Wind loading on lightweight structures

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Wind loading in codes and standards are developed from the wind tunnel testing on scale models of various structural shapes. The range of building forms that have been tested to a level of confidence allowing codification is typically limited to rectilinear buildings. Limited pressure data is available for large span barrel vaulted roofs, and domes that may be of value to the design of air-supported roof designs. However, without significant extrapolation, the pressure information contained within standards is not applicable to the complex shapes common in tensioned fabric structure architecture, or to smaller sized elements. The pressures in the design standards on elements such as free roofs with differential wind pressure creating the loading should be viewed as an indicative guide.

The wind pressures contained in design standards are primarily for the design of the primary wind resisting structural system. The design information for secondary structural elements is not well represented. Simplified peak loading factors are provided for the design of rigid cladding elements, for which design loading is instigated by small scale turbulence. Compared with rigid structures, tensioned fabric structures distribute the wind load differently so an appreciation of the intent of the wind loading standard is important for design.

The derivation of accurate wind loads on complex structures and tensioned membrane structures generally requires the use of wind tunnel testing. The cost of wind-tunnel testing on smaller structures may be prohibitive, however, factors that make the use of wind loading derived from design standards appropriate are:

- curvilinear shapes of membranes will in the majority of cases have lower wind pressures than the planar elements considered by design standards.
- continuous membranes have good ability to redistribute high localized pressures, such that substantial underestimation of localized pressures does not generally result in failures, as it might on the rigid cladding elements.

There is little data available in design standards for the unusual and complex shapes of most tensioned membrane structures. However, there are some generic mean pressure coefficient data presented in the appendix of Forster and Mollaert (2004) that apply to some simple isolated shapes. These mean pressure coefficients are for use with the Eurocode framework, which assumes quasi-steady theory. Hence, the mean pressure coefficients can be used with the design gust wind speed in Standards Australia (2011). Nett pressure coefficients for a limited range of free-standing, empty under, hyperbolic paraboloid roof is given in Standards Australia (2011) based on the work of Pun and Letchford (1993). Again, these are mean pressure coefficients intended for use with a gust wind speed at mean roof height to provide information for the main wind resisting structural system. The wind loading on porous shade materials are discussed by Letchford et al. (2000).

Tensioned fabric structures with opposite sign curvatures may be the roof of a fully enclosed building (e.g. Denver International Airport Terminal), a free standing canopy with no walls at all (e.g. the Haj Terminal in Saudi Arabia), or something in between. Both the complex geometry and the variable wall conditions should lead the designer to seek guidance on the design 50-year wind pressures from a physical model study in the wind tunnel. The same may be true of the air-supported, same-sign-curvature fabric roofs, although these are generally fully enclosed structures, with limited/controlled openings, and a roof shape closer to that found in code data.

Wind-tunnel testing flexible structures can be complicated, depending on whether the deformed shape would significantly affect the pressure distribution over the structure. Fortunately, the vast majority of tensioned fabric structures do not displace the surface under wind load sufficiently to substantially alter the flow pattern over that surface. Hence, when investigating the design pressures in the wind tunnel a rigid model of the equilibrium static shape is adequate to represent the structure.

Typically the wind tunnel model would be of a geometric scale of 1:50 to 1:500 depending on the size of the structure and the wind-tunnel capabilities. A rigid model of a fabric clad structure is shown in Figure 1. Pressure tappings are located on the top and underside of the barrel-vaulted surface and a 'tube' is fabricated into the model to the lower edge where they are connected to flexible tubing for routing to the pressure transducers located under the turntable.

