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Influence of Wind Direction on Wind-induced response of Tall Buildings with rectangular Section

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Abstract

When using the codes/standards to estimate the wind load of the rectangular tall buildings, it is usually assumed that the wind direction perpendicular to the building's windward is the most unfavorable wind condition for its wind load, but the actual situation may not always be the case. Based on the high frequency force balance technique, the wind tunnel tests of 71 tall building rigid models with different dimensions are carried out in four different wind fields and the wind-induced responses under different wind directions are analysed with different side ratios, wind fields, natural periods and damping ratios. The results show that (1) when the side ratios are between 0.5 and 2, the most unfavorable value of the base responses occur when the airflow is parallel to the body axis; (2) when the side ratio is larger than 2 or smaller than 0.5, the most unfavourable value of the responses occur when the airflow is 10 °-15 ° inclined angle with the body axis and the largest increase of base responses is less than 15% by using 1% damping ratio. The results can help the structural engineers to design large side ratio tall buildings and provide reference for the codes/standards revision.

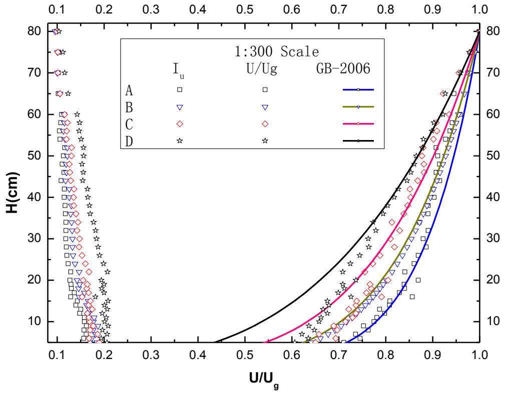
Introduction

With the increasing use of light-weight/high-strength materials, tall buildings are becoming flexible and low in damping and are more sensitive to the wind loads [2, 3]. When the airflow through the tall buildings, it will produce a complex flow around the buildings and wind pressure distribution around the surface is changed with the wind direction changes [1]. The structural engineers shall ensure that the structure system can withstand wind-induced responses from any wind direction [8]. At present, it is concluded that the method to get the wind load of tall buildings is mainly composed of the load standard design method and the wind tunnel test method. The load standard design method assumed the largest wind-induced responses of tall buildings are the body axis of the structural system, which are normal/parallel to windward surface. The researchers have done lots of researches and provide the empirical formula to calculate the wind loads of tall buildings with rectangular section [7, 9, 10]. The wind tunnel test method is to find out the most unfavorable conditions for all wind direction angles through the wind tunnel test data. But the almost all the scholars just to analyse the effects of wind directions on aerodynamic coefficients and spectrums[4,5,6] and found that the largest values are not consistent with the codes, which are not easily to use for the structural engineers by judgement by the non-dimensional coefficients. The most useful data is the effects of wind directions on the wind-induced responses, such as base shear forces, base moments and torsions, which ca let the structural engineers know the data from the code whether are ok easily.

In order to obtain the direct information on the effect of wind direction, the wind-reduced responses of tall buildings with different directions are analysed based on the wind tunnel test of 71 different high-rise building rigid models. The influence of the wind direction angle on the wind-induced responses is analysed. The effect of wind fields, natural frequencies and damping ratio are also analysed. The results can help the structural engineers to design the tall buildings with large side ratio and provide reference for the codes/standards revision.

