Measured and predicted wind induced deflections of a porous steel frame tower

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Abstract

Two methods for measuring the full scale static deflection of a porous steel frame tower are outlined and compared to a theoretical deflection estimate. Field measurements of the along-wind resonant deflection are presented together with a theoretical prediction which incorporates measured parameters. The ratio of static deflection to peak resonant deflection under a given wind speed is then determined.

INTRODUCTION

Many full scale measurements of tall structures in the past have investigated building acceleration response to wind loading. This is the most important design criteria when a building is occupied and human comfort is the primary concern. The need to measure deflection becomes apparent when investigating the response of lattice communication towers. Lattice tower design is governed by minimum deflection requirements since human occupation is rare whilst excessive deflections will distort emitting transmissions.

Both the dynamic and static components of deflection play an important role depending upon the size of the tower. High fundamental frequencies are common amongst short lattice towers situated on hills and escarpments. When the natural frequency of a lattice structure exceeds 1Hz there is little energy in the turbulence spectrum to excite the structure into resonant response. The resulting deflection is then essentially quasi-static being dominated by the mean static deflection. Similarly low natural frequencies associated with tall lattice towers will be more receptive to turbulence buffeting and their deflection will be largely dynamic.

Prospect communications tower (Figure 1) situated in the western suburbs of Sydney provides the ideal structure to measure both deflection components. The tower is situated on flat category 2 terrain and resonates at 1.08Hz. A 486 PC has been continually logging output from accelerometers and cup anemometers installed at the 57m and 35m levels of the tower since June 1992. The measured dynamic characteristics and wind induced dynamic response have been documented in [2] together with a STRAND6 finite element computer model estimate. This paper will present further full scale static and dynamic deflection measurements and compare them to theoretical predictions.

PREDICTED STATIC DEFLECTION

Static deflection along the major axes of the Prospect tower was calculated by applying discrete static wind drag forces to the STRAND6 finite element model. The natural frequency and mode shape of the tower were previously modelled by STRAND6 in [2] and agreed well with those measurements made in full scale (Figure 2). Hence the modelled stiffness of the tower was known to be representative of the real structure. Drag force as defined by AS3995 [5] was calculated as follows:

$$F_d = c_{de} \, A_z \, q_z \qquad (1)$$

Each level of the tower was assigned a panel for which F_d was calculated. Nineteen values of C_{de}, A_z and q_z over the height were then required.

A_z represents the projected 'shadow' area of the tower members in one face of the tower without ancillaries. Drawings and photographs were used to meticulously calculate A_z at each panel. Free stream wind pressure q_z at a height z was estimated using a Deaves and Harris category 2 wind velocity profile.

The effective drag force coefficient for a tower with ancillaries is denoted C_{de} where:

$$C_{de} = C_d + \Delta C_d \qquad (2)$$

Super-critical Reynolds number simulation is extremely difficult to reproduce in small scale wind tunnel models of entire lattice structures due to the small size of individual members. In the case of highly porous lattice structures, it is adequate to estimate the total drag force coefficient by the summation of C_d values of individual members over the whole structure. As the porosity of the structure decreases, downwind members become shielded in the wakes of upstream members and flow is diverted around instead of through the lattice. This approach will then become too conservative and an empirical estimate becomes necessary. The 'Reference Face' approach developed for BS8100 and later used in AS3995 provides an estimate of lattice drag force coefficients C_d based on large scale wind tunnel tests. Estimates of C_d are made for lattice towers of varying solidity ratios built from square and/or circular members. C_d was calculated for each panel of the Prospect tower model using this method.

ΔC_d is the additional drag force coefficient due to ancillaries. Wind tunnel tests have been carried out by Telecom and [3] to determine suitable ΔC_d values for microwave dish ancillaries. The drag on isolated dishes were measured in these tests and an allowance made for the mutual aerodynamic interference between the tower and its ancillaries through an interference factor. Ancillaries on the Prospect tower are predominantly unshrouded parabolic dishes which constitute around 5% of the tower face projected area. ΔC_d values were calculated using the Telecom test result formulae.

