overturning moment coefficients of the 180° Helical and the 90° Helical vary little with wind directions. In particular, the 180° Helical shows almost constant values regardless of wind directions.



(a) Along-wind direction (b) Crosswind direction

Figure 4. Fluctuating overturning moment coefficient.

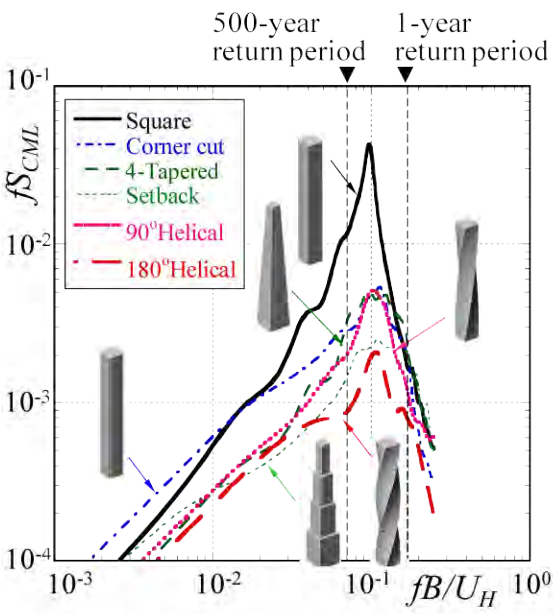


Figure 5. Comparison of power spectra

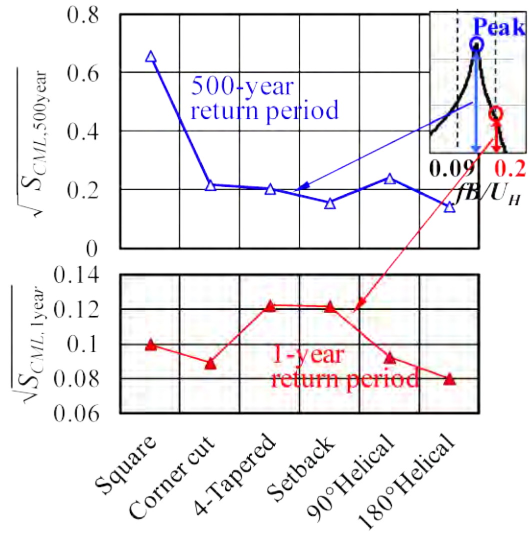


Figure 6. Comparison of spectral values for different design wind speeds (upper: $U_{H,500year}$, lower: $U_{H,1year}$).

Power spectra of crosswind overturning moment coefficients

Figure 5 shows the crosswind power spectra, fS_{CML}, for the specified wind directions at which the peak was the largest. The sharp peak observed for the Square Model was greatly reduced by implementing various modifications. The peak of the Corner Cut, 4-Tapered, Setback and Helical Models, which showed the smaller overturning moment coefficients, decreased significantly when compared with the Square Model, implying that the periodic vortex shedding was effectively suppressed.

Figure 6 compares the square root of power spectra $\sqrt{S_{CML}}$ for the design wind speed corresponding to a 500-year return period $U_{H,500year}$ and the design wind speed corresponding to a 1-year return period $U_{H,1year}$. Here, the square roots of power spectra for $U_{H,500year}$, $\sqrt{S_{CML,500year}}$, are the maximum values of the power spectra when the reduced frequency was larger than 0.07 ($fB/U_H \geq 0.07$), and the square roots of power spectra for $U_{H,1year}$, $\sqrt{S_{CML,1year}}$, were the maximum values of the power spectra when the reduced frequency was larger than 0.17 ($fB/U_H \geq 0.17$). The 1st natural frequency is assumed to be f_1=0.1Hz, and the design wind speeds for the corresponding return periods are $U_{H,500year}$=71m/s and $U_{H,1year}$=30m/s at Tokyo, respectively. The values of $\sqrt{S_{CML,500year}}$ for the Corner Cut, 4-Tapered, Setback and Helical Square Models, which show small mean and fluctuating overturning moment coefficients were almost one third or one fourth that of the Square Model, implying great advantages for safe design. However, the values of $\sqrt{S_{CML,1year}}$ for the Tapered and Setback Models were larger than that of the Square Model. But the values for the Corner Cut and Helical Square Models were smaller than that of the Square Model, meaning that these building shapes are superior to the Square Model in respect of habitability design as well as safe design.

