Wind Engineering for Lightweight Structures

A.W. Rofail
Windtech Consultants Pty Ltd, Sydney, Australia

1. INTRODUCTION

Lightweight structures are by definition wind–sensitive. This is particularly the case where spans become very large or where the structure is supporting large areas of lightweight panels or fabric. Hence the structural design of lightweight structures becomes dominated by the design wind loads. Structures that would fall under the category of lightweight structures include but not limited to:

1. long–span cable–stayed or suspension bridges
2. long–span or cantilevered roof structures (such as for large warehouses or stadiums)
3. special structures such as large roof fins, large screens & signposts or large clad sculptures

This paper presents an overview of the techniques employed by leading wind engineering consultants in providing accurate estimates of the wind loads for such structures. The emphasis will be on the second and third items, which have benefited by new wind tunnel testing techniques. These new techniques that have come about over the past decade or so are now possible due to advances in both signal processing and computer capability. These have significantly improved the reliability and accuracy of the wind load predictions. With the increased accuracy has come a significant increase in both cost efficiency and robustness of the structures that are amenable to these techniques.

2. HISTORICAL OVERVIEW

The failure of the Tacoma Narrows Bridge due to aerodynamic effects in 1940, only 3 months after commissioning, lead to the recognition of the need for proper study of the dynamic response of such lightweight structures to wind. After an extensive investigation involving wind tunnel modeling performed in Canada, it became evident that the failure was a result of a resonant response in the second torsional mode with the frequency of vortex shedding generated by the subject bridge deck form.

It was not until the mid–sixties that wind engineering began to merge with the engineering of tall building structures. Wind engineering became recognised as a discipline in 1970.

The techniques used for modeling the complex behaviour of strong winds over the earth’s surface in terms of their structure and turbulence have not changed much since the 1970’s. However, the techniques for measuring and analyzing the effect of the wind on the structure have changed significantly over that period. These changes have not affected the techniques for modeling the wind effects on bridges as much as other types of structures such as stadium roofs, special structures and even tall buildings.

There are now much more sophisticated techniques that allow us to know a lot more about what the wind is doing to the structure and enable us to model much more complex structures than was previously possible. Complex structures can be either in terms of their form or their dynamic behaviour (or both). It turns out that these techniques have an added benefit in that the resulting loads for some structures tend to be substantially lower than was previously thought due to the effect of low correlation of the peak pressures across the structure. Stadium roofs are an example of such structures. This paper discusses the methodology, background and application of the pressure correlation technique with examples. It also discusses how the modeling of the effect of wind on some unusual structures is possible.

3. PRESSURE CORRELATION TECHNIQUE

The pressure correlation technique was developed by Dr Michael Kasperski (Germany) and Dr John Holmes (Australia) about 15years ago (Kaspeski and Niemann, 1992 and Holmes, 1992). This technique is applicable to structures where the dynamic component of the structural response predominantly consists of the background component of the response and there is little chance of aerodynamic damping effects. Structures that fit into this description are stadium and long–span roofs as well as any canopy or large roof–fin structure. This technique is also applicable to quasi–static structures, where the form is relatively complex such that the use of wind loading standards is not possible.

This technique requires the use of the simultaneous pressure measurement technique (in real–time). The entire surface of the structure is pressure–tapped and the pressure signals measured simultaneously. The importance of having the pressures being read in real–time (minimal phase lag between the various pressure taps) stems from the need to accurately determine the following:

- a pressure correlation matrix, representing the relationship between the pressure signal at different areas of the building surface
- the various load effects, which are determined by area–weighting the pressures from the different areas (pressure integration)

It is important that the structural engineer carefully selects the various load effects that are to be monitored as these will determine the load cases that would be used to design the rest of the structural elements. Hence the load effects need to be for key structural members from different parts of the structure that are sensitive to pressures from the different areas of the building surface. In some cases it would also be helpful to determine different types of load effects such as displacement, shear force, axial force, bending moments (about different axes) for the same member.

