FULL SCALE WIND LOADS ON A POROUS FABRIC CANOPY ROOF

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1. SUMMARY

A full scale experimental facility to measure wind loads on a porous fabric canopy roof is described. Characteristics of the wind loading under light to moderate wind conditions are presented. A proposed wind tunnel testing program for flat porous fabric roofs is detailed.

2. INTRODUCTION

In the last several years, the use of porous fabric structures has increased greatly in Australia. These structures can now be seen in all areas of civilization – inner city, suburban and rural. The main applications of porous fabric structures are for provision of shade, hail protection and wind protection. The advantages of porous fabric construction are low costs, ease of construction and removal, and visual attractiveness. Wind is the dominant loading consideration for the design of these lightweight structures. Unfortunately, the prediction of wind loading is made complicated by the inherent qualities of these structures – viz. porosity, flexibility and curved geometry.

Currently, shade structures are being designed based on pressure coefficients for solid canopy roofs of similar shape, with a reduction factor to allow for the porosity of the fabric. A recent study [1] has shown that porosity may increase the loading on windward parts of the structure. There seems to be no consistency in the use of these reduction factors, with different designers adopting their own 'in-house' values. Also, there is no consideration of dynamic excitation in the design of these lightweight, flexible structures that have the potential to be wind sensitive. The aim of this research is to develop a standard design method for porous fabric structures that will replace the current mainly ad-hoc approach.

This paper describes a full scale testing facility that is being used to investigate the wind loading and response of a porous fabric canopy roof.

3. EXPERIMENTAL SET-UP

A full scale shade structure was erected at The University of Queensland. The shade structure is square in plan with dimensions of 8mx8m. The structure is of hip roof form (i.e. square based pyramid). The columns are 4m high at the eaves and the roof pitch is 19°. Steel circular hollow section members are used for the columns and rafters. The porous fabric membrane is constructed from 90% shadecloth (i.e. 10% porosity). Tension in the shadecloth roof is controlled by a continuous wire rope which traverses a hem in the perimeter of the membrane. Increasing the tension in the perimeter cable causes the shadecloth tension to increase. Wind speed and direction at the site are measured by a 3-cup anemometer and wind vane respectively. Fluctuating tensions in the perimeter cable are measured on each side of the structure near the column supports with 1 Tonne capacity S-shape load cells. The experimental shade structure is shown in Figure 1.

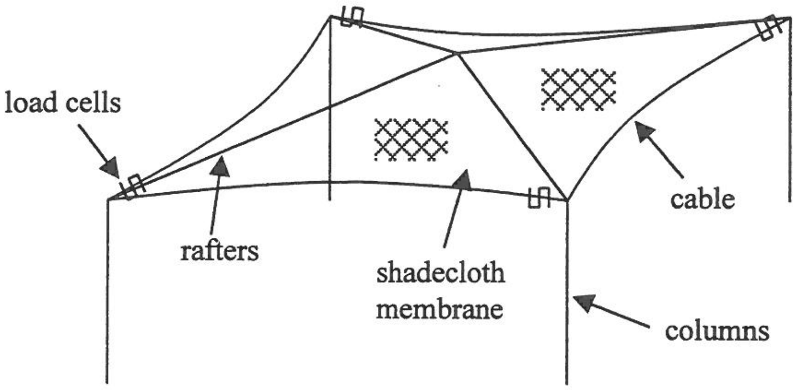


Figure 1 Experimental shade structure

4. RESULTS

4.1. Dynamic Structural Properties

Natural frequency and damping of the frame of the structure and the cable/membrane roof were measured from traces of free vibrations recorded by the load cells. The fundamental natural frequency of the column/rafter frame (diagonal oscillation) was determined to be 1.94 Hz and damping varied between 1% and 3% of critical in this mode. The natural frequency and damping of the cable/membrane roof depends on the amount of tension in the cable and membrane. Values of natural frequency and damping of the cable/membrane (first symmetric out-of-plane mode) are given for varying values of cable tension in Figure 2. Typical design cable tensions are of the order of 1 kN.