Local mean wind force coefficients

Figure 7 shows the distribution of local mean wind force coefficients for the Square Model, Corner Cut Model, Setback Model and 180°Helical Model. The along-wind direction shown in Figure 7(a) is 0° for the Square Model, Corner Cut Model and Setback Model, and that of the 180°Helical Model is 35° which is normal to the one surface at z/H=0.7. The local mean wind force coefficients of crosswind (Figure 7(b)) and torsional moment (Figure 7(c)) are shown for the wind directions at which the mean $|\overline{C_{fL}}|$ and $|\overline{C_{mT}}|$ become maximum.

The local mean wind force coefficients for along-wind direction $\overline{C_{fD}}$ increased with z/H except for the Setback Model whose local mean wind force coefficients for along-wind direction $\overline{C_{fD}}$ decreased with z/H because of its smaller projected width. The local mean wind force coefficients for along-wind direction $\overline{C_{fD}}$ for the Corner Cut Model was 60% that of the Square Model. For the 180°Helical Model, while the $\overline{C_{fD}}$ at z/H=0.7 at which the approaching wind was perpendicular to the surface was similar to the Square Model, the local mean wind force coefficients for along-wind direction $\overline{C_{fD}}$ at other heights were smaller. The local mean wind force coefficients $\overline{C_{fL}}$ of the Square Model in the crosswind direction was the largest throughout its height. The local mean wind force coefficients for crosswind direction $\overline{C_{fL}}$ for the Corner Cut Model was smaller than that of the Square Model. Although there were some differences in the local mean wind force coefficients for crosswind direction $\overline{C_{fL}}$ for the Setback Model at $z/H \geq 0.6$ with the Square Model, the differences were not as significant as those for the along-wind coefficients $\overline{C_{fD}}$. For the 180°Helical Model, the local mean wind force coefficients for crosswind direction $\overline{C_{fL}}$ became positive or negative depending on z/H, reflecting the building shapes. This results in smaller overturning moments as shown in Figure 3. The torsional moment coefficient $\overline{C_{mT}}$ of the Setback Model showed smaller values such as along-wind direction coefficient $\overline{C_{fD}}$. The torsional moment coefficient $\overline{C_{mT}}$ for the Corner Cut Model was less than half that of the Square Model throughout its height. The torsional moment coefficient $\overline{C_{mT}}$ for the 180°Helical Model showed positive or negative values depending on z/H, resulting in very small torsional moments.

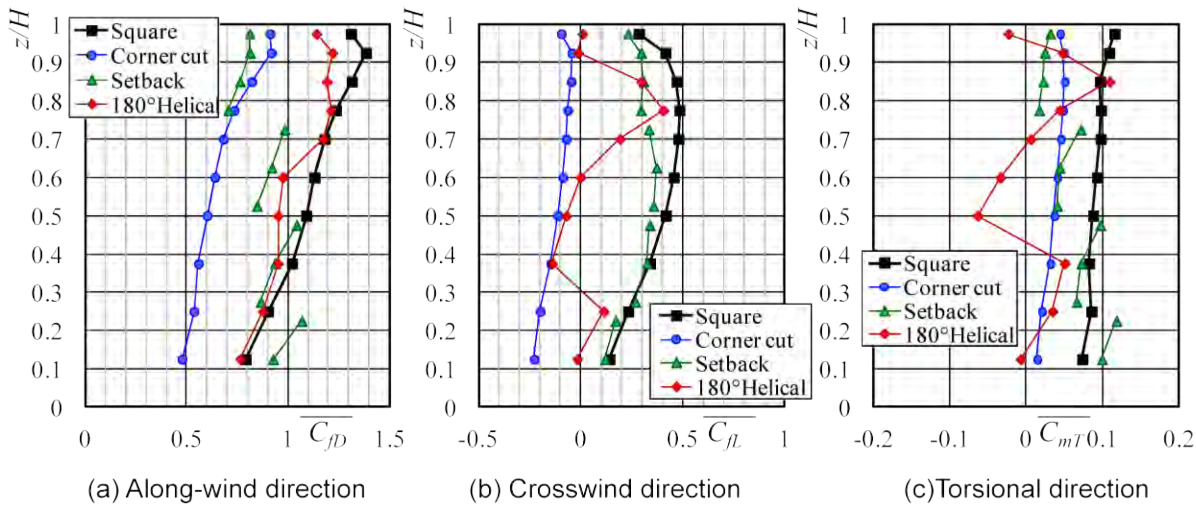


Figure 7. Vertical distributions of local mean wind force coefficients.