For quasi–steady structures, the only input required by the structural engineer is a pressure correlation matrix. A stadium or long–span roof structure is considered quasi–steady if the first natural frequency is greater than 0.8Hz, whereas a vertical structure such as roof fin is considered quasi–steady is the first natural frequency is greater than 1.2Hz. A pressure correlation matrix determined by first dividing the envelope of the structure into a number of patches. There are typically between 30 and 60 patch areas for a stadium roof structure. The patch roof is divided into patches in line with areas that would be expected to have different range of pressures for the same wind direction (such as due to surface discontinuities or for aerodynamic reasons, such as wall or roof edges). Each patch consists of a number of pressure taps that are area averaged.

A pressure correlation matrix is determined by applying a unit pressure (such as 1kPa) normal to the surface of one patch and then read out the reactions for each of the key load effects that are being monitored. This would provide the data for one row of the matrix. The process is then repeated for the next patch area and so on..

For structures that are likely to have a significant resonant component, the following additional inputs are required from the structural engineer for the various modes that have natural frequencies less than 0.8Hz in the case of a stadium or long–span roof or 1.2Hz in the case of vertical structures such as roof fins:

- the natural frequency and mode–shape for each of the applicable modes of vibration. The mode–shape is normally expressed in the form of the displacement at the middle of each patch, normal to the patch surface.
- The mass and area per patch

This additional information is required to determine a generalised force for each of the load cases being monitored. This generalised force is then analysed spectrally to determine the prototype response of the structure. Usually the resonant response will comprise no more than 10 to 20% of the peak values of critical load effects and this contribution can be calculated separately and added to the fluctuating background response using a 'root–sum–of squares approach'. The effective static load distribution corresponding to each peak load effect can then be scaled up to match the recalculated peak load effect. When the resonant response is more significant, the inertial loading from the resonant component is correctly combined with that from the direct wind pressure, by a weighted summation (Holmes, 2002).

The advantages of this technique can be summed up as follows:

- no limitation to the complexity of the structural behaviour as there is no need to model such structures
- More accurate information regarding the critical load combinations between the various patches taking into account the effect of correlation of pressures across the structure
- an ability to accurately determine any number of load effects directly, without having to make assumptions regarding pressure distributions
- more accurate than traditional aeroelastic model techniques, which are limited in their ability to accurately model the dynamic behaviour of the structure and provide little guidance in relation to critical load cases
- the technique is more cost effective and requires less time that the traditional technique, provided that the computers can be effectively mobilized to perform the extensive data analysis required

3.1 CASE STUDY 1: GOLD COAST STADIUM

A study of the wind loads on the structure and cladding for this stadium was commissioned by SKM and Tensys as part of a value engineering exercise to meet tight cost constraints. A wind tunnel study was carried out on a 1:150 scale model of the stadium. A model scale as large as 1:150 was required to ensure correct simulation of the flow regime around the curved surface of the stadium roof, due to Reynolds Number effects. A photograph of the model in the wind tunnel is shown in Figure 1.

The pressure correlation technique was used in analysing the wind loads on the structure. In addition, a number of options were investigated to alter the roof edge configuration with a view to further reduce the wind loads. It was later decided not to modify the roof edge configuration. The entire envelope of the roof structure was divided into 64 panels. Each panel was pressure tapped on both sides using between 4 and 8 pressure taps per panel. Pressures on the entire roof structure were measured simultaneously to derive a correlation matrix as well as to determine time series of the generalised forces to determine the peak responses. A total of 15 load effects were monitored for maximum and minimum responses. These include 6 bending reactions, 6 axial loads, 2 tip deflections and 1 pile reaction. The corresponding 30 critical load combinations were rationalised to 24 load cases. The maximum 100year return patch pressure was approximately 2kPa represents a substantial reduction over the estimate by AS/NZS1170.2:2002. Furthermore, the effect of the correlation study is such that it significantly reduces the incidence of large pressures on more than a couple of patches at a time in a given load combination.

In the study of the wind loads on the cladding, area averaging was used as the cladding consisted of a tensile fabric. This approach resulted in reductions in the design loads for the cladding of the order of 20% over the measured point pressures. The maximum 10year return panel pressure was around 2kPa, which represents more than 40% reduction over the estimates in AS/NZS1170.2:2002, even with the effect of the area reduction factor of 0.80. This is significant reduction in the loads is largely attributable to the curved, aerodynamic form of the roof.

