Load combination and response combination of wind-excited tall buildings and the effects of structural eccentricity

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Abstract

Wind tunnel aeroelastic model tests of the CAARC standard tall building were conducted. The experimental results highlight the significant effects of coupled translational-torsional motion and eccentricity between centre of mass and centre of stiffness on the normalised along-wind and cross-wind responses for reduced velocities ranging from 4 to 20, especially at operating reduced velocities close to a critical value of 10. Wake excitation remains the dominant excitation mechanism in cross-wind direction. In addition, the contribution from torsional motion was found to be greatly amplified by the resonance mechanism, which occurs when the frequency of the shed vortices coincides with the torsional frequency of the building model.

1. Introduction

Recent advances in the use of high strength materials, innovative structural systems, structural analysis methodology, and efficient construction methods have allowed a global increase in the number of tall and slender buildings and towers. Modern tall buildings with complex geometrical shapes, such as cut-outs and/or multiple level of set-backs, or buildings which have an asymmetric stiffness distribution in plan, such with lift core structures at the corner, are likely to have a significant torsional motion in addition to two translational motion. The resultant building responses, which are coupled translationally and torsionally, may be greatly amplified at the corner region of the building.

The effects of coupled translational-torsional motion on wind-induced response characteristics of tall buildings have been studied analytically by Tallin and Ellingwood (1985), Kareem (1985), and Yip and Flay (1995), for example. However, a comprehensive study of wind-induced coupled motion and wind excitation mechanisms is limited due to lack of relevant information from wind tunnel aeroelastic model tests.

This paper presents experimental results from wind tunnel aeroelastic model tests of the CAARC (Commonwealth Advisory Aeronautical Research Council) standard tall building with a special emphasis on the effects of coupled translational-torsional motion and eccentricity between centre of mass and centre of stiffness on wind-induced response characteristics and wind excitation mechanisms.

2. Experimental programs

A three-degree-of-freedom base hinged assembly (BHA), as shown in Fig. 1, was used in this study. A BHA independently simulates building translational motion using two independent perpendicular plane frames, denoted as ABCD and KLMN respectively in Fig. 1, and torsional motion using a flexural pivot. Development and refinement of this modelling technique have been ongoing since 1994, and this technique has been found to be a satisfactory method in simulating building motion by Kwok et al. (1994), Thepmongkorn et al. (1997), and Thepmongkorn and Kwok (1998).

In the aeroelastic model and balance system shown in Fig. 3, a 1:400 scale rigid timber model of the CAARC building was attached to a BHA by a screwed connection. Eccentricities e_x and e_y

for a building model are introduced by physically offsetting the centroid of the building model with respect to the vertical axis of a flexural pivot, which coincides with the vertical axis of a BHA. This can be achieved by adjusting the centriod of the top plate of a BHA, as shown in Fig. 3.

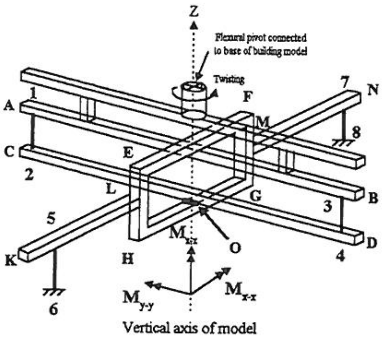

Fig. 1 Base hinged assembly test rig.

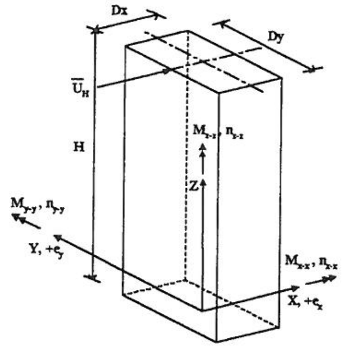

Fig. 2 Building model and notations.