Distribution of wind pressure coefficients

Figure 8 shows a contour of the mean wind pressure coefficients of the Square, Corner Cut, Setback and 180°Helical Model. Although a building surface of the 180°Helical Model changes arbitrarily among windward surface, sideward surface, and leeward surface depending on the height, the mean wind pressure coefficients show its maximum at z/H=7/8, and decrease near peripheral part, showing similar distribution to the other test models. For the Corner Cut Model, the large negative wind pressures occur at leading edge of sideward surface, and their distribution varies largely from leading edge and trailing edge, showing different distribution from the Square Model. And the absolute values of mean wind pressures at leeward surface is smaller than those of the Square Model, resulting in smaller local wind forces than the Square Model by 60%~70%. The distributions of sideward surface and leeward surface of the Setback Model are similar to the Square Model. The distribution of sideward surface of the 180°Helical Model is very complex, and the absolute values of leeward surface are smaller than those of the other models

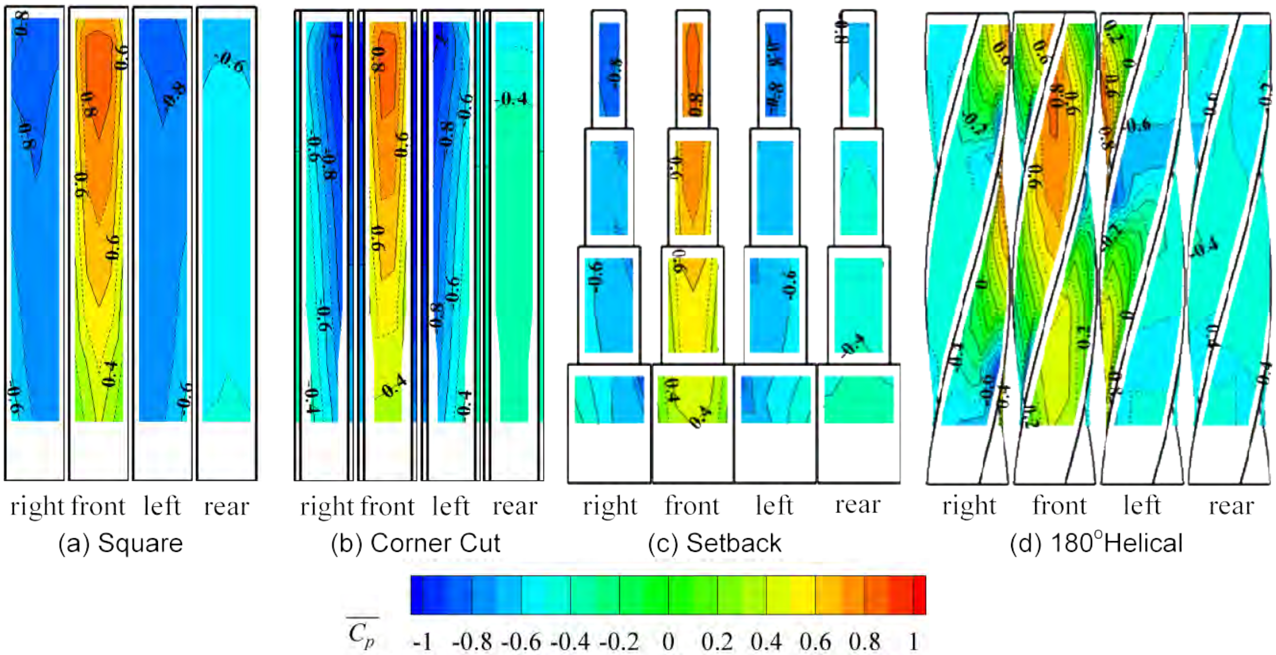
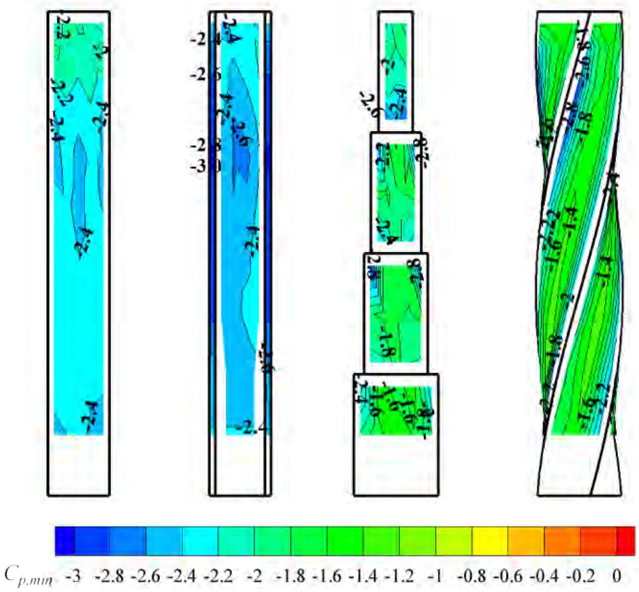