3.2 CASE STUDY 2: NANJING STADIUM

This was the main stadium used for the 2006 China Games. This stadium roof structure consists of a perimeter truss support as well as cable ties supporting the end of the cantilever by means of overhanging arches (see Figure 2). This relatively complex structure would be virtually impossible to model using the traditional aeroelastic modeling technique. Windtech Consultants were engaged by SKM to perform the wind tunnel study for this structure.

An accurate 1:300 scale perspex model of the structure was prepared using the computer–aided rapid prototyping process, as shown in Figure 3. This scale is more than sufficient for modeling of Reynold number effects for this structure. The entire envelope of the structure, including the overhanging arches was divided into 64 panels as shown in Figure 3. A total of 512 pressure taps were distributed over the entire surface of the roof structure and simultaneous pressure measurements were performed over the entire structure. A total of 15 load effects were monitored for one quarter of the structure to take advantage of the double symmetry. The load effects consist of a mid–span displacement, 5 moment reactions and 9 axial loads.

The maximum and minimum load effects resulted in 30 critical load cases, which were rationalised down to 8 load cases as shown in Figure 4. Note the difference between the instantaneous peak patch pressures required based on the pressure correlation technique in comparison to the maximum and minimum pressures derived from a simple discretised area–averaged patch pressures indicated as solid lines in Figure 4.

Figure 1: The 1:150 scale model of the Gold Coast Stadium in Windtech's Boundary Layer Wind Tunnel.

Figure 2: A perspective image of the Nanjing Stadium

Figure 3: The 1:300 scale model (left) and a diagram showing the different patch areas (right)

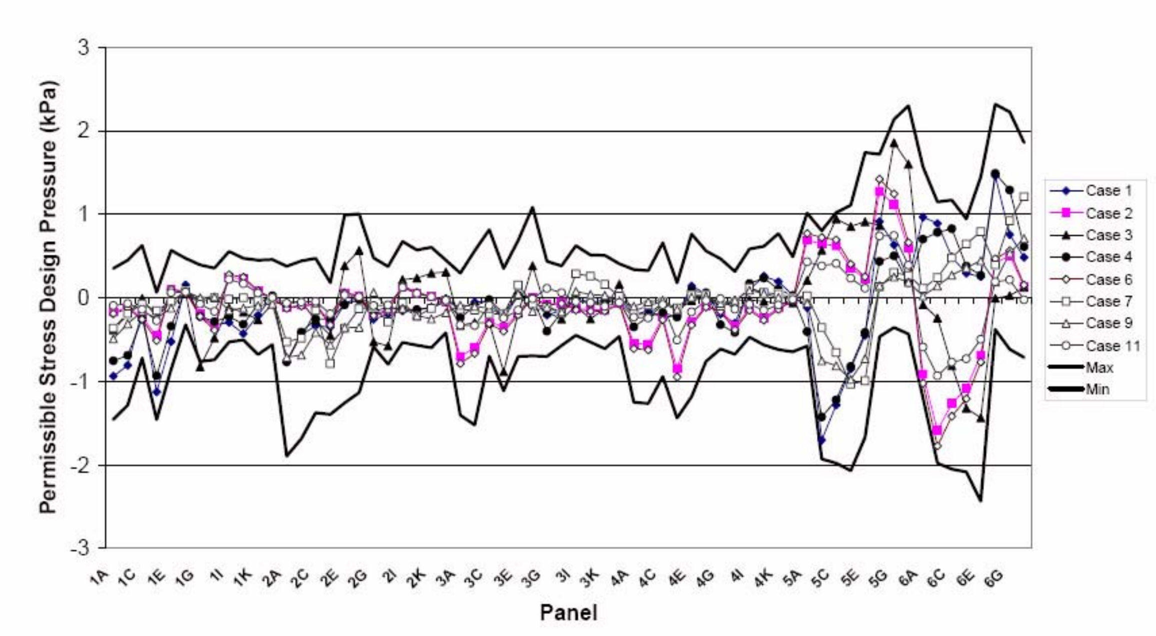

Figure 4: Discretised panel pressures (Max and Min) versus the 8 load cases for Nanjing Stadium

The natural frequencies for the first 5 modes were 0.75Hz, 0.77Hz, 0.79Hz, 0.81Hz, 0.95Hz. Hence in addition to the pressure correlation technique, a pressure integration method was applied to analyse the resonant response from the first four modes of vibration. For this structure, modes higher than the fourth mode would have a negligible contribution to the resonant response. The results of this analysis indicate that the resonant component of the response has a maximum additional contribution of 10% to the total dynamic response.

