Wind Tunnel Testing of the Second Generation Wind-Excited Benchmark Building

K. T. Tse, K.C. S. Kwok, P. A. Hitchcock
CLP Power Wind/Wave Tunnel Facility, The Hong Kong University of Science and Technology, Hong Kong S.A.R., P.R.China

B. Samali
Faculty of Engineering, The University of Technology, Sydney, Australia

C. M. Chan, J. K. L. Chui
Department of Civil Engineering, The Hong Kong University of Science and Technology, Hong Kong S.A.R., P.R.China

Abstract: The first generation wind-excited benchmark building was introduced to compare control algorithms and devices suppressing uncoupled sway modes of vibration. The second generation wind-excited benchmark building is proposed in this paper to incorporate complex lateral-torsional motions, which are typical of a significant number of modern tall buildings. A finite element model has already been constructed and hence mass, damping and stiffness matrices can be extracted for numerical analysis. Wind tunnel pressure tests were conducted at the CLP Power Wind/Wave Tunnel Facility, The Hong Kong University of Science and Technology to determine translational and torsional wind forces acting on the benchmark building. The testing details and methodology are presented in this paper.

INTRODUCTION

Over the years, there have been significant developments in structural control algorithms and devices [Ankireddi and Yang (1996), Cao et al (1997), Samali et al (1985), Wu and Yang (1998), Yang et al (1997)]. Each algorithm and device has its own merits and is developed for particular applications. To make direct comparisons between these algorithms and devices, structural control benchmark problems have been developed for earthquake and wind excitations, respectively [Spencer et al (1998), Yang et al (1998)].

The first generation wind-excited benchmark building is a 76-storey 306 metre concrete office tower, with square cross-section, and is chamfered at two diagonal corners. Its axes of shear centre and mass centre coincide, therefore essentially avoiding coupled lateral-torsional motion . For further simplicity, all rotational degrees of freedom were eliminated by static condensation, resulting in only the lateral degrees of freedom being retained [Yang et al (2001)]. Hence, the model is amenable to research of the suppression of sway modes of vibration.

The second generation wind-excited benchmark building is proposed to incorporate complex lateral-torsional motions, which are typical of a significant number of modern tall buildings undergoing such motions due to wind excitation. A finite element model has been constructed and a numerical model, including mass, damping and stiffness matrices, can hence be resolved for subsequent numerical analysis. The purpose of the current wind tunnel tests is to determine translational and torsional wind forces experienced by the second generation benchmark building under certain wind conditions.

SECOND GENERATION BENCHMARK BUILDING

The second generation benchmark building is a 55-storey, 240 metre tall structure with a uniform rectangular cross-section of 72 m by 24 m as shown in Fig.1. The aspect ratio (H:W:D) is 10:3:1. Steel out-rigger trusses are employed at approximately one-third and two-thirds building height as a stabilization system. The two identical cores, symmetrical about its slender axis, are connected by link beams. Core setbacks at Level 19 and Level 37 cause eccentricities between the level-by-level shear centre, mass centre and the geometrical centre over the building height. With such an arrangement, the building undergoes complex three-dimensional modes of vibration when dynamically excited.

A finite element model has been constructed and the mode shapes corresponding to the first three modes of vibration are displayed inFig. 2. The first mode is a complex lateral-torsional mode due to the eccentricity of shear centre from mass centre. The second mode is translational and the third mode is predominantly torsional. The corresponding natural frequencies are 0.127, 0.211 and 0.231 Hz, respectively.

