Torsional Moments of Tall Buildings with various Planform Shapes

J C K Cheung[1] and W H Melbourne[2]

[1]Department of Mechanical Engineering, Monash University, Victoria 3800, Australia
[2]MEL Consultants Pty. Ltd., 17 Kingston Street, East Malvern, Victoria 3145, Australia

Abstract

Mean and fluctuating torsional moments of tall buildings with various planform shapes have been measured in wind tunnel boundary layer flows for suburban terrain. The cause of the high torsional moments are seen to be the combination of a sharp-edged separation from a building edge providing a significant moment arm, and the building surface in the wake producing complementary areas with low pressures. The torsional moments are hence normalised in coefficient form with the maximum projected width and the maximum projected area of the building. These torsional moment coefficients are shown to be related to the ratio, f, of minimum projected width to the maximum projected width of the building planform in two categories: the slab-like structures ($f<0.3$) and the non-slab type ($f>0.3$). For non-slab structures, the torsional moment coefficients are shown to vary with building planform shapes within the range of values for circular and rectangular planform to those for triangular planform. For slab type structures, the mean and fluctuating torsional moment coefficients are approximately 0.1 and 0.07 respectively.

Introduction

Asymmetric wind pressure distribution around a building planform can induce a net force eccentric to the shear (twist) centre, causing significant wind excited torsional moments about the vertical axis of the building. The resulting mean and fluctuating response can be further complicated by the building structural properties and mass distribution, nearby building interference and combined modes of torsional displacement with sway motion.

The significance of this torsional response of tall buildings has been recognised for some time, e.g. Hart, Di Julio and Lew [1]. Isyumov and Poole [2, 3] collated measurements of mean and fluctuating torsional moment for tall buildings of various planform and generalised wind tunnel data to relate these moments about the vertical axis Z as a function of reduced velocity V_r. Whilst this empirical model can be used to estimate the torsional response of a tall building, particularly of simple planform, the procedure requires a line integral parameter which would become difficult to evaluate for unusual building shapes and can be over-estimated for buildings with many re-entrant corners. Cheung and Melbourne [4] have attempted to generalise the mean torsional moment coefficients and plotted as a function of the building planform aspect ratio squared, f^2. Further research on the effects of building axis eccentricity and nearby building interference has been carried out by Zhang, Xu and Kwok [5, 6]. Also, Tamura, Kikuchi and Hibi [7] have recently studied the correlation of alongwind, crosswind and torsional response with combined modes. For most structural designers, the evaluation of the torsional loads and effects with respect to building planform shape has still been reliant on wind tunnel model studies.

This paper describes the experimental technique used in model studies in the boundary layer wind tunnel at Monash University to provide the data for this study. However since some experimental data included are extracted from case studies of proprietary nature, the source and the exact building shape of those are not identified for reference. An attempt to reduce the mean torsional moment measurements in coefficient form as a function of the building planform aspect ratio squared was reported by Cheung and Melbourne [4]. The mean and standard deviation torsional moment data were further presented in logarithmic form in terms of the building planform aspect ratio f in 8th International Conference on Wind Engineering in Canada in 1991; however, the full paper was not published. This paper presents these additional data from fundamental research studies and identifies three basic relationships for the torsional moment, both mean and fluctuating, with respect to the building planform aspect ratio. Also, standard deviation torsional moment coefficient data evaluated from the draft ISO/CD 4354 are included for comparison.

Experimental Technique

Wind tunnel tests were carried out in a 1/400 scale model of the natural wind generated by flow over roughness elements augmented by vorticity generators at the beginning of the wind tunnel working section. The basic wind model was for flow over suburban terrain for fundamental research studies and with relevant city buildings for other model case studies.

Some building models for case studies were fully aeroelastic and were constructed using aluminium for the columns and equivalent beams and clad with aero-modeller's doped paper; others were linear mode models. The torsional stiffness as defined by the moment M_Z applied at the top of the building to give a rotational displacement of one radian was scaled. The torsional frequency and damping were obtained from the oscillatory decaying curve from an initial pure rotational displacement. Due to the cost and time involved in this method of model making, a similar strain gauged support system was used in some other building models for initial exploration and in those for fundamental research studies. The building model, made with foam and balsa, was bolted onto a square steel bar located at the shear centre of the building. The whole rigid building model rotated about the bar support, i.e. the Z axis. Strain gauges were installed at 45° at ground level to measure the torsional response. This simpler strain gauge system was not scaled for stiffness and mass distribution, but the moment of inertia about the Z axis was often sufficiently high to measure standard deviation moments in the full scale reduced velocity range.

Mean, standard deviation and minimum and maximum peak torsional moments were measured for different wind directions on the building models with various planform, namely, square, rectangular, triangular, hexagonal, octagonal, elliptical, circular and some other combined complex shapes. The shear centre, through which the measured moment axis was located, with a few exceptions, coincided with the centroid of the building planform shape.