MEASURED STATIC DEFLECTION

Accelerometers were used to measure the component of gravity induced by tower tilt and hence the angular rotation of the structure. Tower deflection was then calculated from tilt angle assuming that the tower deflected under wind loading according to its first mode shape. Agreement is seen between the STRAND6 deflected shape of the tower under a 15m/s wind and the first mode shape in Figure 2.

The ratio of dynamic acceleration to tilt acceleration at the 57m level of the Prospect tower is around 100:1. The dynamic response saturates the tilt signal acting as noise. Two methods were employed to reduce this ratio. Firstly the accelerometers were moved from the 57m to the 35m level of the tower to reduce the magnitude of the dynamic response. Tilt at the 57m level was then determined from tilt at the 35m level according to the first mode shape. Secondly the resulting signal was low pass filtered at 0.5Hz and amplified before digitisation so that both components of the signal were of similar magnitude. Figure 3a)&b) represents such a signal as measured under the wind loading shown in Figure 3c)&d). The abscissa in Figure 3a)&b) has been converted from tilt acceleration to displacement based on the above assumptions. Tower static deflection is seen to be closely aligned to the wind yaw angle as would be expected.

A second method for measuring static deflection involved the use of a laser beam. A He-Ne laser was placed at the base of the tower and magnified through a theodolite onto a grid placed at the 57m level of the tower. The relative movement of the gid to the stationary beam was then filmed for later analysis. Tower displacement as mapped by the laser pad is superimposed upon the simultaneously recorded tilt accelerometer displacement in Figure 3a)&b). Agreement between these data sets serves as a full scale calibration of the tilt accelerometer technique.

A problem inherent to the analysis of deflection data obtained using either of these full scale measurement methods is that of gradual electronic drift of the instrumentation and tilt induced in the tower by temperature fluctuations. For this reason it is not possible to compare the absolute deflection under a certain wind speed with its resting position during still conditions hours earlier. Instead the incremental change in deflection with change in wind speed between 10 second averaged samples was plotted as shown in Figure 4. This plot represents those wind speeds originating from between 8-10m/s and increasing or decreasing by an amount shown on the ordinate. The rate of change in deflection with respect to wind speed over this interval is found using a line of best fit. Finally the slopes of every wind speed interval are joined to form the plot shown in Figure 5a)&b). The STRAND6 predicted deflection is seen to be slightly conservative when compared to the measured deflection data of Figure 5.

PREDICTED ALONG-WIND DYNAMIC RESPONSE

Along-wind dynamic response a' was evaluated using the gust factor approach advocated by Davenport [1] and developed by Vickery [4]. The method works entirely in the frequency domain and has been incorporated into the dynamic analysis method of AS3995.

The dynamic response spectrum is split into two dynamic terms. One term B for background effects and the other term SE/ζ for resonant effects as seen in equation 3. The background factor represents the response of the structure neglecting dynamic amplification near the natural frequency n_o. It accounts for the quasi-static dynamic response below the natural frequency associated with large gusts and the attenuation of frequencies greater than n_o. The resonant component is an estimate of the amplified response of the tower to frequency components near the natural frequency.

$$\bar{a}' = \bar{a}r(SE/\zeta + B)^{0.5} \qquad (3)$$

where $\bar{a}$ = Mean generalised deflection.

Roughness factor r is a function of the terrain roughness and tower mode shape and is approximately twice the longitudinal turbulence intensity at a height h. Turbulence intensity has been measured in [2] at the 57m level of the tower at 0.15.

Incident turbulence approaching the tower consists of turbulent eddies of varying size. Eddies very much larger than the tower apply a uniform pressure whilst much smaller eddies tend towards local pressure effects. Size factor S acts as an admittance function to account for the correlation of these pressures induced by turbulent flow over the height of the tower. AS 3995 defines S in terms of the overall sizes defining the envelope of a tower. S is an appropriate factor to be used on a porous lattice structure since pressure at any point on the structure will approximate the free stream velocity that would exist in the absence of the structure. The tower is loaded by wind but has minimal affect on the flow field.