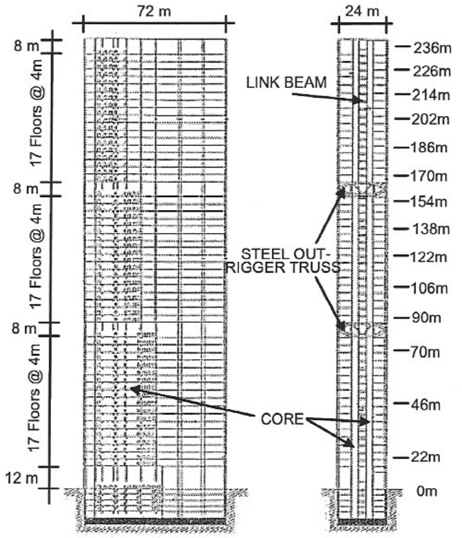

Figure 1. Second generation wind-excited benchmark building

EXPERIMENTAL SETUP

A 1:400 scale rigid model of the second generation wind-excited benchmark building, as shown in Fig.3, was constructed and tested at the CLP Power Wind/Wave Tunnel Facility (WWTF) at The Kong Hong University of Science and Technology. The model was installed with 14 layers of pressure taps over its height with 32 pressure taps in each layer. Each tap was connected to one of 16 ports of an ESP-16HD pressure scanner with a 750 mm single lumen PVC tube of 1.5 mm internal-diameter, without any restrictor. The elevation of the 14 layers is shown in Fig.1. The amplitude and phase distortion due to the tubing system were compensated by numerical post-processing.

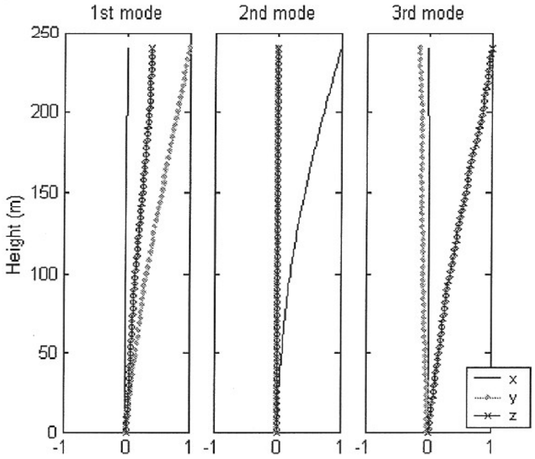

Figure 2. Mode shapes of second generation benchmark building

The simulated wind model corresponded to AS/NZS 1170.2:2002 (Australian/New Zealand Standard 2002) Category 3 terrain. It was established using a combination of trip boards and roughness elements over a 21m fetch length. Gust wind speed and turbulence intensity profiles are presented in Fig.4 and the measured spectrum of longitudinal wind speed at the top of the building is presented in Fig.5.

In order to achieve a minimum Reynolds number of 5×10^4, as recommended by AWES-QAM-1-2001 for a building model with sharp corners, the tests were carried out at velocity

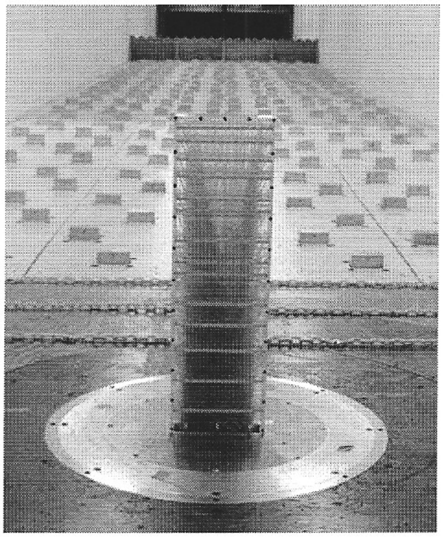

Figure 3. Pressure-tapped building model inside wind tunnel

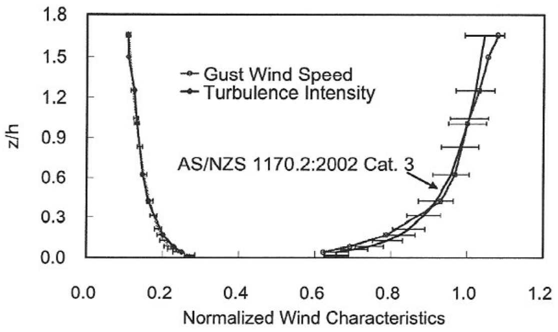

Figure 4. Simulated wind characteristics

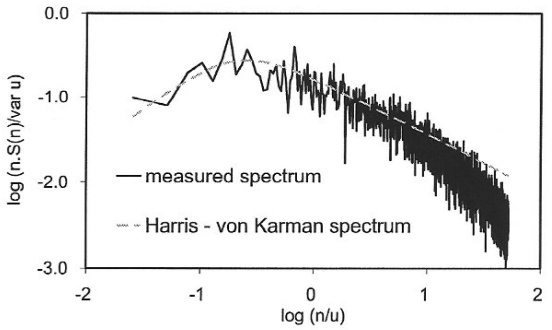

Figure 5. Longitudinal wind spectrum

scale of 1:4, resulting in a time scale of about 1:100. Similarly, the frequency ratio was 100:1. The sampling frequency was 400 Hz, which means pressure fluctuations were captured with frequencies up to 2 Hz at prototype scale. The pressure data were recorded for 36 s, which is equivalent to approximately 1 hour at prototype scale. Measurments were taken at every 22.5° from 0° to 90°, where 0° corresponds to wind normal to the wide face.