The torsional moments were found to be proportional to the mean wind dynamic pressure and can be normalized with the building height and some building characteristic lengths. The cause of the high torsional moments are seen to be the combination of a sharp-edged separation from a building edge far away from the shear centre under which a low pressure region was formed, providing a significant moment arm and the building surface in the wake producing complementary areas with low pressures. The moment arm can be related to the building maximum projected frontal width and the building surface producing negative pressures can be related to the building maximum projected frontal area. Hence, the torsional moments are normalized in coefficient form as follows:

Mean torsional moment coefficient

$$C_{\overline{M}Z} = \frac{\overline{M}_Z}{\frac{1}{2}\rho \overline{V}_h^{\,2}\, b_{max}^{\,2}\, h}$$

Standard deviation torsional moment coefficient

$$C_{\sigma_{M_Z}} = \frac{\sigma_{M_Z}}{\frac{1}{2}\rho \overline{V}_h^{\,2}\, b_{max}^{\,2}\, h}$$

Peak torsional moment coefficient

$$C_{\hat{M}Z} = \frac{\hat{M}_Z}{\frac{1}{2}\rho \overline{V}_h^{\,2}\, b_{max}^{\,2}\, h}$$

and Reduced Velocity

$$V_r = \frac{\overline{V}_h}{n_Z\, b_{max}}$$

The building planform shape aspect ratio is defined as $f = \dfrac{b_{min}}{b_{max}}$

where b_{min} = minimum projected width of building platform
b_{max} = maximum projected width of building platform

Examples of the projected widths for different building planform shapes are given in Figure 1 below.

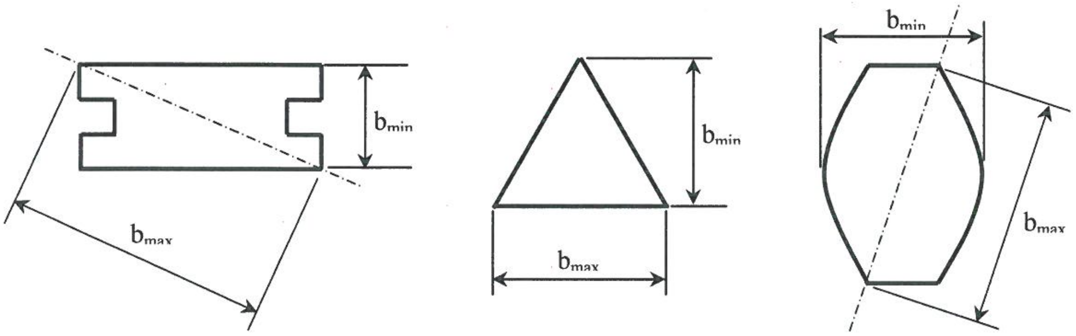
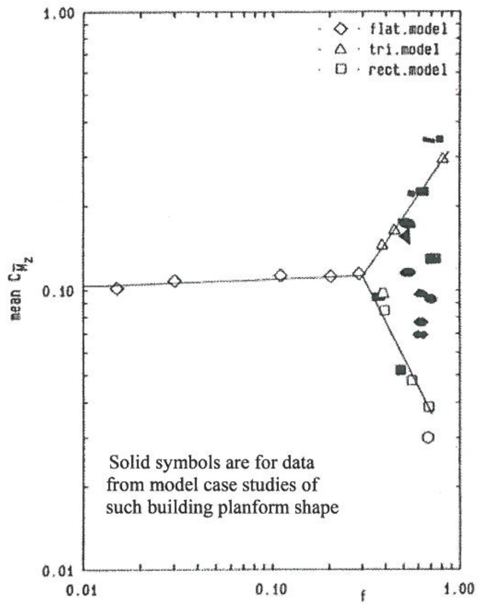


Figure 1 Examples of projected widths b_{min} and b_{max} for buildings with different planform shapes

Experimental Results

Torsional moment coefficients were measured as a function of wind direction. The highest mean and standard deviation torsional moments for various building models were found to occur generally for a wind direction about 5° or 70° from the normal of the widest building face. For the critical wind directions, where the highest torsional moments occurred, measurements were also made for a range of reduced velocity and damping. The values of $C_{\overline{M}Z}$ were found to be approximately constant with reduced velocity and the values of the standard deviation torsion were found to be approximately proportional to the wind velocity to a power of 2.2. Also it has been noted that the gust factor $C_{\hat{M}Z}/C_{\overline{M}Z}$ varies from 2 to 4 and the correction slope for $C_{\sigma_{M_Z}}$ as a function of structural damping is generally small (< -0.1). A damping correction slope of -0.06 has been used in this paper. The highest mean and standard deviation torsional moment coefficients were found to vary with the building planform shape aspect ratio and are shown plotted in Figures 2 and 3 respectively. The highest $C_{\overline{M}Z}$ and $C_{\sigma_{M_Z}}$ for buildings with f below 0.3, which are typical slab structures, are seen to be approximately 0.1. For f above 0.3, the torsional moment coefficients increase for triangular buildings, but decrease for rectangular buildings.