Gust energy factor E is derived from the Harris-von Karman spectral density of the micrometeorological peak multiplied by the mechanical admittance at the natural frequency of the structure.

$$E = 0.47N/(2 + n^2)^{5/6} \qquad (4)$$

$$\text{where} \quad N = n_oL(h)/V(h) \qquad (5)$$

A turbulence length scale L(h) of 1500m has been measured at the 57m level of the tower. The corresponding Harris-von Karman spectrum has been fitted to the full scale data points as shown in Figure 6.

The critical damping ratio ζ under serviceability loading was measured in [2] at 1%.

MEASURED ALONG-WIND DYNAMIC RESPONSE

The relationship between the standard deviation of along-wind acceleration response and mean wind speed was measured in [2] using horizontally aligned accelerometers at the 57m level. Acceleration response time histories shown in [2] were seen to be dominated by mode 1 resonant response. σacc could then be related to the SE/ζ component of equation 3 which is plotted in Figure 7 against the measured full scale data. Acceleration was converted to displacement assuming sinusoidal response at mode one.

Peak factor measurements made in [2] estimated peak displacement to be four times larger than displacement standard deviation over a 1 hour period. Comparison between the data shown in Figures 5 and 7 then reveals that the peak resonant deflection is approximately half the static deflection over the measured wind speed range.

No attempt has yet been made to separate and estimate the background response from the preceding data.

CONCLUSIONS

An inexpensive and readily available method for measuring the static deflection of tall structures in full scale has been tested on a porous steel frame tower. The measurements made agree with a full scale laser calibration and a theoretical static deflection estimate. Agreement between the measured data and theoretical estimates confirms the use of code drag force coefficients which have been derived from large scale wind tunnel tests.

Along-wind resonant deflection was predicted using the gust factor approach of AS3995 which incorporated values measured in full scale including natural frequency, critical damping ratio, turbulence intensity and turbulence length scale. These results agreed well with full scale resonant deflection measurements made using horizontally aligned accelerometers.

Both theoretical estimates and full scale measurements reveal that the static deflection is approximately twice the magnitude of the peak resonant deflection at any given wind speed.

REFERENCES

1. Davenport, A.G., "The application of statistical concepts to the wind loading of structures", Proceedings of the Institution of Civil Engineers, (1961), 19 449-471.

2. Glanville,M.J., and Kwok,K.C.S., "Dynamic characteristics and wind induced response of a steel frame tower", Third Asia-Pacific Symposium on Wind Engineering, Hong Kong, (1993), Vol 1, P.367.

3. Holmes,J.D., Banks,R.W., and Roberts,G., "Drag and aerodynamic interference on microwave dish antennas and their supporting towers", Second International Colloquium on Bluff Body Aerodynamics and Applications, Melbourne, (1992), Vol 2, Session 11B.

4. Vickery,B.J., "On the reliability of gust loading factors", The Institution of Engineers, Australia Civil Engineering Transactions, Volume CE13-1971.

5. Standards Australia. AS3995-1994 "Design of steel lattice towers and masts", Standards Australia, North Sydney, (1994).

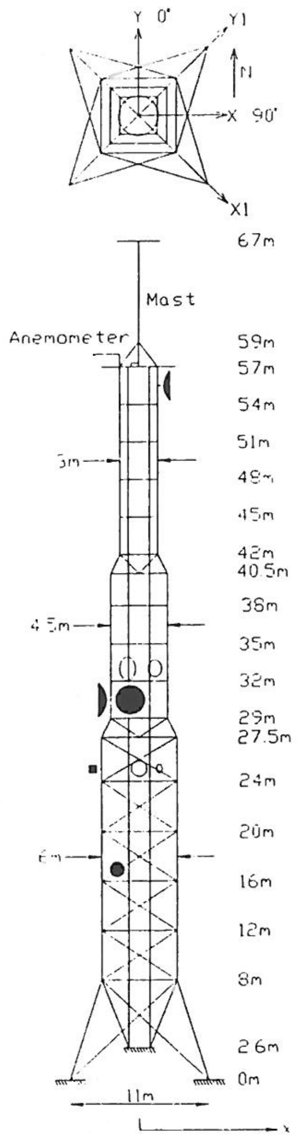


Figure 1 General arrangement of the Prospect tower.

