A parametric study of 3D effects on the wind-induced response of a tall building

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INTRODUCTION

As well understood as wind effects on tall buildings are, the increased complexity in form and structure of many modern residential highrises can present significant design challenges. The effects of shape, interference excitation, dynamic characteristics and/or the combination of all three have the potential for torsional wind loads to be a significant design concern. Some of these issues were highlighted by Boggs et al. [1] for a number of tall building configurations, typically of rectangular or modified rectangular cross-section. These 3D effects can be exacerbated by buildings with complex 3D mode shapes, due to the configuration of the structural system, eccentricities between shear centre and mass centre and architectural form.

A number of analytical and experimental studies have been conducted into 3D effects, including Tallin and Ellingwood [2], Kareem [3], Kawai [4], Yoshie et al. [5] and Katagiri et al. [6]. Thepmongkorn and Kwok [7] conducted a detailed study of eccentricity effects on aerodynamically coupled translational-torsional motion using a 3DOF aeroelastic model of the CAARC building to investigate the wind excitation mechanisms by analysing response and wake spectra, upcrossing frequency and correlations between response components.

The CAARC building has been used as a benchmark building for wind tunnel model studies for several decades, Melbourne [8] for example. Its original structural characteristics (i.e. linear sway mode shapes with equal and orthogonal fundamental natural frequencies) are relatively simplistic approximations and assumptions, but its geometrical characteristics are representative of many modern tall buildings, e.g. premium residential towers in Hong Kong, having rectangular planforms with a dominant geometrical axis.

This paper focuses on the study of wind load data obtained from high-frequency force balance measurements to provide further insight into the wind excitation mechanisms, directional effects, eccentricity between centres of mass and stiffness and complex 3D mode shapes on wind-induced torsional and 3D load effects.

EXPERIMENTAL SETUP

Wind tunnel tests were conducted on a 1:400 scale model of the CAARC standard tall building using a high-frequency force balance. The CAARC standard tall building is illustrated in Fig. 1, where b = 45 m, d = 30 m, h = 180 m and the structural density is 160 kg/m^3.

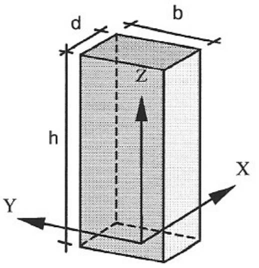


Fig. 1: CAARC standard tall building

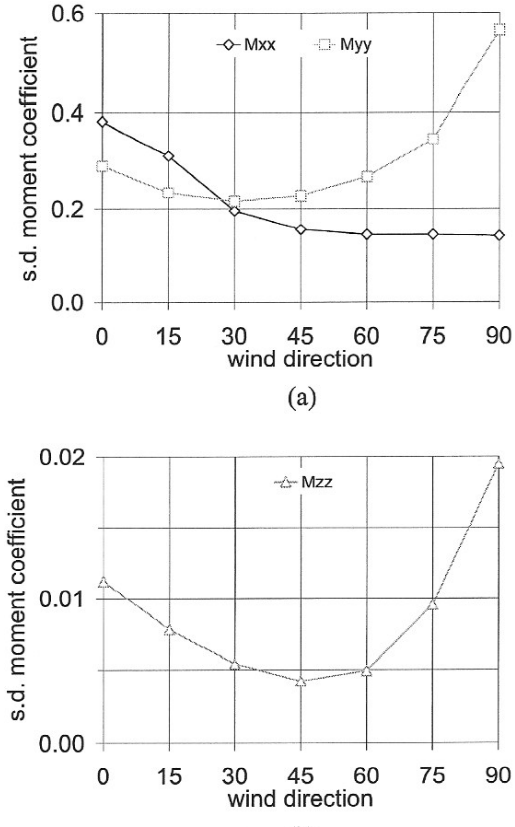
For response analysis, the first three modes of vibration were assumed to have natural frequencies of 0.2 Hz, 0.2 Hz (translation) and 0.3 Hz (torsion) y and damping ratios were assumed to be 1%, 1% and 1.4% of critical respectively. In the simplest form of the model building, the first two modes of vibration correspond to fundamental, linear sway modes and the third mode corresponds to a twist mode. The model building was tested at 1:400 scale using a high-frequency force balance to measure moments about X, Y and Z axes (M_{XX}, M_{YY} and M_{ZZ} respectively). The simulated wind model corresponded to that used by Melbourne [8].