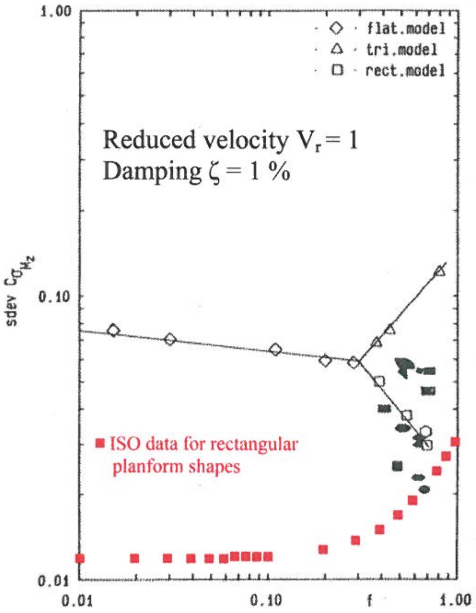


Figure 2 $C_{\overline{M}Z}$ from model case and research studies Figure 3 $C_{\sigma_{M_Z}}$ from model case and research studies

The data were fitted with power relationship and can be summarized in Table 1 as follows:

Table 1

Building shape aspect ratio	Mean torsional coefficient	Standard deviation torsional coefficient
Slab structures: $f \leq 0.3$	$C_{\overline{M}Z} = 0.116\, f^{0.025}$	$C_{\sigma_{M_Z}} = 0.054\, f^{-0.073}\, \zeta^{-0.06}\, V_r^{0.2}$
Triangular structures: $f \geq 0.3$	$C_{\overline{M}Z} = 0.360\, f^{0.79}$	$C_{\sigma_{M_Z}} = 0.145\, f^{0.75}\, \zeta^{-0.06}\, V_r^{0.2}$
Rectangular structures: $f \geq 0.3$	$C_{\overline{M}Z} = 0.023\, f^{-1.32}$	$C_{\sigma_{M_Z}} = 0.022\, f^{-0.82}\, \zeta^{-0.06}\, V_r^{0.2}$

The torsional moment coefficients for other building planform shapes generally lie between the values for the triangular and rectangular building shapes. However, these values can be significantly different due to other effects such as interference and building core eccentricity.

From draft ISO/CD 4354 [7], Tamura, etc. [8] have given $C_{\sigma_{M_Z}} = \left\{0.0034 + 0.0078\left(\frac{d}{b}\right)^2\right\}^{0.78}$ where b is the horizontal breadth of the structure normal to the wind direction and d is the horizontal depth of the structure parallel to the wind direction. A comparison of the present studies for reduced velocity $V_r = 1$ and damping $\zeta = 1\ \%$ with the ISO empirical formula is made for a square and a slab planform as follows:

Table 2

	d/b	f	ISO formula	Present study
Square planform	1	0.7071	$C_{\sigma_{M_Z}} = 0.0301$	$C_{\sigma_{M_Z}} = 0.0292$
Slab planform	0.1	0.0995	$C_{\sigma_{M_Z}} = 0.0121$	$C_{\sigma_{M_Z}} = 0.0639$

Conclusions

The torsional moment of a tall building can be very significant, particularly for those buildings with a triangular planform of equal sides. This high torsional moment is further aggravated by interference effects and the eccentricity of shear centre from the centre of mass of the building. The torsional moment measurements presented in this paper only relate to building models with the shear centre at the geometric centroid and without nearby building interference. These experimental data compare well with the ISO formula for the square planform shape and can provide a quick reference for an initial estimation of the torsional response for tall buildings with various planform shapes.

References

[1] Hart G.C., Di Julio R.M. and Lew M. (1975) Torsional response of high-rise buildings, *ASCE J. Struct. Eng.*, Vol. 101, No. ST2.

[2] Isyumov N. (1983) Estimation of torsional wind loads on tall buildings, *Tall Buildings State of the Art Review*, Section 4.

[3] Isyumov N. and Poole M. (1983) Wind induced torque on square and rectangular building shapes, *Jnl Wind Eng & Ind Aerodynamics*, 13, pp. 183-196.

[4] Cheung J.C.K. and Melbourne W.H. (1992) Torsional moments of tall buildings, *Jnl Wind Eng & Ind Aerodynamics*, 42, pp. 1125-1126.

[5] Zhang W.J., Xu Y.L. and Kwok K.C.S. (1993) Torsional vibration and stability of wind-excited tall buildings with eccentricity, *Jnl Wind Eng & Ind Aerodynamics*, 50, pp. 299-308.

[6] Zhang W.J., Xu Y.L. and Kwok K.C.S. (1995) Interference effects on aeroelastic torsional response of structurally asymmetric tall buildings, *Jnl Wind Eng & Ind Aerodynamics*, 57, pp. 41-61.

[7] Tamura Y., Kikuchi H. and Hibi K. (2003) Quasi-static wind load combinations for low- and middle-rise buildings, *Jnl Wind Eng & Ind Aerodynamics*, 91, pp. 1613-1625.

[8] Committee Draft ISO/CD 4354 Reference No. ISO/TC 98/SC 3, pp.47

[9] Tamura Y., Kawai H., Uematsu Y., Marukawa H., Fujii K. and Taniike Y. (1996) Wind load and wind-induced response estimations in the Recommendations for Loads on Buildings, AIJ 1993, Engineering Structures, Vol. 18, No. 6, pp. 399-411.