3.3 CASE STUDY 3: CAULDRON FOR ASIAN GAMES 2006, DOHA

This complex structure consists of 2 slim rotating rings that revolve around a main ring located on a 25m high shaft. This is a temporary structure and is intended to be in place for about 4 months from December 2006. A 1:50 scale model of the structure was prepared using the rapid–prototyping technique, as shown in Figure 5. This model was placed within a 1:50 scale model of the Khalifa Stadium.

A model was also configured with pressure taps within each ring and over the supporting shaft to enable the use of the pressure correlation technique. The model was designed such that the rings can be rotated to simulate the effect of different stages of the rings' revolution relative to each other and for the erection mode configuration. A total of five ring configurations were tested.

Before commencement of testing, a study was carried out using a 1:300 scale model of the sports precinct to determine the effect of the surrounding structures on the upstream velocity and turbulence intensity profile for wind incident from different wind directions. These wind profiles were replicated at 1:50 scale to be used for this study. Also an extensive analysis was carried out of the wind climate for Doha. This included a seasonal extreme wind speed analysis to correspond with the time of year when this structure is to be in place. Fortunately, the December to April season co–incided with the most benign season for extreme winds in Doha and therefore a lower design wind speed was adopted.

For each of the five ring configurations, two wind tunnel testing techniques were performed:

- high–frequency force balance
- pressure correlation technique

The high–frequency force balance technique was important as a check on the results of the pressure correlation technique. The need for the pressure correlation technique stems from the need to determine the relative displacements of the ring elements, as they need to operate within very strict limits to avoid the rings colliding into each other (there is only a few centimeters gap between them). The pressure correlation technique is also useful in providing a more accurate set of equivalent static loads for such an unusual structure.

The results showed that the value of drag from the pressure correlation technique was about 20 percent higher than those obtained using the high frequency force balance. This is due to complexity of the form of the structure and the curved form. Nevertheless it provided an acceptable level of confidence in the predictions.