All reduced frequencies and reduced velocities stated in this paper were calculated using the mean wind speed measured at the top of the model and the model building's widest dimension (b).

EFFECTS OF WIND DIRECTION

With no eccentricity between mass and stiffness centres, wind-induced dynamic torsional moments

(M_{ZZ}) are typically an order of magnitude smaller than the corresponding translational moments (M_{XX}, M_{YY}) as highlighted in Fig. 2 for a reduced velocity of 6.



(a)

(b)

Fig. 2: Standard deviation moment coefficients, no eccentricity; (a) M_{XX}, M_{YY} (b) M_{ZZ}

Representative power spectra for the three components of moment are presented in Fig. 3.

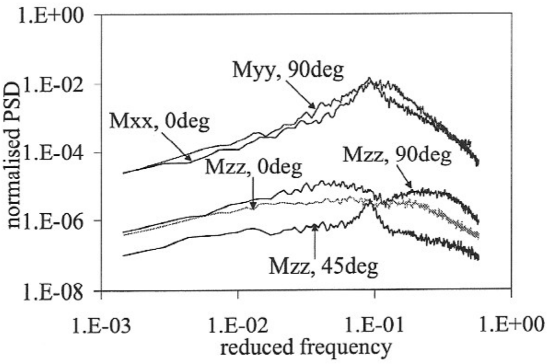


Fig. 3: Representative moment spectra

Correlation coefficients were calculated using Eq. (1), the largest of which was $\rho[M_{XX}, M_{ZZ}] \approx \pm 0.6$ for wind directions of 45° and 75°, as shown in Fig. 4.

$$\rho[i,j]=\frac{\mathrm{Cov}(i,j)}{\sigma_i\sigma_j} \qquad (1)$$

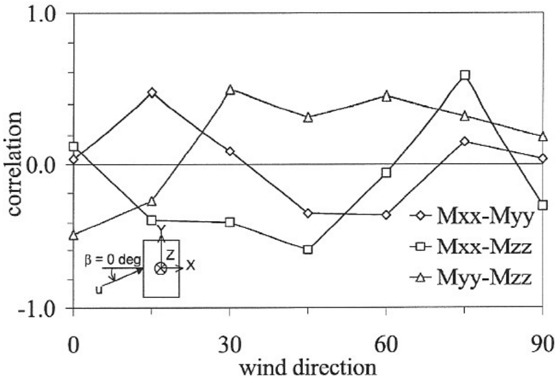


Fig. 4: Correlation of wind loads

At 45°, the correlation can be attributed to periodic flow separation and reattachment, which is indicated by the dominant spectral peak at a reduced frequency of about 0.1 in Fig. 3. However, as the magnitude of the PSD of M_{ZZ} at 45° is significantly less than for 0° and 90°, the likelihood of skew wind directions causing the design loading case will be dependent on the separation of the modal frequencies and deflected mode shapes, and can be more significant for narrower buildings with longer after bodies.

It can also be seen in Fig. 2 that the fluctuating component of M_{ZZ} was largest for a wind direction of 90°. As shown in Fig. 3, this is due to a significant increase in the magnitude of the PSD of M_{ZZ}, particularly in the typical tall building operating range of reduced frequency (0.125 – 0.25). This is attributed to fluctuating loads caused by flow reattachment.

EFFECTS OF ECCENTRICITY

The effects of eccentricity were studied by physically offsetting the centre of stiffness, as shown in Fig. 5.

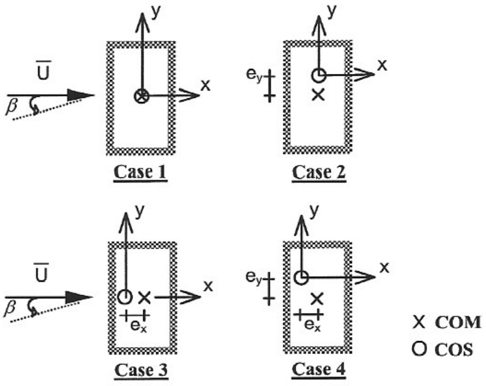


Fig. 5 Eccentric model configurations

Eccentricities of 10 mm at model scale were introduced so that $e_X/d \approx 13\%$ and $e_Y/b \approx 9\%$. For rigid model studies, the introduction of eccentricities allows the direct measurement of the torsional wind loads. The corresponding translational moments are essentially unaffected, within the limits of experimental repeatability.