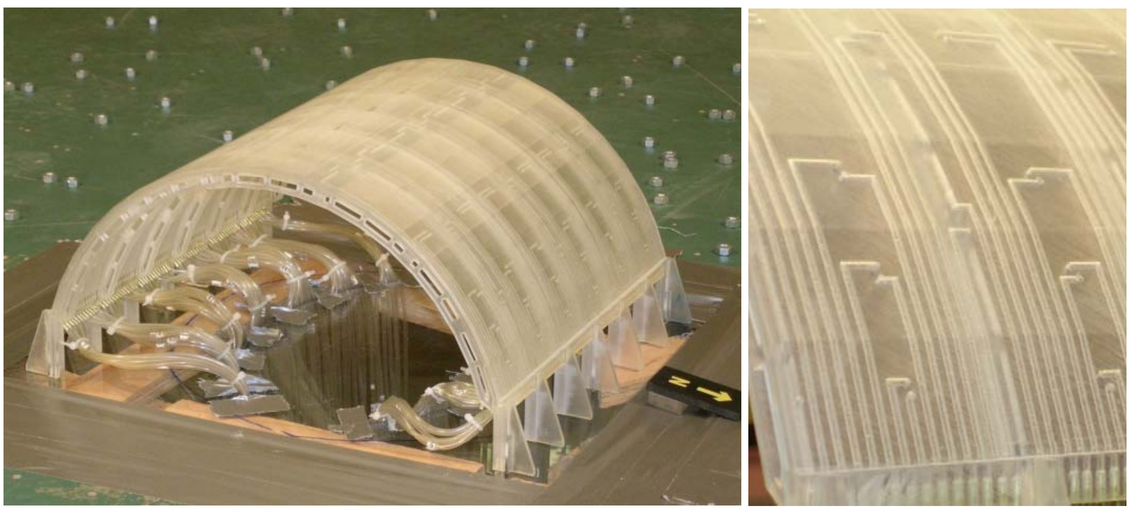

Figure 1: Rigid pressure model of a bulk storage structure

The testing outcome is a simultaneous time series of fluctuating pressures over the structure measured for a range of incident wind directions. This is relatively straightforward for an enclosed structure, but is significantly more problematic when the fabric material is open to the air on both sides and a nett pressure is required hence twice as many tappings are required. In this instance, the requirement to maintain the model as thin as possible from an aerodynamic modelling perspective, while having sufficient thickness to route the pressure tubing from a practical perspective is problematic. Routing the pressure tubes through the model without causing disturbance to the flow is essential to reproduce the pressure distribution. The number of pressure tappings required to define the pressure distribution over the surface of the model is a sensitivity issue relating to the response of the element. Additional modelling may be required to ascertain the effect of the model thickness and effect of external tubes for small scale models.

The pressure measurements can be analysed in a variety of ways to provide appropriate information for design and serviceability issues such as fatigue. The most basic output would be local peak surface or nett pressures both towards and away from the surface. These are often of value to the designer to illustrate where local isolated regions occur and do not have to be measured simultaneously. The data may be further area-averaged to yield patch loads over portions of the canopy fabric that is of interest to the designer. Good communication is required between the designer and the wind engineer so that pressure taps are placed in the model at locations that aid in the development of patch loads. This is particularly true for large structures with complex primary structure.

As the data are typically measured simultaneously with hundreds of pressure transducers, more sophisticated data analysis techniques are available to determine the response of the structure. If influence coefficients for responses of interest can be produced (e.g. anchor uplift, edge cable tension, compression of support column, total base shear, maximum unbalanced load, local displacement etc.) then the entire simultaneous pressure data can be provided for further structural analysis, or more normally can be reduced to a time series of the structural response of interest for each wind direction tested. The peak events and corresponding simultaneous pressure distribution can be extracted. Simultaneous companion actions (on, say, another cable or support column) may be generated for the maximized primary response and vice versa. With the structural dynamic properties of the structure, the dynamic response of the structure can be incorporated into the analysis. By integrating with the long term climate information an estimate of the cyclic loading for fatigue analysis can be conducted.

A related procedure described by Kasperski and Niemann (1992) and Kasperski (1992), called the LRC Method, is applicable to large-area roofs (fabric and conventional) and this may also be used by the wind-tunnel laboratory in the presentation of design quasi-static data. Lastly, included in the discussions that the designer must have with the wind-tunnel laboratory is the method of evaluating Reynolds Number dependence. Many fabric roofs are formed by smooth surfaces with few edges or corners. Thus, the data from the wind tunnel will have larger uncertainties associated with it than would a conventional building study. The wind-tunnel laboratory may have a suggestion on how to better assess Reynolds Number scaling and its impact on the data.

The flexible fabric and cable structures that form many of these geometrically complex designs have the potential to deform under strong wind load. As discussed previously, if the tension in the fabric is sufficient to maintain the shape then measurement of the simultaneous pressure distribution over the surface of a rigid model is sufficient for design. However, in some cases, the small amount of deformation that does occur may have the potential to develop a dynamic response.

For a large fabric roof or canopy, the dynamics will be design and geometry dependent, however there are some general observations that can be made. Large air-supported roofs, such as sports stadia, have an increased stiffness and damping due to the volume of air, close to the fabric, that moves with it under dynamic load. This is sometimes called an entrained mass of air, and the altered dynamic properties are referred to as ‘pneumatic stiffness’ and ‘pneumatic damping’. Both of these serve to reduce the dynamic response (Kind 1984). The influence of these pneumatic effects is largely restricted to the volume-changing symmetric modes rather than the asymmetric ones. As the structure becomes smaller, the pneumatic stiffness remains important, but the pneumatic damping may become less influential. Typically the pneumatic damping is large at low natural frequencies; hence the more substantial impact on large roof dynamics. These dynamic parameters for an air-supported structure will depend on many aspects of the design (geometry, leakage paths, air changes, fan system, inherent structural stiffness, etc.).