RESULTS

External pressures were measured and normalized with respect to the mean wind speed at building height. Instantaneous pressure coefficients were determined at each tap location and subsequently analyzed to determine maximum, minimum, mean, and standard deviation C_p's. Fig.6 displays the mean pressure coefficients developed on the surfaces of the benchmark building model due to flow normal to the wide face. It is noticed that the stagnation point is located at about three-quarters of building height and the pressure distribution is symmetrical about the centerline of the windward face. As expected for a symmetrical building, the pressure distribution is nearly identical for the side faces.

Equation (1) was used to convert the measured pressure coefficients into prototype scale wind forces,

$$F(t)=\frac{1}{2}\rho\overline{U}^2C_p(t)\Delta A \tag{1}$$

where ρ is density of air in kgm^{-3}; $\overline{U}^2$ is the mean wind speed at building height in ms^{-1}; $C_p(t)$ is pressure coefficient time history recorded from the wind tunnel tests; and ΔA is tributary area of each tap in m^2. In this study, a 50 year return period serviceability mean wind speed at building height of 51.1 ms^{-1} was used. It was obtained from AS/NZS 1170.2:2002, assuming that the building is located in a coastal cyclone region. For alternative locations, the wind forces may be adjusted by multiplying by $\overline{U}_d^2/51.1^2$, where $\overline{U}_d$ is the desired prototype mean wind speed at building height.

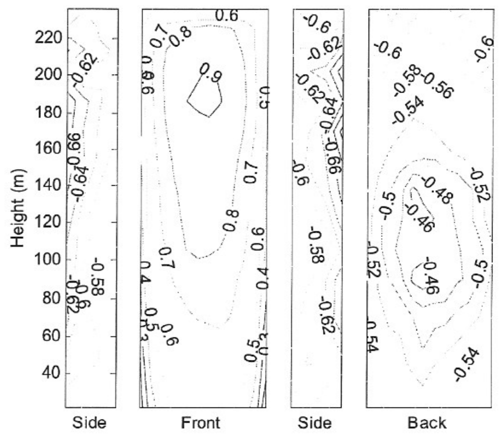

Figure 6. Contour of mean C_p on surfaces due to flow normal to wide face

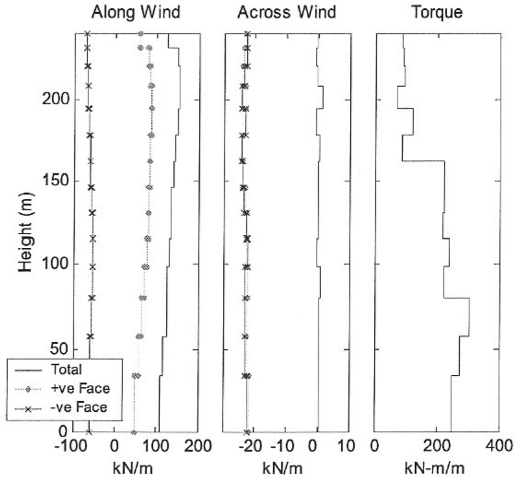

Figure 7. Distributed wind forces about mass centers

To be consistent with the numerical model, translational and torsional wind forces were calculated and applied at the mass centre of the corresponding floor. The distributed wind forces along the building height are presented in Fig.7. It is observed that, due to the symmetrical cross-section, the mean cross-wind forces on the side faces are similar over the height, resulting in resultant mean cross-wind forces of approximately zero. The distributed torsional wind forces were found to be relatively small since the mass centres are close to the centerline and the pressure distributions are symmetrical about the centerline as well. It can be readily shown that the torsional wind forces increase as the mass centre is offset further from centerline.