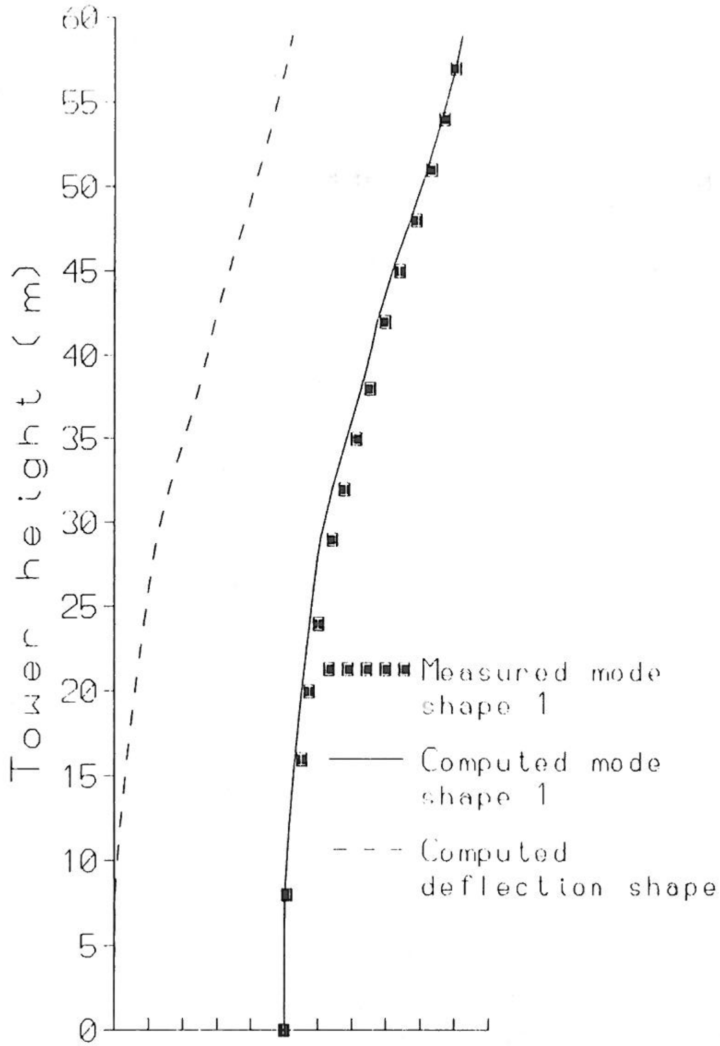
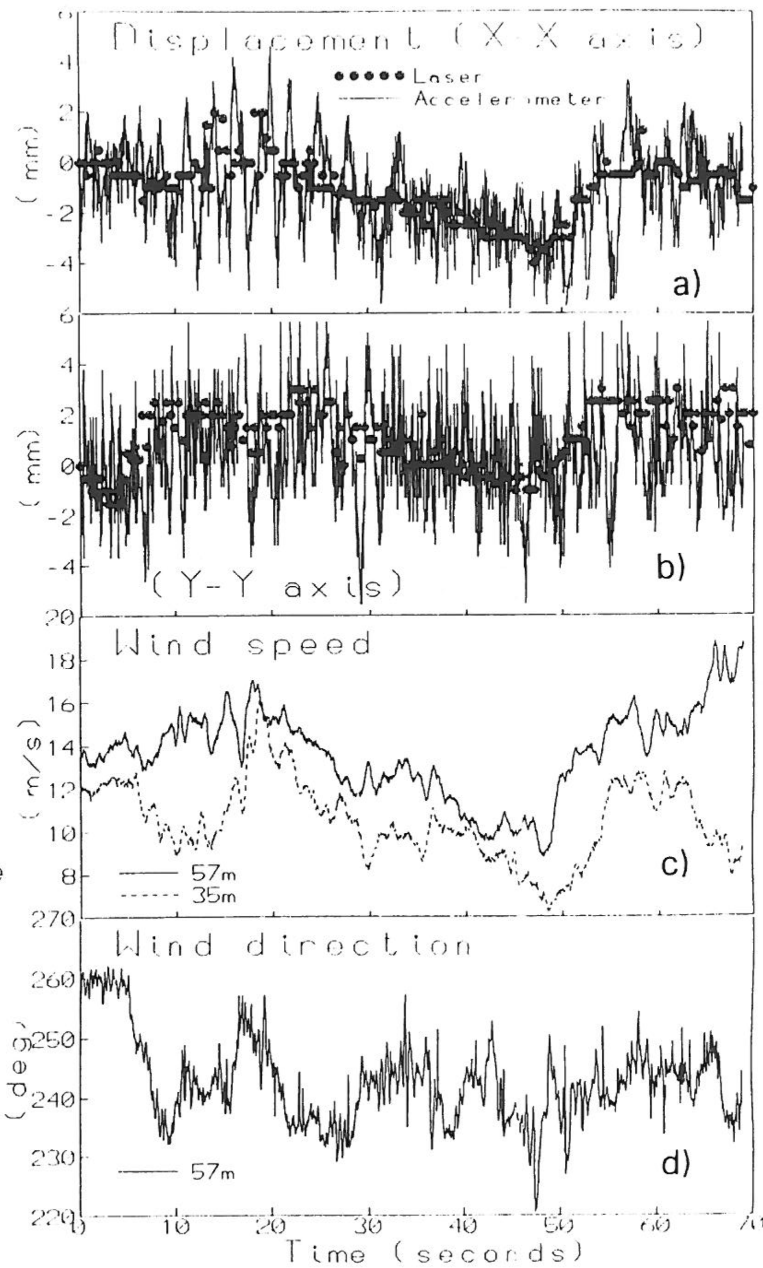