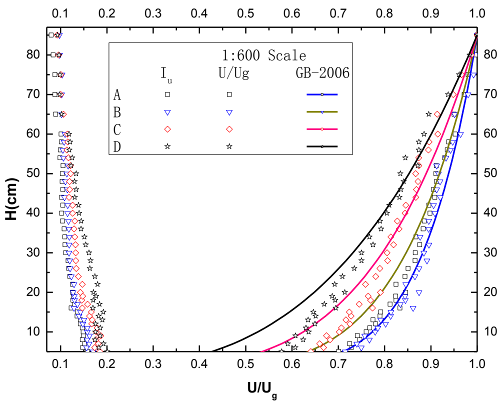
Wind Tunnel Test Information

The test is carried out in TJ-1 Boundary Layer wind Tunnel with a test section of 1.8m wide and 1.8m high, and the wind speed ranges from 3 to 32m/s. Four kinds of wind fields, corresponding to terrain categories A, B, C and D, are simulated in the wind tunnel with length scales of 1/300 and 1/600 in accordance with the Chinese code. The exponents of the mean wind profiles for the terrain categories A, B, C and D are 0.12, 0.16, 0.22 and 0.30, and the corresponding gradient heights are 300, 350, 400 and 450m, respectively. The wind characteristics are achieved by a combination of turbulence generating spires, a barrier at the entrance of the wind tunnel, and roughness elements along the wind tunnel floor upstream of the model. Figure 1 shows the simulated mean wind speed profiles and the turbulence intensities for the terrain categories A, B, C and D. The cross-section shapes of the building models for the test are shown in table 1. The height of most models are between 600mm and 833mm, the aspect ratio are between 4 and 7.5 and the side ratios are between 0.2-5.



(a) 1/300 scale wind filed

Figure 1 Simulated wind parameters of the terrain categories



(b) 1/600 scale wind filed

Figure 1 (cont.) Simulated wind parameters of the terrain categories

$\frac{H}{\sqrt{BD}}$	H$_M$ (mm)	Side ratio（D/B）
4	600	0.2，0.25，0.33，0.5，1，2，3，4，5，
5	600	1/4.7，0.25，0.33，0.4，0.5，1/1.75，0.67，0.75，0.8，1，1.25，1.33，1.5，1.75，2，2.5，3，4，4.7
5.7	800	0.2，0.25，0.33，1/2.4，0.5，1/1.75，0.67，0.75，0.8，1，1.25，1.33，1.5，1.75，2，2.4，3，4，5
6.5	650	0.5，1/1.75，0.67，0.75，0.8，1，1.25，1.33，1.5，1.75，2
7.5	833	0.5，0.67，0.75，0.8，1，1.25，1.33，1.5，2

Note:
1) There are 4 terrain roughness categories for all the models;
2) The model scale of the models with 6.5/7.5 aspect ratio(H/$\sqrt{BD}$) is 1/600 and the other models are 1/300;
3) All the models have almost 25 different wind angles.

Table 1 Models for the test

In order that the frequencies of the model-balance systems are high enough for the test, the models should be light, and all of the models are thus built with aluminium core as the cores and light foamed plastics as their ‘‘clothes’’. A six-component force balance is used for the test. The lowest frequency among these model-balance systems is about 60 Hz. The testing wind speeds are selected to be 6 and 8m/s.

Wind Tunnel Test Data Processing

In order to facilitate the comparison of the wind-induced responses, the structural coordinate system and the wind angles are defined as the geometric centroid of cross-section, as shown in Figure 2. B is the breadth of the building which is normal to the wind stream and D is the depth of the building which is parallel to the wind stream. The 0 angle is the wind flow normal to the longer side. M$_X$ means the base moment induced by the wind loads from Y direction, M$_Y$ means the base moments induced by the wind loads from the X direction, M$_Z$ is the torsional moment and the structural system is at the centroid of area [8].

For simplicity, the base bending/torsional moment response coefficients are used to access the wind-induced responses, which is the ratio of the base bending /torsional moment response to the average bending/ torsional moment.

$$G_{Mx\_Peak}(\theta)=\frac{M_{Mx\_Peak}(\theta)}{q_H BH^2} \qquad (1)$$

$$G_{My\_Peak}(\theta)=\frac{M_{My\_Peak}(\theta)}{q_H DH^2} \qquad (2)$$

$$G_{MT\_Peak}(\theta)=\frac{M_{MT\_Peak}(\theta)}{q_H BDH} \qquad (3)$$

In which, $q_H=0.5\rho U_H^2$ is the reference wind pressure at the top of the tall buildings; B is building width normal to the oncoming wind and it’s the longer side, D is the depth of the building, and H is the height of the building; ρ is the air density, U_H is the mean wind speed at building height H; $G_{Mx\_Peak}(\theta)$, $G_{My\_Peak}(\theta)$ and $G_{MT\_Peak}(\theta)$ are the base moment response coefficients of M$_X$, M$_Y$ and M$_Z$ at wind direction θ respectively and $M_{Mx\_Peak}(\theta)$, $M_{My\_Peak}(\theta)$ and $M_{MT\_Peak}(\theta)$ are the overall base moments M$_X$, M$_Y$ and torsional moment M$_Z$ at wind angle θ.