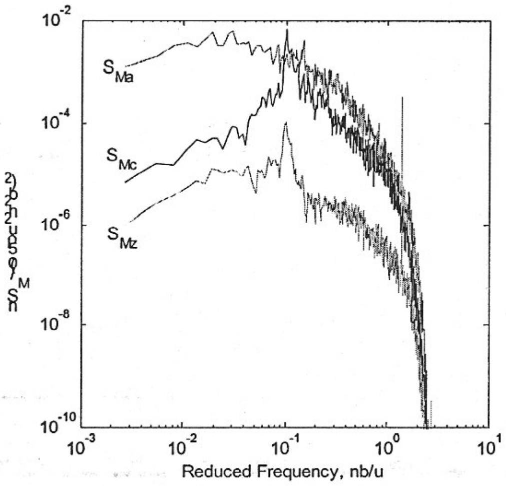

Figure 8. Normalized power spectral density of base moments

The along-wind and cross-wind base moments, M_a and M_c respectively, were determined by multiplying storey forces by the appropriate layer height while the base torque, M_z, was determined by summing storey torque for entire building. The normalized power spectral density ($nS(n)/\sigma^2$) of the base moments and torque are shown in Fig.8. As expected for a rectangular building, the spectral peak occurring at 0.1 indicates vortex shedding. A similar characteristic was also found in the normalized power spectral density of the base torque.

CONCLUSIONS

A finite element model of the second generation wind-excited benchmark building has been developed and a numerical model including mass, damping and stiffness matrices, can hence be extracted. The translational and torsional wind forces, determined from wind tunnel tests, can be used with the numerical model for subsequent comparisons among control algorithms and devices to suppress wind-induced, complex building vibrations. The wind forces and the numerical model will soon be available for download from the WWTF's website: http://www.wwtf.ust.hk

ACKNOWLEDGEMENTS

This research project is funded by a Research Grants Council of Hong Kong Central Allocation Grant (Project CA02/03.EG03) and a HKUST High Impact Areas Grant (HIA02/03.EG01). Thanks also go to the staff of the CLP Power Wind/Wave Tunnel Facility at HKUST.

REFERENCE

[1] Ankireddi, S. and Yang, H.T.Y. (1996), “Simple ATMD Control Methodology for Tall Buildings Subject to Wind Loads”, *ASCE J. Struct. Engng*, 122(1), 83-91.

[2] Cao, H., Reinhorn, A.M. and Soong, T.T. (1997), “Design of an Active Mass Damper for Wind Response of Nanjing TV Tower”, *J. Engng Struct.*, 20(3), 134-143.

[3] Samali, B., Yang J. N. and Yeh, C. T. (1985), “Control of Lateral-Torsional Motion of Wind-Excited Buildings.” *ASCE J. Engng Mech.*, 111(6), 777-796

[4] Spencer, Jr. B. F., Christenson, R.E., and Dyke, S. J.(1998), "Next Generation Benchmark Control Problem For Seismically Excited Buildings", *Proc. 2nd World Conf. on Structural Control*, Vol.2, pp.1351-1360, John Wiley & Sons, N.Y.

[5] Wu, J. C. and Yang, J. N. (1998), "Active Control of Transmission Tower Under Stochastic Wind", J. Struct. Engng, ASCE, Vol.124, No.11, pp.1302-1312

[6] Yang, J. N., Wu, J.C., Agrawal A. K. and Hsu, S. Y. (1997), “Sliding Mode Control with Compensators for Wind and Seismic Response Control,” *J. Earthquake Engng and Struct. Dynamics*, Vol. 26, pp. 1137-1156.

[7] Yang, J.N., Wu, J.C., Samali, B. and Agrawal, A.K. (1998), “A Benchmark Problem for Response Control of Wind-Excited Tall Buildings”, *Proc. 2nd world Conf. on Struct. Control*, Vol.2, pp. 1407-1416, John Wiley & Sons, New York.

[8] Yang, J N. Agrawal, A K. Samali, B. Wu, J C. (2001) “A Benchmark Problem for Response Control of Wind-Excited Tall Buildings”, *Proc. of the International Modal Analysis Conference - IMAC.* Vol.1, pp. 151-157.