WIND LOADS ON THE MACAU TOWER – APPLICATION OF THE EFFECTIVE STATIC LOAD APPROACH

J.D. Holmes (Monash University)

Introduction

The Macau Tower is currently under construction on reclaimed land at Macau, China. This paper describes wind tunnel tests of a full aeroelastic model (1/150 scale) and calculations of response of the tower. The response in the along-wind direction was calculated using the 'effective static wind load approach'.

The Macau Tower

The main part of the tower (Figure 1) is basically cylindrical in cross-section tapering from 16 metres at ground level to 12 metres at 248 metres. The overall height to the top of the communications tower is 338 metres. Between 200 metres and 238 metres is a 'pod' containing observation and restaurant areas. The steel communications tower extends from 248 metres to 338 metres.

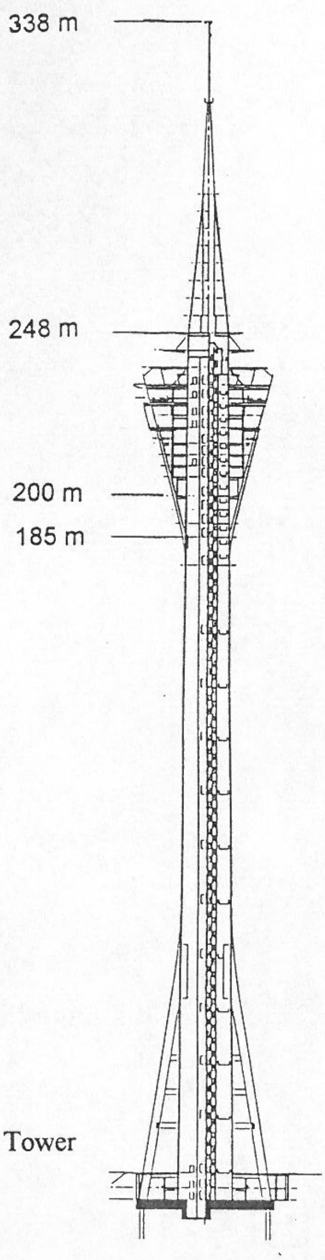

Figure 1. The Macau Tower

Design Procedure for Wind loads

The procedure used to derive wind loads for the tower was a combination of wind tunnel tests with a full aeroelastic model, and calculations based on theoretical/ empirical models of the along- and cross-wind response. The along-wind response was found to be dominant, and the design calculations were calibrated by matching the measured response in the wind tunnel to the calculations for the flow and model conditions during the tests.

Wind-tunnel tests

The aeroelastic model was constructed to a geometric scale of 1/150. The model was designed and constructed to reproduce as far as possible the elastic and inertial properties of the prototype tower.

To obtain correct scaling between elastic forces in the structure and inertial forces in the air, the Cauchy Number should be equal in full and model scale :

$$E / (\rho\, V^2) = \text{constant} \tag{1}$$

where E is Young's Modulus, ρ is the air density, and V is a flow velocity.

This can be expressed in the form of a ratio of model to full-scale values, denoted by the subscript, r :

$$E_r / \rho_r\, V_r^2 = 1 \tag{2}$$

When bending and axial stresses are dominant, the Cauchy Number scaling can be modified to the forms :

$$(EI)_r / \rho_r\, V_r^2\, L_r^4 = (EA)_r / \rho_r\, V_r^2\, L_r^2 = 1 \tag{3}$$

where, A is a cross-section area, I is a second moment of area, and L, is a representative length on the model.

Then giving :

Bending stiffness ratio	$(EI)_r = \rho_r\, V_r^2\, L_r^4$
Tension/compression stiffness ratio	$(EA)_r = \rho_r\, V_r^2\, L_r^2$

This enables the stiffness properties of each structural element or member to be concentrated in a 'core' or 'spine'. This approach was taken here for the main shaft and legs of the tower.

Another non-dimensional ratio which is also required to be unity is the ratio of model to full-scale density :

$$\rho_r = 1 \tag{4}$$

Since the wind tunnel testing is carried out in air at normal temperature and pressure, the ratio of air densities is automatically unity. However it is also required to maintain the densities of the structure equal in model and full scale.

The velocity ratio (model wind speed to full-scale wind speed) was chosen to be 1/3 to match the available wind-tunnel speeds.

Based on these values of length, density and velocity ratios, we have,

Bending stiffness ratio	$(EI)_r = \rho_r V_r^2 L_r^4 = (1/3)^2 (1/150)^4 = 1/ (4.56 \times 10^9)$
Axial stiffness ratio	$(EA)_r = \rho_r V_r^2 L_r^2 = (1/3)^2 (1/150)^2 = 1/202500$
Time ratio	$T_r = L_r / V_r = 1/50$
Frequency ratio	$f_r = 1/T_r = 50$
Mass / unit length ratio	$m_r = L_r^2 = (1/150)^2 = 1/22500$
Force ratio	$F_r = \rho_r V_r^2 L_r^2 = (1/3)^2 (1/150)^2 = 1/202500$
Moment ratio	$B_r = \rho_r V_r^2 L_r^3 = (1/3)^2 (1/150)^3 = 1/(3.04 \times 10^7)$