For open structures, if the fundamental natural frequency is greater than about 1 Hz the dynamic response would be governed by the turbulence (temporally and spatially) in the approach flow. Many of the small fabric structures routinely designed would fall into this stiff, non-resonant response category. Larger fabric canopies have lower natural frequencies and so some dynamic amplification may be expected. Pneumatic damping often applies to large canopies and so the expected dynamic response is diminished. The difficult part is quantifying this additional damping. Depending on the geometry and the supporting structure the wind-engineering laboratory may elect to collect data via the simultaneous pressure approach described above, or by using a lightweight, aeroelastic, strain-gauged model of the static canopy shape, Kind (1982). The dynamic loads generated from either approach may be presented for a range of damping values to show the sensitivity of the response of the structure to this value. A range of 1.5 to 3 percent of critical damping is suggested in Forster and Mollaert (2004), which would provide a significant range in the magnitude of response. In summary, for the vast majority of fabric roof and canopy designs (that remain in tension over the whole surface) dynamics is typically not a critical concern.

There are a number of publications describing numerical techniques linking CFD and structural packages to determine the wind induced response of flexible membranes (Knight et al., 2010, Wu et al. 2008, Yuan et al. 2010). These papers are based on relatively low turbulence flow situations, such as vehicle transport as the accurate modelling of turbulent flow around rigid bodies currently requires significant computational resources and the verification of the method has not been rigorously benchmarked for relatively simple rigid structures.

Case Study: Curved roofs

Several projects have been conducted on curved roofs with rigid pressure models, Figure 1. These tests have indicated that the design loads in the design standard are non-conservative for the majority of responses; particularly at the open end of the structure where highly asymmetric load patterns can be generated. The smaller the structure, the more asymmetric the loading becomes due to the smaller scale turbulence influencing the response of the structure. As noted above most of the wind-tunnel testing conducted on non-rectilinear structures for inclusion in design standards was based on large structures, hence the sensitivity of smaller structures to small scale turbulence was neglected.

Case Study: Carrara Stadium

A rigid model of Carrara Stadium on the Gold Coast was tested primarily for structural and cladding loads. Through discussions with the fabric consultant a range of critical wind loading cases were developed in terms of peak localised pressures. The measured pressures were integrated with the local wind climate and the peak responses from the time series were extracted for design.

Case Study: Singapore Sports Hub

A rigid model of the Singapore Sports Hub was again primarily tested for the structural response and local cladding pressures. The moveable roofs over the centre of the stadium are to be constructed from ETFE pillows. Whereas typical cladding pressures on such a roof would be a direct nett pressure between the top and underside of the panel, for ETFE design the peak topside and peak underside pressure with corresponding simultaneous pressure on the opposite surface are required, as well as the nett pressure.

Figure 2: Photograph of Carrara Stadium wind-tunnel model and completed structure

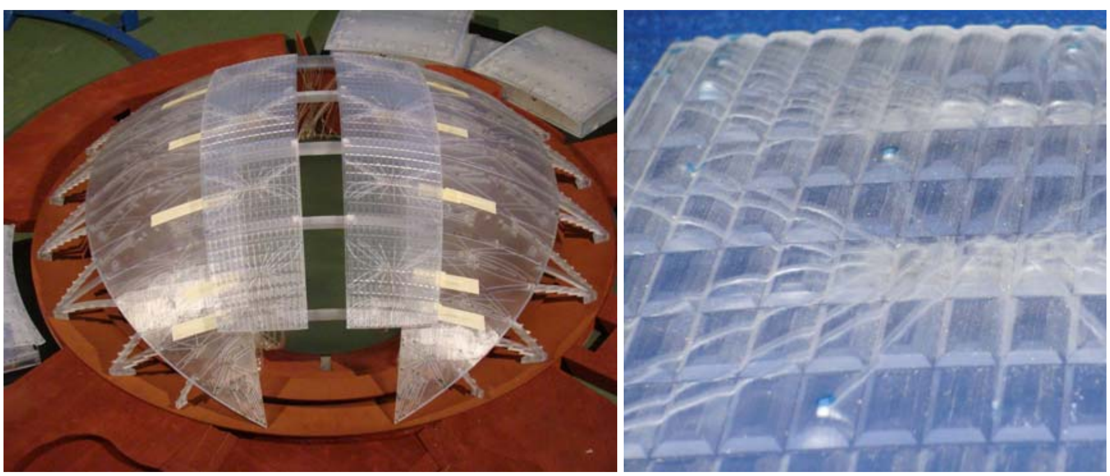

Figure 3: Photograph of the Singapore Sports Hub

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