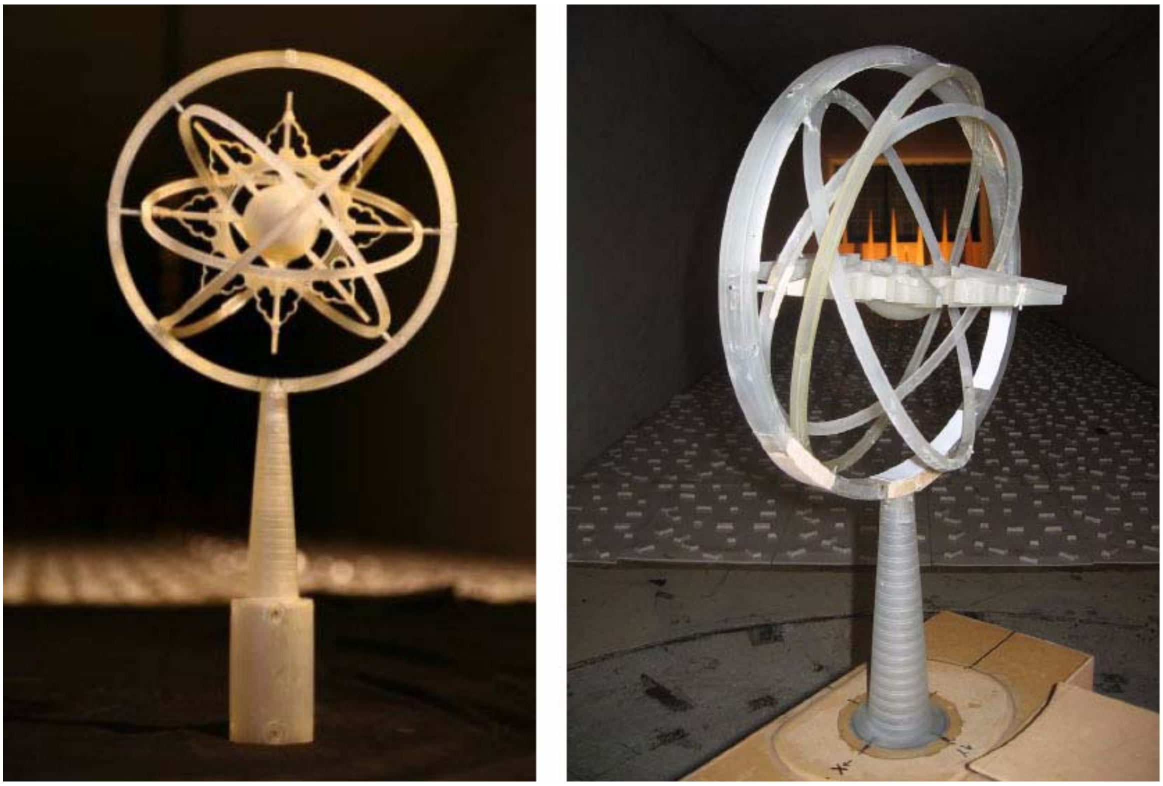

Figure 5: The 1:50 scale model of the Cauldron for the 2006 Asian Games, Doha. Left: On the force balance before inclusion of the Khalifa Stadium section model. Top Right: Within a section of the Khalifa Stadium and using the pressure correlation technique.

4. TECHNIQUES FOR POROUS STRUCTURES

The modeling of porous screens requires special care. Where a screen consists of elements of circular section Reynolds's Number effects can be significant. The Reynolds Number is a non–dimensional number that is proportional to wind speed and scale. The flow regime around bluff bodies varies with different Reynolds Numbers. Flow around Circular Cylinders is particularly sensitive to Reynolds Number. In some cases the only way to accurately model the drag of such screens is to artificially enlarge the diameter of the cylindrical elements such that the flow around them in the wind tunnel is operating under the same Reynolds Number Regime.

For net–type screens with a relatively even porosity, our research shows that the porosity of the wind tunnel model of the screen will need to be increased by a certain factor to provide equivalence in the value of the drag.

4.1 CASE STUDY: LED SCREEN FOR ASIAN GAMES 2006, DOHA

Windtech was engaged by SKM to investigate the wind drag forces on this 150m long and 58m high porous screen. This screen consists of a matrix of LED screens connected via 25mm diameter vertical cables. The screen was used for the opening and closing ceremonies of the 2006 Asian Games in Doha. The aim is to determine the amount of wind drag for which to design the supporting structural frame, which consists of a series of 8 vertical space trusses.

To be able to model the effect of the Khalifa stadium on this structure, a scale of 1:300 was required. However, to be able to model the flow regime around the cables the scale of the cables was exaggerated by 60 times relative to the model scale (1:5 scale). This was to ensure similarity of flow regime between the model and full–scale.

Figure 6: The 1:300 scale porous model of the LED screen for the 2006 Asian Games, Doha connected to the force balance.

Figure 7: The 1:300 scale impermeable model of the LED screen for the 2006 Asian Games, Doha connected to the force balance.

The model was attached to a force balance and was tested with two configurations: a porous screen configuration as shown in Figure 6 and an impermeable screen configuration as shown in Figure 7. In addition the drag on the force balance shaft alone was also measured and he drag subtracted from the two measurements. This enabled the determination of the porosity factor for wind from different wind directions. An example of the results (for the main axis) is as shown in Figure 8.