Figure 2 Mode one and deflected shape comparison.

Figure 3 Time history of tower deflection, wind speed and direction.



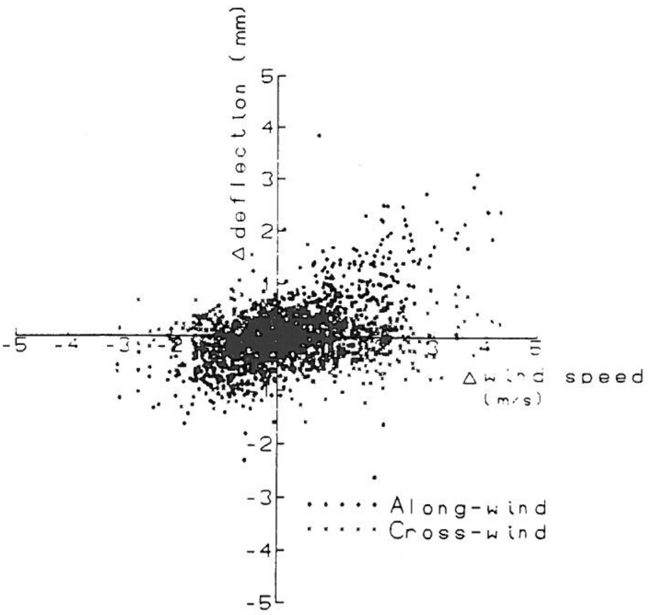


Figure 4 Change in deflection versus change in wind speed.