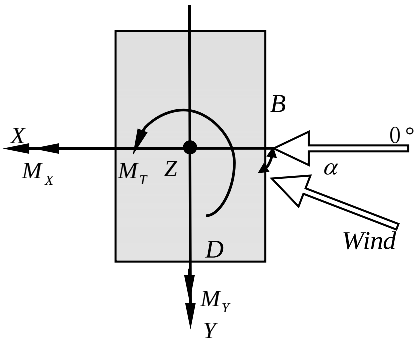


Figure 2 Simulated wind parameters of the terrain categories

According to the stochastic vibration theory, the wind-induced response of the structure can be expressed as the three parts: mean response, background response and resonance response. Assuming that the 1st mode shape of tall building is the ideal mode, the influence of the base bending/torsional moments of the high-order mode is negligible. The base bending/torsional moment response coefficients in any directions can be expressed as below:

$$G_{Mx\_Peak}(\theta)=C_{Mx}(\theta)\pm\sqrt{(g_B C'_{Mx}(\theta))^2+g_R^2\frac{f_{x1}S_{Mx}(f_{x1},\theta)}{(q_H BH^2)^2}\frac{\pi}{4\zeta_{x1}}} \qquad (4)$$

$$G_{My\_Peak}(\theta)=C_{My}(\theta)\pm\sqrt{(g_B C'_{My}(\theta))^2+g_R^2\frac{f_{y1}S_{My}(f_{y1},\theta)}{(q_H DH^2)^2}\frac{\pi}{4\zeta_{y1}}} \qquad (5)$$

$$G_{MT\_Peak}(\theta)=C_{MT}(\theta)\pm\sqrt{(g_B C'_{MT}(\theta))^2+g_R^2\frac{f_{T1}S_{MT}(f_{T1},\theta)}{(q_H BDH)^2}\frac{\pi}{4\zeta_{T1}}} \qquad (6)$$

$$C_{Mx}(\theta)=\frac{\overline{M}_x(\theta)}{q_H BH^2},C_{My}(\theta)=\frac{\overline{M}_y(\theta)}{q_H DH^2},C_{MT}(\theta)=\frac{\overline{M}_T(\theta)}{q_H BDH} \qquad (7)$$

$$C'_{Mx}(\theta)=\frac{\sigma_{Mx}(\theta)}{q_H BH^2},C'_{My}(\theta)=\frac{\sigma_{My}(\theta)}{q_H DH^2},C'_{MT}(\theta)=\frac{\sigma_{MT}(\theta)}{q_H BDH} \qquad (8)$$

In which, $\frac{f_{x1}S_{Mx}(f_{x1},\theta)}{(q_H BH^2)^2}$, $\frac{f_{y1}S_{My}(f_{y1},\theta)}{(q_H DH^2)^2}$ and $\frac{f_{T1}S_{MT}(f_{T1},\theta)}{(q_H BDH)^2}$ are the non-dimensional base spectrum of M$_X$, M$_Y$ and M$_T$ respectively; f_{x1}, f_{y1} and f_{T1} are natural frequency of X,Y and Z axis respectively; ζ_{x1}, ζ_{y1} and ζ_{T1} are the damping ratio of X, Y and Z axis; g_B and g_B are the peak factor for background response and resonance response respectively, and used 3.5 for analysis.

In order to find out the influence of the natural frequency and damping ratio on the the base bending /torsional moment response coefficients of the tall buildings with rectangular section, two cased are considered:

1) **Rigid structure**: ignored the resonance component, the dimensionless base bending /torsional moment response coefficients can be expressed as[8]:

$$G_{Mx\_Peak}(\theta) = C_{Mx}(\theta) \pm g_B C'_{Mx}(\theta) \tag{9}$$

$$G_{My\_Peak}(\theta) = C_{My}(\theta) \pm g_B C'_{My}(\theta) \tag{10}$$

$$G_{MT\_Peak}(\theta) = C_{MT}(\theta) \pm g_B C'_{MT}(\theta) \tag{11}$$

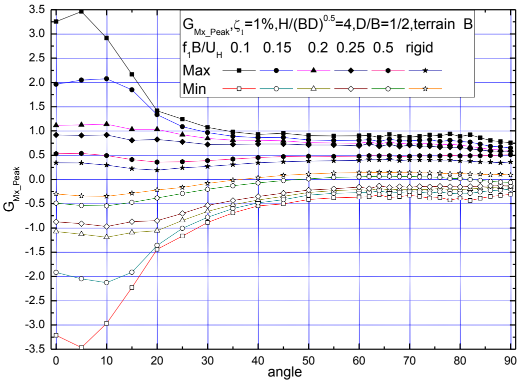
2) **Flexible structure**: different reduced frequencies (f_1B/U_H ,0.1,0.15,0.20,0.25,0.5) will be considered and 1% damping ratio for the steel structure and 3% damping ratio for concreted structure are used to analyse the effect of damping ratio.

Analysis Results

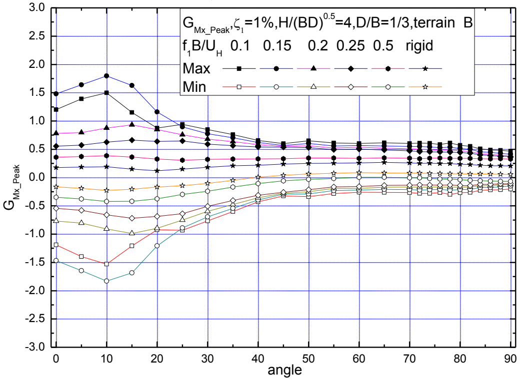
Based on the above parameters (different wind angles, reduced frequencies, damping ratio and terrain roughness), the dimensionless base bending /torsional moment response coefficients are analysed and the base moment coefficients $G_{Mx\_Peak}(\theta)$ and base torsional moment coefficients $G_{Mz\_Peak}(\theta)$ with different side ratio are shown in Figure 3 and Figure 4 respectively.

In Figure 3, it can be found that when side ratio D/B <2, the most unfavourable value of base moment Mx occurs when the wind flow is parallel to the body axis and there will be 10-15 degree interaction angles between the body axis when the side ratio D/B >2. The largest increase of base bending moment responses are sensitive to the reduced frequencies, especially the across-wind responses, and the increase is less than 15% when used 1% damping ratio in open terrain roughness.

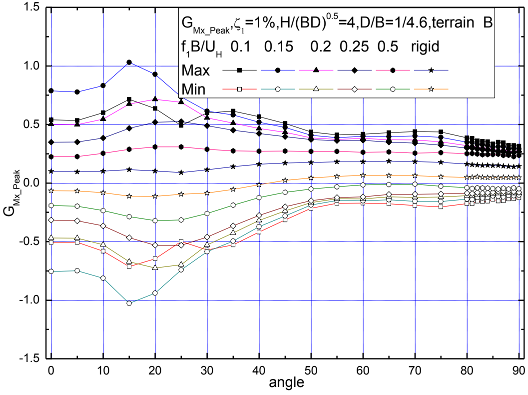
In Figure 4, it can be found that when side ratio D/B <2, the most unfavourable value of base torsional moment Mz occurs when the wind flow is parallel to the body axis and there will be 10-15 degree interaction angles between the body axis when the side ratio D/B >2. The largest increase of base torsional moment responses are not like the base moment and is less than 10% when used 1% damping ratio in open terrain roughness.