The stiffness properties of the main shaft of the tower were modelled with an aluminium alloy spine to reproduce the correct flexural stiffness, as outlined previously section. The spine up to 248 metres was a series of shafts of circular cross-section with diameters ranging from 39 mm to 24 mm. These cross-sections resulted from calculations of the second moment of area for bending about two orthogonal axes. For the steel communications section of the tower, a spine consisting of stepped tubular cross-sections from aluminium alloy and stainless steel was used

The legs at the base were also modelled elastically for bending by the use of an aluminium alloy spine of dimensions. The diameter and mass of the main shaft were reproduced by attaching to the spine independent sections of length 70 mm (10.5 metres in full scale), which were attached to the spine only at their centre, and separated by 1mm vertical gaps, so that they didn't provide any significant additional stiffness. These sections were main from high-density modelling foam, clad with a thin plywood veneer to give a relatively smooth surface finish, and with lead added to bring the mass per unit height to the correct value as outlined in the previous section.

A similar cladding construction was used for the lower legs and the horizontal members connecting the legs to the main shaft. The 'pod' section of the tower including the eight inclined vertical columns, was modelled only for its aerodynamic shape and attached to the main spine using a wood-based material 'craftwood', and the lattice tower structure at 248 metres and above was modelled from aluminium alloy rod sections.

The wind-tunnel tests were carried out in the large 1MW wind tunnel at Monash University. Measurements were made of the bending moments at two different levels on the main shaft of the tower. The mean wind speeds, at a height equivalent to 250 metres, were equivalent to a range from 10 to 70 metres/second in full scale.

The 'Effective Static Wind Load' Approach

The effective static wind load approach to along-wind loading of cantilevered towers and chimneys differs somewhat from the more conventional 'gust factor' approach. In the latter case, the mean wind loading distribution is determined, and used to calculate load effects such as bending moments at various levels on a tower. The gust factor is calculated from the calculated ratio of peak to mean *deflection* at the top (actually the generalized coordinate in the first mode of vibration), including resonant effects, and this factor is used to determine peak load effects from the corresponding mean values. Thus the implication is that the peak loading distribution has the same form as the mean wind load distribution. In contrast, in the effective static wind loading approach, separate distributions are set up for the mean, background dynamic and resonant dynamic components of the total wind load. The peak dynamic components are then combined on a root-sum-of squares basis, and added to the mean loading to give a peak combined effective static wind load, with which the structure can be designed.

The distributions of the effective static loads per unit height for the base bending moment and shear on the Macau Tower, calculated for the ultimate limit states design condition, are shown in Figure 2. It may be seen from this figure that the contributions from the mean, background and resonant components are generally similar in magnitude, although the resonant component dominates in the region of the pod where the masses are high.

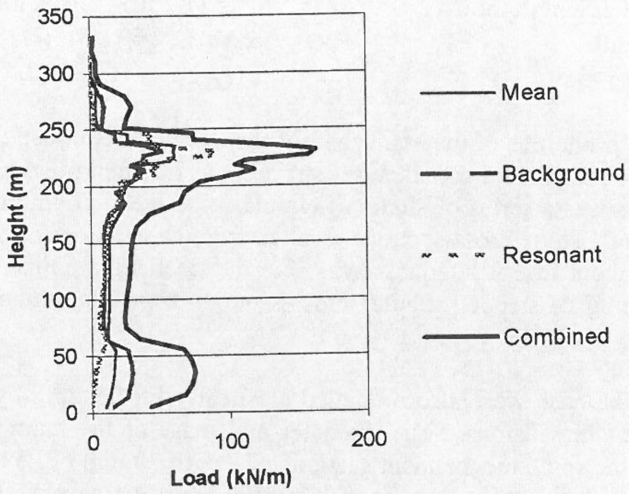

Figure 2. Effective static load contributions for load effects at the base

The ratio of the combined to the mean, which represents a gust factor for the wind loads at each height level is plotted in Figure 3. This shows that the gust factor is far from being constant with height, which is the implied assumption of the conventional gust factor approach. In fact there is a variation of more than 4 to 1 over the height of the structure. Due to the dependence of the background component on the height of the load effect, s, the distributions in Figure 2 are only valid for the case of s equal to 0.

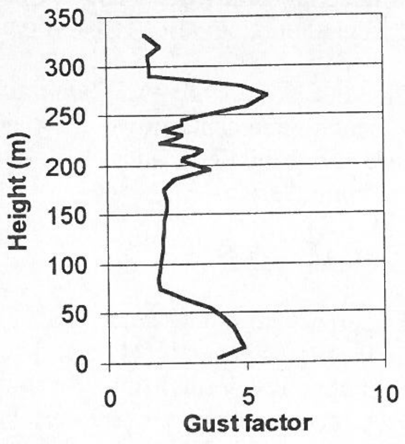

Figure 3. Gust factors for load per unit height

References

J.D. Holmes. Along-wind response of lattice towers – III. Effective load distributions. *Engineering Structures*. Vol. 18. pp 489-494, 1996.

J.D. Holmes and M. Kasperski. Effective distributions of fluctuating and dynamic wind loads. *Australian Civil/Structural Engineering Transactions*. Vol. CE38. pp 83-88, 1996.