Three uni-directional accelerometers were located at point A, B and C at top of the building model as shown in Fig. 4. It was assumed that the acceleration caused by torsional motion manifested as the translational acceleration when angle of twist is small, therefore, the translational acceleration at point C, $\ddot{x}$, and point A, $\ddot{y}_a$, were used as an indicator of wind-induced response characteristics and discussions were made based on these two accelerations.

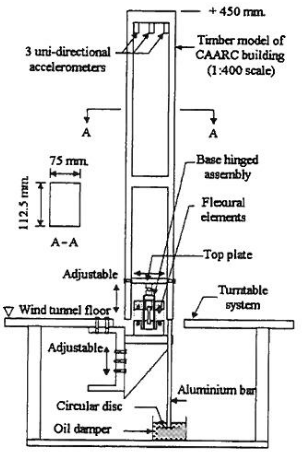

Fig. 3 BHA model and balance system.

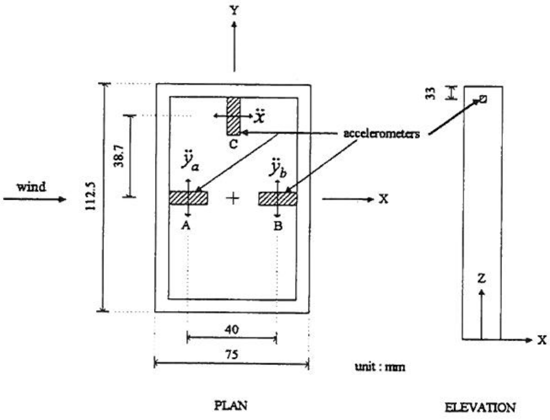

Fig. 4 Arrangement of accelerometers at top of the model.

3. Experimental results

The normalised resultant rms accelerations $\sigma_{\ddot{x}}/(2\pi n_{y\text{-}y})^2 D_y$ and $\sigma_{\ddot{y}_a}/(2\pi n_{x\text{-}x})^2 D_y$ for the incident wind normal to the wide face of the building model are plotted as a function of reduced velocity, $U_r = \bar{U}_H / (n_{x-x} . D_y)$, and are presented in Figures 5 and 6.

It was found that coupled translational-torsional motion tends to decrease the normalised cross-wind response of the CAARC building model for the range of reduced velocity tested and this effect of coupled motion is independent of the cross-wind/torsional frequency ratio as shown in Fig. 5*b*. In addition, a significant reduction by more than 50% of the normalised cross-wind response for both cases of cross-wind/torsional frequency ratio at operating reduced velocity close to a critical value of 10 highlights the significant impact on the amplitude-dependent excitation caused by the vortex resonant process and the resultant cross-wind response of tall buildings.

On the other hand, the normalised along-wind response of the CAARC building model varies with the cross-wind/torsional frequency ratio as it affects the transfer of energy of vibration from cross-wind oscillation. It was found that, for a cross-wind/torsional frequency ratio of 0.84, the normalised along-wind response was significantly amplified by more than 100% and a more prominent peak at operating reduced velocities close to a critical value of 10 is evident.

For a cross-wind/torsional frequency ratio of 0.84, the eccentricity between centre of mass and centre of stiffness has a significant effect on both the normalised along-wind and cross-wind acceleration responses for the range of reduced velocity tested as shown in Fig. 6. The eccentricity down-wind (Case 4) tends to increase the normalised cross-wind response, in particular at operating reduced velocities close to a critical value of 10, which is thought to be related to a significant increase of the interdependence between the excitation and response processes. On the other hand, the eccentricity side-wind (Case 6) generally decreases the normalised cross-wind response except at the critical reduced velocity for torsional motion, i.e., $(U_{cr})_T = \overline{U}_H \big/ (n_{z-z}.D_y) \cong 10$, at which the cross-wind response is amplified by the resonance mechanism as the frequency of the shed vortices coincides with the torsional frequency of the building model.