As shown in Fig. 6, the largest torsional moments for a reduced velocity of 6, determined using a simplified procedure similar to that described in Boggs and Peterka [9], occur for incident winds normal to the narrow face of the building, i.e. $\beta = 90°$ and 270°. However, for these wind directions, the eccentric configurations (Cases 2, 3, 4) did not cause a significant variation in the wind-induced dynamic loads within a reduced frequency range of 0.25 to 0.125 (corresponding to a reduced velocity range of 4 to 8).

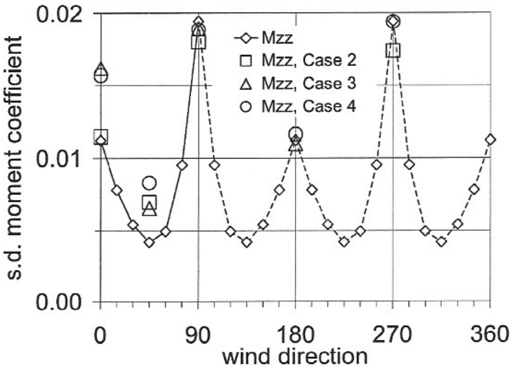


Fig. 6 Standard deviation moment coefficients, M_{ZZ}, for eccentric configurations

For an incident wind direction of $\beta = 45°$, each eccentric configuration increased the magnitude of the measured torsional moment spectra. As shown in Fig. 7, the spectral peak for Case 3 is approximately 3 times greater than that for Case 1. For Cases 2 and 4, the spectral peak was suppressed.

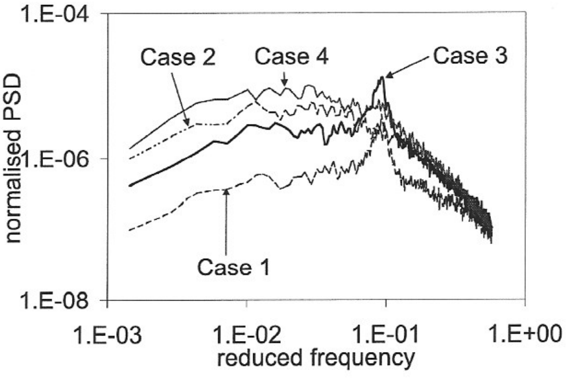


Fig. 7: Effects of eccentricity on M_{ZZ}, $\beta = 45°$

For incident winds normal to the wide face, the introduction of an eccentricity e_X (Cases 3 and 4) caused a significant increase in the magnitude of the measured torsional moment spectra in the reduced velocity range of 4 to 8, as shown in Fig. 8. For an incident wind direction of $\beta = 180°$, dominant spectral peaks were observed around a reduced frequency of 0.1.

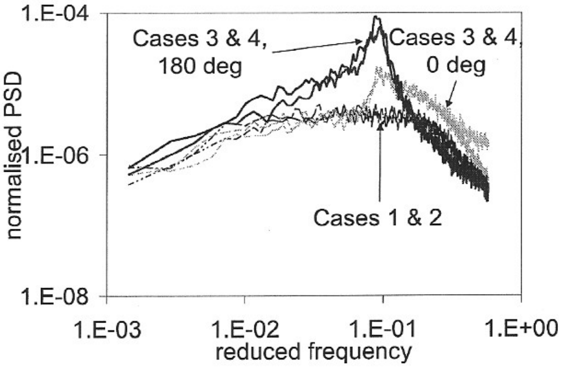


Fig. 8: Effects of eccentricity on M_{ZZ}, $\beta = 0°, 180°$

For incident winds normal to the narrow face, the magnitudes of the torsional moment spectra were similar for all cases in the reduced velocity range of 4 to 8, as reflected in Fig. 6. Spectra for Cases 2 and 4 exhibited increased magnitudes around a reduced velocity of 10 for a wind direction of 90°.