Figure 8. Distribution of mean wind pressure coefficients

Figure 9 shows the minimum wind pressure coefficients for all wind directions. As the distributions of coefficients on the four surfaces are almost the same, average values at the same pressure tap positions are used. For the minimum wind pressure coefficients, a moving average with points corresponding to 0.5sec in full time scale is applied, and 9 samples corresponding to 10 minutes in full time scale are used. While the coefficients of the Square Model change smoothly, ranging from $C_{p,min}$=-1.92 to $C_{p,min}$=-2.56, the coefficients of the 180°Helical Model vary rapidly, showing very narrow isobar distribution. For the 180°Helical Model, the smaller $C_{p,min}$ i.e. larger absolute value of $C_{p,min}$, near the corner is observed, but the larger $C_{p,min}$, i.e. smaller absolute value of $C_{p,min}$, than the other models near the center is observed. The minimum coefficients of the Corner Cut Model are small throughout the surface, and those values are smaller by 0.2 than the Square Model especially near the corner. For the Setback Model, the minimum coefficients become smaller near the setback, but in most part, the $C_{p,min}$ is small when compared with the Square Model. As for minimum wind pressure coefficients for the design of exterior wall/curtain wall, the coefficients are the Square Model: -2.56, the Corner Cut Model: -3.00, the Setback Model: -2.94, and the 180°Helical Model: -2.91.

Response analysis

In order to investigate the habitability, the eigenvalue analysis and response analysis were conducted based on the result of the wind pressure measurement. The responses for each mode were obtained by the spectral modal method, and the responses for each mode were not superimposed and were plotted individually because the degree of sensitivity for vibration is dependent on the acceleration for each mode and the corresponding frequency. The damping ratio was set to be 0.7% for all modes. Figure 10 shows the maximum acceleration responses of top floor among all considered wind directions for horizontal vibration, being plotted on the guideline for the evaluation of habitability to building vibration. The acceleration response of 180° Helical is the smallest among all test models, and although the acceleration response for the 1st mode exceeds the H-90 line, the acceleration responses for other modes are slightly lower than H-50 line.



(a) Square (b) Corner Cut (c) Setback (d) 180°Helical

Figure 9. Distribution of minimum wind pressure coefficients

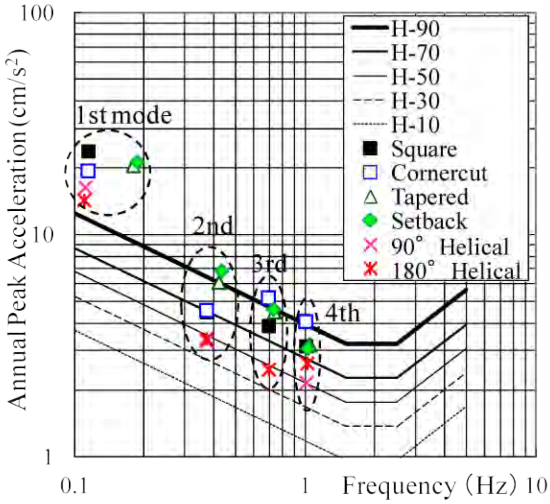


Figure 10. Results of response analysis for habitability

Conclusions

Although the wind force coefficients for the Setback model were the smallest among the models tested, the response analyses show that the acceleration of the Setback model was larger than that of the Square model, thus showing worse habitability than the Square model. However, the helical models showed better results than the Square models based on both safety and habitability criteria, and this trend becomes significant for the more twisted model. From the wind pressure measurements, although the negative peak wind pressure coefficients of the helical models were 20% larger than those of the Square model, the area were very limited. The acceleration response for the 180° Helical is smallest, and especially the acceleration responses for the 2nd ~ 4th mode are slightly lower than H-50 line. From the above discussion it can be concluded that for the helical models vortex shedding became random and irregular through all heights, showing the most effective aerodynamic force characteristics among the models tested.

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