b) D/B=1/2

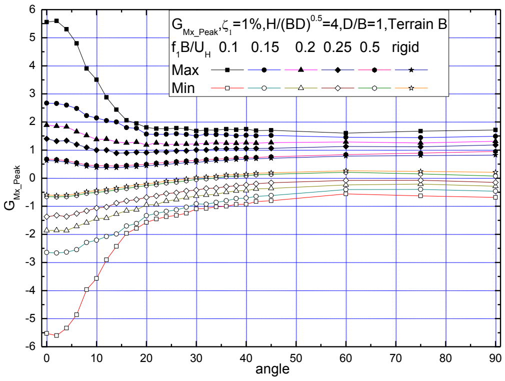


c) D/B=1/3

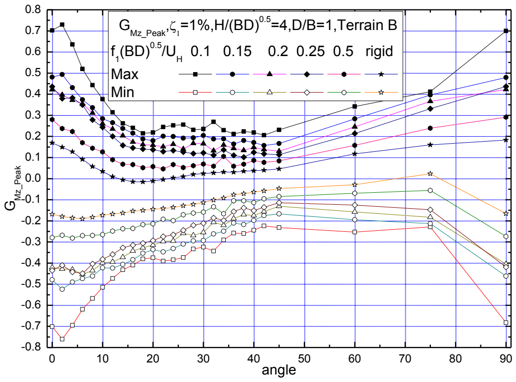


d) D/B=1/4.6

Figure 3 $G_{Mx\_Peak}(\theta)$ changed with different side ratio in Open terrain (Chinese terrain B)

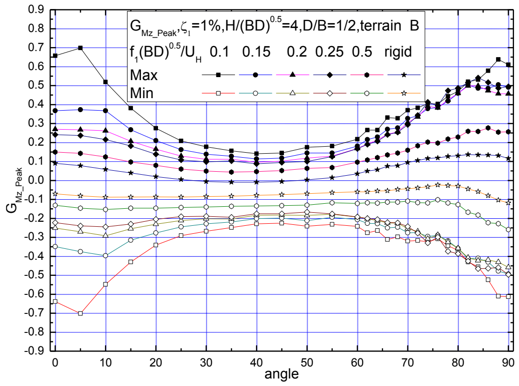


a) D/B=1

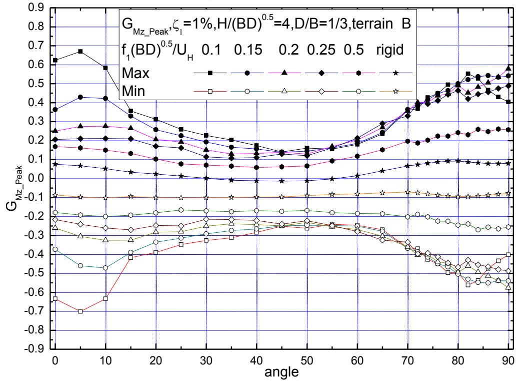


a) D/B=1

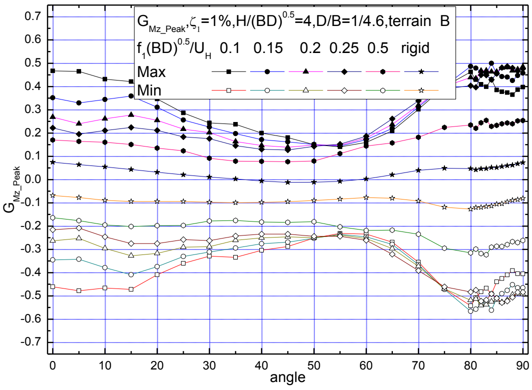
Figure 4 $G_{Mz\_Peak}(\theta)$ changed with different side ratio in Open terrain (Chinese terrain B)



b) D/B=1/2



c) D/B=1/3



d) D/B=1/4.6

Figure 4 (cont.) $G_{Mz\_Peak}(\theta)$ changed with different side ratio in Open terrain
(Chinese terrain B)

Conclusions

Based on the HFFB wind tunnel test data of 71 rectangular tall building with different side ratio and slender ratio, the wind-induced responses are analysed and some conclusions are as following:

(1) The wind angels of most unfavourable value of the base bending/twist moment responses of tall buildings with rectangular section are changed with the side ratio. When 0.5≤D/B≤2, the most unfavourable value of the base bending/twist moment responses occur when the airflow is parallel to the body axis; when D/B>2 or D/B<0.5, the most unfavourable value of the responses occur when the airflow is 10° -15° angle.

(2) The largest increase of base bending/twist moment responses are sensitive to the damping ratio, reduced frequencies and terrain roughness and is less than 15% when the damping ratio is 1%. A larger damping ratio and reduced frequency with rougher terrain roughness, the increase will be less than 5%.

(3) For the tall building with large side ratio (D/B>2 or D/B<0.5), only considered the wind angles parallel to the body axis will underestimate the wind-induced responses, especially across-wind responses as using low damping ratio.

(4) The results can help the structural engineers to design the tall buildings with large side ratio and helpful to provide reference for the codes/standards revision.

Acknowledgments

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