In general, the introduction of eccentricities was also observed to enhance the correlation between translational and torsional moments as shown in Fig. 9 and 10. The combination of increased responses for Cases 3 and 4 at $\beta = 0°$, Fig. 6, and the enhanced correlation between M_{XX} and M_{ZZ} have potentially significant implications for buildings with 3D complex mode shapes.

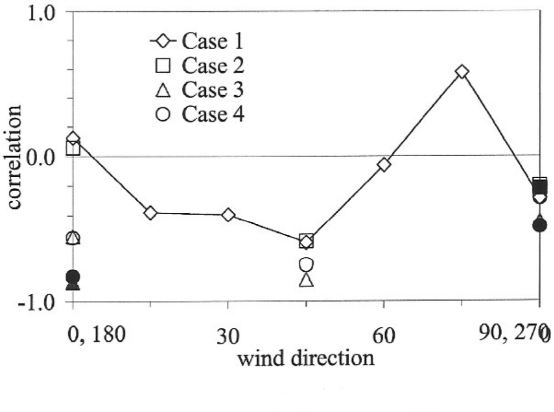


Fig. 9: Correlation, M_{XX} - M_{ZZ}

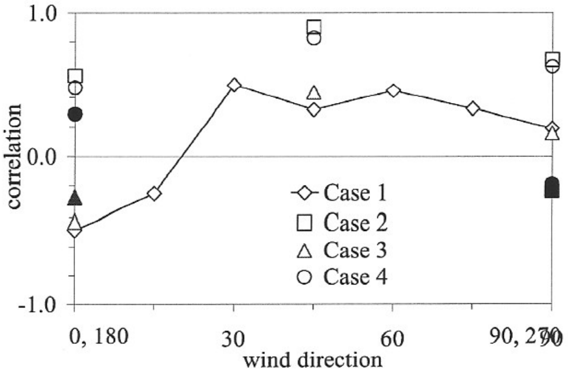


Fig. 10: Correlation, M_{YY} - M_{ZZ}

EFFECTS OF COMPLEX MODE SHAPES

Modern tall buildings with eccentricities are highly likely to have 3D complex mode shapes (i.e. comprising X, Y and Z components) due to asymmetry in the stiffness and/or mass distribution. The effects of complex mode shapes were investigated by analysing the test results in a fashion similar to that described by Holmes et al. [10]. Modal acceleration responses were determined for Case 3 with the incident wind normal to the wide face (i.e. $\beta = 0°$) at a reduced velocity of 6. For all analyses, mode shapes were assumed to be of the form shown in Eq. (2).

$$\phi(z) = z/h \begin{pmatrix} \phi_X \\ \phi_Y \\ \phi_Z \end{pmatrix} \qquad (2)$$

Analysis results for the third mode acceleration response are presented in Table 1 for various components of ϕ_Y and ϕ_Z while maintaining $\phi_X = 0$. The results are normalised with respect to the acceleration determined for the fundamental twist mode of Case 1.

The significantly greater energy associated with M_{XX} increased the modal response when $\phi_Y = 0.05$. However, increasing the contribution of M_{XX} (i.e. increasing ϕ_Y) caused a progressive shift in energy towards the critical reduced frequency, i.e. away from the region of the current analysis (reduced velocity = 6).

Table 1: Effects of complex mode shapes, mode 3

Case	ϕ_Y	ϕ_Z	Normalised Response
1	0.00	1.00	1.0
3	0.00	1.00	1.4
3	0.05	1.00	1.5
3	0.11	1.00	1.4
3	0.25	1.00	1.2
3	0.43	1.00	1.0
3	0.67	1.00	1.0
3	1.00	1.00	1.2

CONCLUSIONS

High-frequency force balances can provide useful information concerning wind excitation mechanisms through their direct measurement of the wind loads acting on a building model. It is expected that eccentricities between mass and stiffness centres will increase torsional moments, if only because of the increased moment arm. However, excitation mechanisms, and the distribution of wind energy, may also be altered thereby affecting torsional responses. This may be complicated further for tall buildings with 3D complex mode shapes.

ACKNOWLEDGEMENTS

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