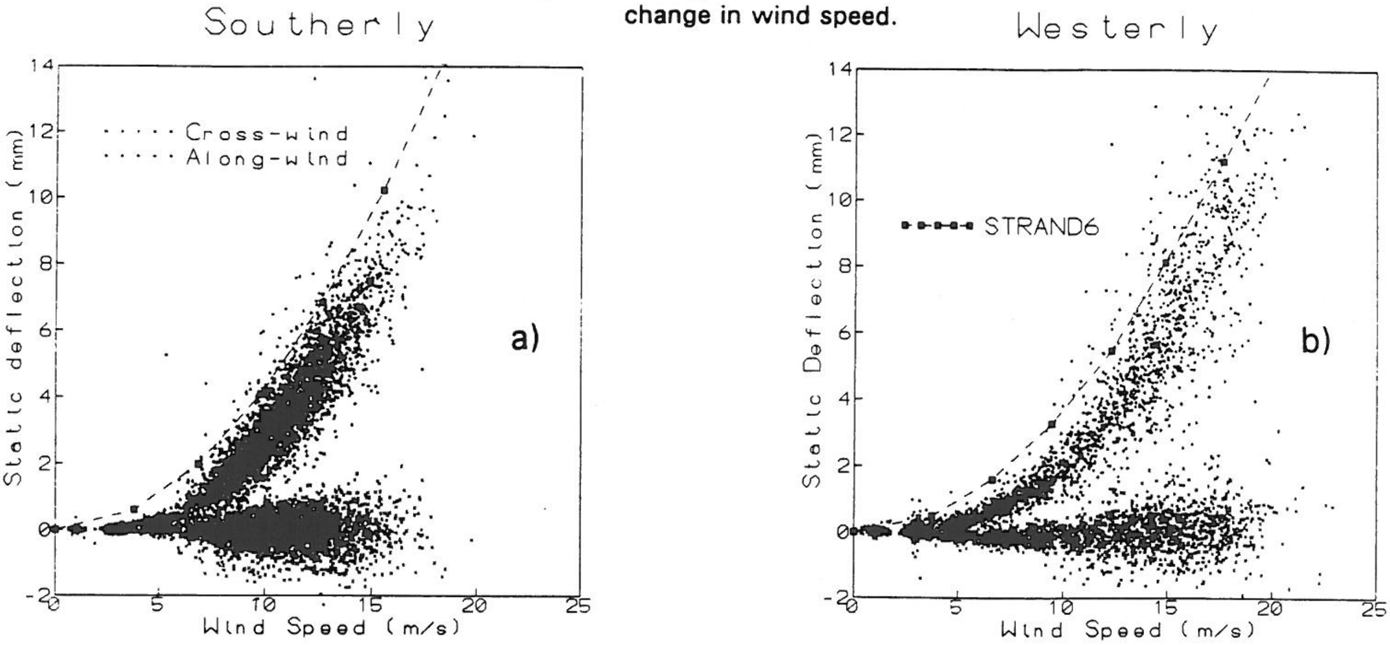


Figure 5 Static deflection versus wind speed.

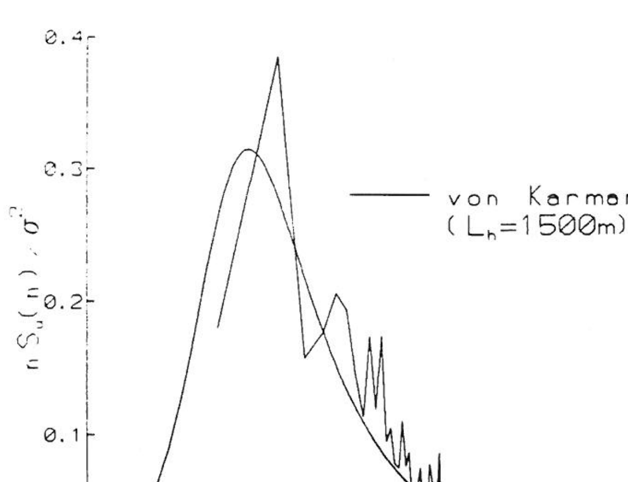


Figure 6 Spectral density for a 15m/s southerly wind sampled at the 57m level.

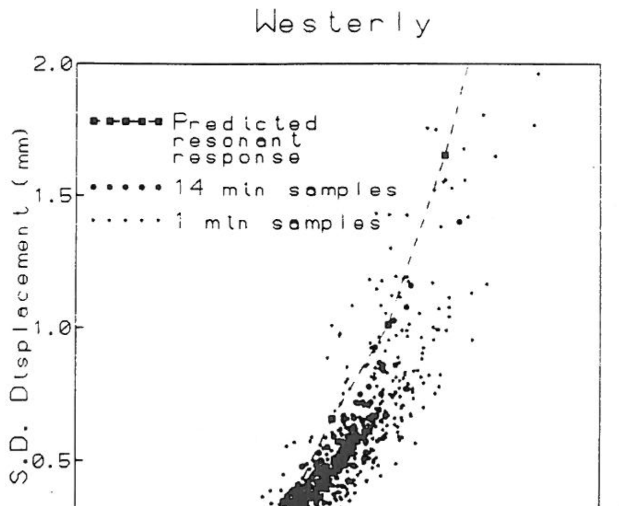


Figure 7 Standard deviation of displacement versus mean wind speed.