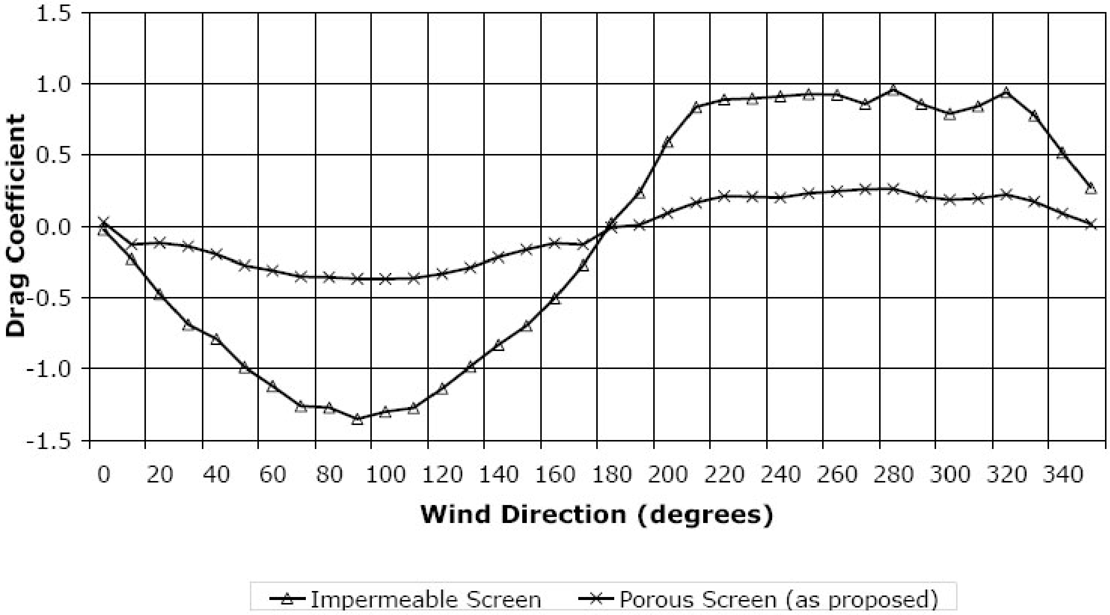

Figure 8: Drag Coefficient Comparison between the Impermeable and Porous Screen (along the East–West axis) Note that the results for wind from the critical west direction are somewhat affected by the presence of the Khalifa stadium structure.

The pressure tapped model was then used to provide an accurate distribution of the loads between the 8 panels areas that correspond to the 8 supporting space trusses (refer to Figure 9, below). A photograph of the pressure tapped model before inclusion of the Khalifa Stadium model is shown in Figure 10. The test using this model was also used as a check on the results of the force balance tests using the impermeable screen option.

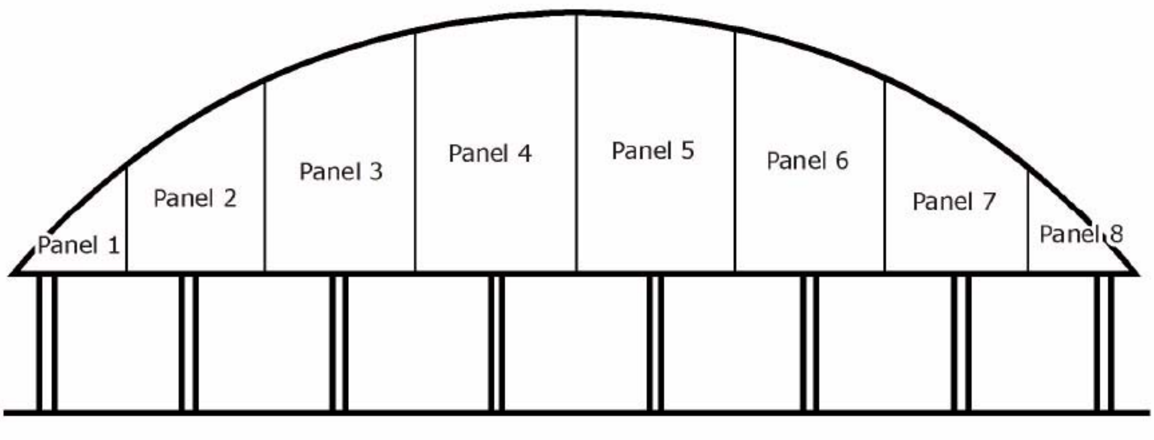

Figure 9: The tributary areas for each supporting vertical space frame structure.

Figure 10: The 1:300 scale pressure–tapped impermeable model of the LED screen for the 2006 Asian Games, Doha.

REFERENCES:

Kasperski, M. and Niemann, H.–J. (1992) The L.R.C. (Load–Response–Correlation) method: A general method of estimating unfavourable wind load distributions for linear and non–linear structural behaviour, *Journal of Wind Engineering & Industrial Aerodynamics*, v.43, 1753 1763.

Holmes, J.D. (1992) Optimised Peak Load Distributions, *Journal of Wind Engineering & Industrial Aerodynamics*, v.41, 267–276.

Holmes, J.D. (2002) Effective static load distributions in wind engineering, *Journal of Wind Engineering & Industrial Aerodynamics*, v.90, 91 109.