At operating reduced velocities close to a critical value of 10, the eccentricity between centre of mass and centre of stiffness has a significant effect on the normalised along-wind response, in which a significant increase by more than 100% was observed when the centre of stiffness was located laterally down-wind, and a decrease by 20% was evident when the centre of stiffness was located laterally side-wind. However, for the other reduced velocity tested, the eccentricity appears to have a negligible effect on the normalised along-wind response.

4. Conclusions

Coupled translational-torsional motion was found to have a significant effect on both the normalised along-wind and the normalised cross-wind responses of the CAARC building model for reduced velocities ranging from 4 to 20, especially at operating reduced velocities close to a critical value of 10. Cross-wind/torsional frequency ratio and eccentricity between centre of mass and centre of stiffness were found to have a significant effect on the amplitude-dependent mechanism resulting from the vortex shedding process, and the transfer of vibrational energy between the along-wind and cross-wind directions. Furthermore, wake excitation remains the dominant excitation mechanism in the cross-wind direction, even in cases of tall buildings with coupled translational-torsional motion and with eccentricity. The contribution from torsional motion to the cross-wind response was found to be greatly amplified by the resonant mechanism, which occurs when the frequency of the shed vortices coincides with the torsional frequency of the building model.

References

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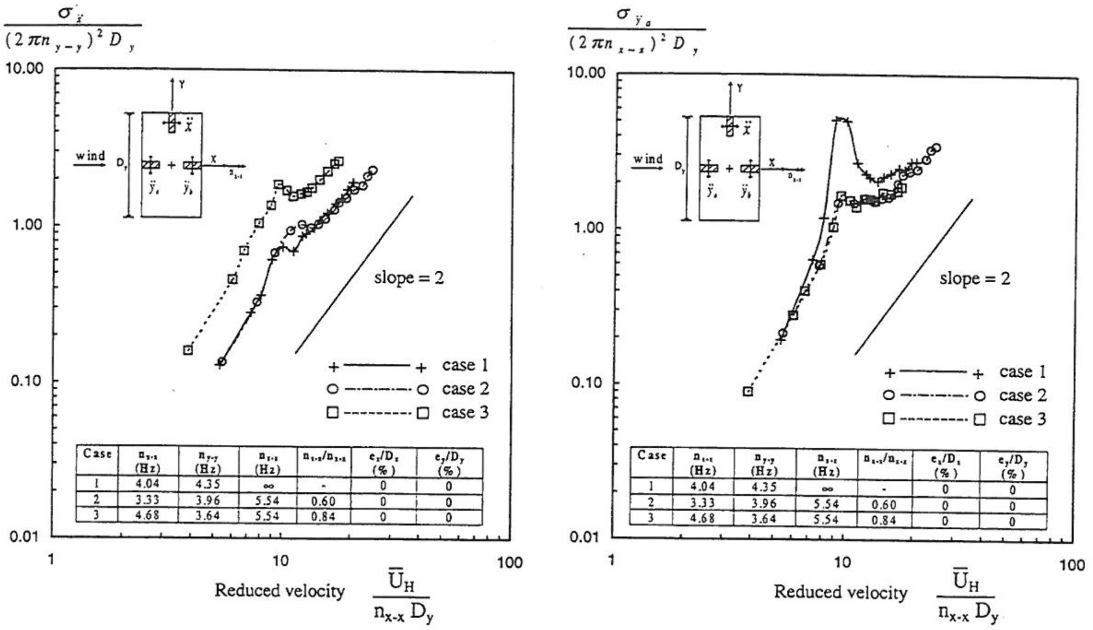
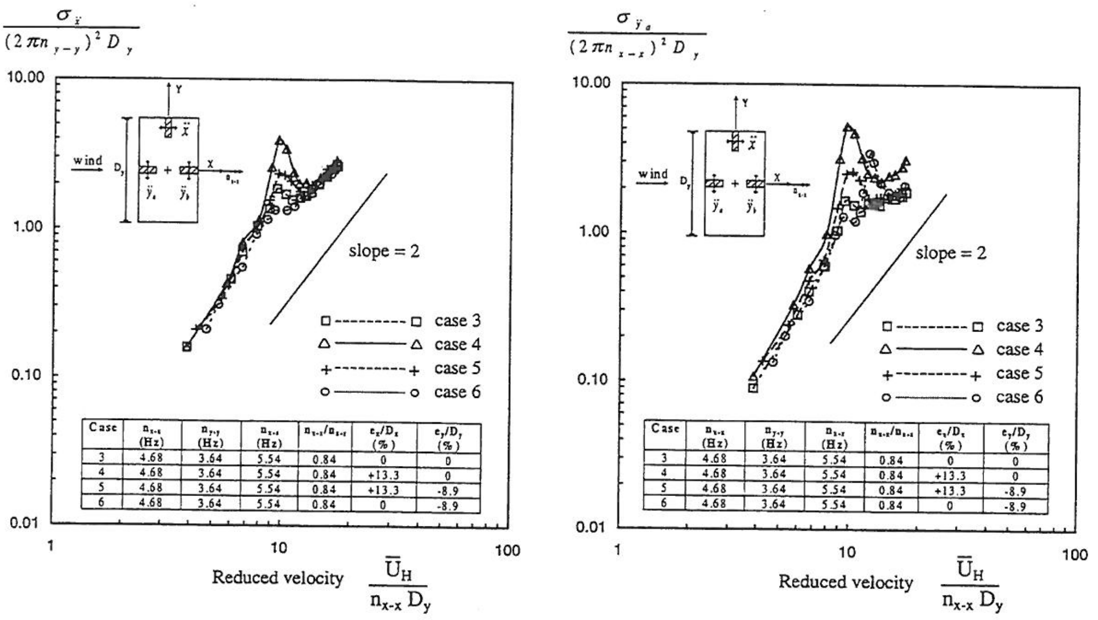


Case	n_{x-x} (Hz)	n_{y-y} (Hz)	$n_{\theta-\theta}$ (Hz)	$n_{x-x}/n_{\theta-\theta}$	e_x/D_x (%)	e_y/D_y (%)
1	4.04	4.35	∞	-	0	0
2	3.33	3.96	5.54	0.60	0	0
3	4.68	3.64	5.54	0.84	0	0

Case	n_{x-x} (Hz)	n_{y-y} (Hz)	$n_{\theta-\theta}$ (Hz)	$n_{x-x}/n_{\theta-\theta}$	e_x/D_x (%)	e_y/D_y (%)
1	4.04	4.35	∞	-	0	0
2	3.33	3.96	5.54	0.60	0	0
3	4.68	3.64	5.54	0.84	0	0

(a) *(b)*

Fig. 5 Normalised resultant rms acceleration response at top of the CAARC building model as a function of reduced velocity for different cross-wind/torsional frequency ratios: (a) along-wind response; (b) cross-wind response.



Case	n_{x-x} (Hz)	n_{y-y} (Hz)	$n_{\theta-\theta}$ (Hz)	$n_{x-x}/n_{\theta-\theta}$	e_x/D_x (%)	e_y/D_y (%)
3	4.68	3.64	5.54	0.84	0	0
4	4.68	3.64	5.54	0.84	+13.3	0
5	4.68	3.64	5.54	0.84	+13.3	-8.9
6	4.68	3.64	5.54	0.84	0	-8.9

Case	n_{x-x} (Hz)	n_{y-y} (Hz)	$n_{\theta-\theta}$ (Hz)	$n_{x-x}/n_{\theta-\theta}$	e_x/D_x (%)	e_y/D_y (%)
3	4.68	3.64	5.54	0.84	0	0
4	4.68	3.64	5.54	0.84	+13.3	0
5	4.68	3.64	5.54	0.84	+13.3	-8.9
6	4.68	3.64	5.54	0.84	0	-8.9

(a) *(b)*

Fig. 6 Normalised resultant rms acceleration response at top of the CAARC building model as a function of reduced velocity for different eccentricities: (a) along-wind response; (b) cross-wind response.