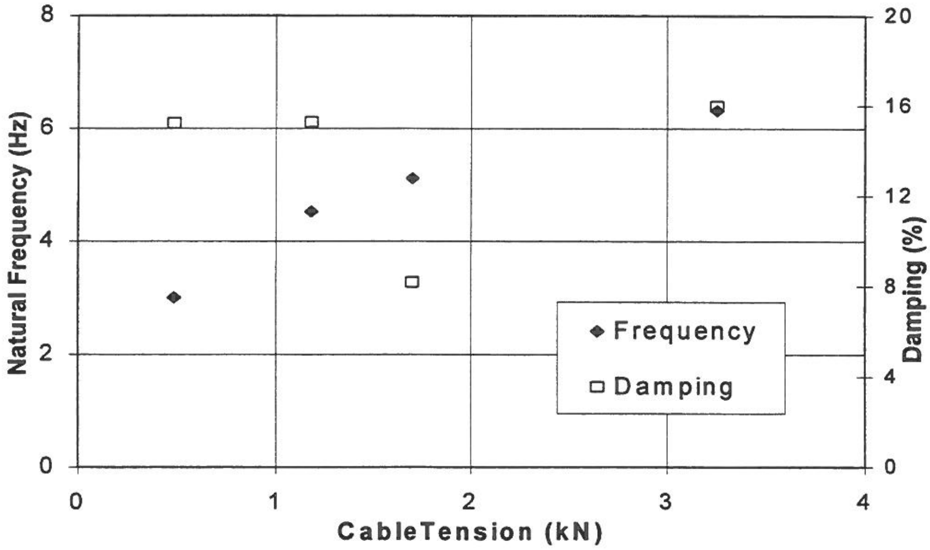
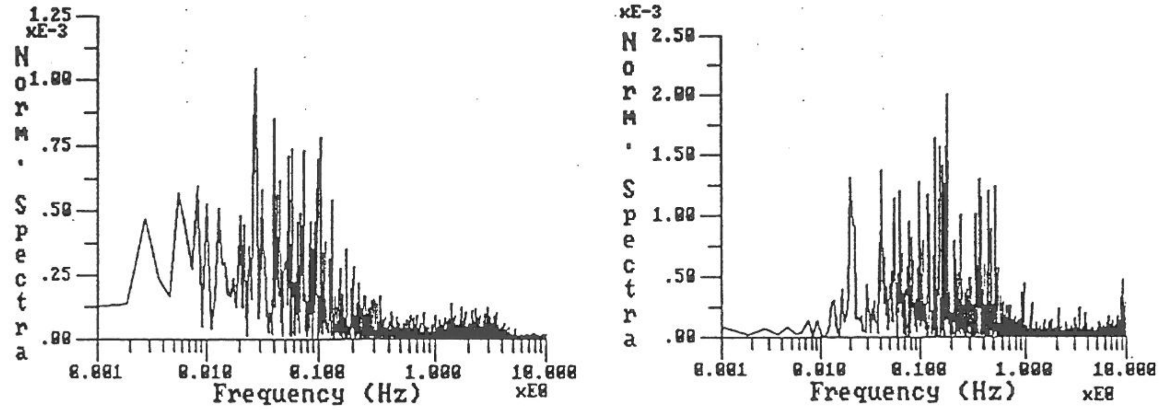


Figure 2 Dynamic properties of cable/membrane roof

4.2 Full Scale Testing

Eight 15 minute records of full scale data has been gathered during light to moderate wind conditions. For four of the records, the wind was blowing at an attack angle of 0° (i.e. parallel to the sides of the structure). Maximum wind speeds of 8 m/s were recorded with turbulence intensities of approximately 30%. For the remaining four records, the wind was blowing at an attack angle of 45° (i.e. along the structure diagonal). These winds were gustier with maximum wind speeds of 12 m/s and turbulence intensities of approximately 45%.

Typical spectra of the fluctuating wind velocity and cable tension are shown for an attack angle of 0° in Figure 3.



(a) Velocity spectra

(b) Tension spectra

Figure 3 Normalized power spectra

Most of the fluctuating energy of the wind is contained below 0.5 Hz. It is important that most of the fluctuating energy of the tensions is also below 0.5 Hz. This means that the wind loading on the structure fluctuates in accordance with the turbulence in the incident wind flow. There does not appear to be any power in the tension fluctuations at the natural frequencies of the structure (>2 Hz). This suggests that the structure is not susceptible to aerodynamic instabilities as a result of fluid-structure interaction. A cross-correlation analysis of the tensions showed that there was a high correlation between fluctuating tensions in each side of the structure at zero time delay. Thus, the structure responds to gusts of sufficient size to engulf the entire structure. These factors indicate that a quasi-steady wind loading analysis would be acceptable for the design of porous fabric pitched canopy roofs.

The dominant observed deflected shape of the membrane was associated with pressure on the windward panel, suction on the leeward panel and alternating pressure and suction on the side panels. Letchford et al. [1] measured mean wind loads on rigid porous canopy roofs. Interpolation of their results enables mean pressure coefficients to be estimated for the full scale experimental shade structure (i.e. 10% porous, 19° pitch hip roof) for an attack angle of 0°. Values of $\overline{C}_p$ will be taken as 0.5 for the windward panel, -0.45 for the leeward panel and –0.15 for the side panels. Quasi-steady flow theory allows the peak pressure $\hat{p}$ to be calculated from $\hat{p} = 1/2\,\rho\hat{V}^2\overline{C}_p$, where $\hat{V}^2$ is the maximum velocity. The maximum velocity in each of the four 15 minute records for an attack angle of 0° was used to calculate the maximum pressures on each panel of the shade structure. The maximum cable tensions resulting from these pressures were calculated using a finite element structural analysis package for tension membrane structures. The calculated increases in cable tension due to the maximum gusts differ from the measured increases by an average of 15% over the four records. This represents reasonable agreement considering that the transducer noise was approximately 10% of the measured tension increases, the peak gust at the anemometer may differ from the peak gust at the structure, and that the attack angle of the wind may not have been exactly 0° for the peak gust.

5. WIND TUNNEL TESTING OF FLAT POROUS FABRIC ROOFS

The investigations described above demonstrate that small sized porous fabric pitched canopy roofs are probably not susceptible to dynamic wind effects. However, a significant dynamic response to wind loading has been observed in flat porous fabric roofs. These types of roofs typically utilize continuous span construction to cover large areas (e.g. plant nurseries, orchards, car sales yards). Types of dynamic effects observed in these structures include travelling and standing waves. The inertia of these waves can cause high impulse loading in the fabric roof which may result in a failure of the cable and/or fabric connections.

This is not a new problem. Over the last 30 years there has been a significant amount of analytical and experimental research directed at the dynamic response of flexible membranes under wind loading. This work has been mainly carried out to understand the behaviour of flags, sails and hanging roofs. Both analytical and experimental studies have identified the occurrence of an oscillating instability of the membrane under certain conditions (the instability is known as 'luffing' for sails and 'flutter' for flags and hanging roofs). The theoretical analyses have utilized inviscid flow thin aerofoil theory to describe the flow around and loading on the membrane. Only two investigations [2], [3] have considered the effects of porosity on the response of the membrane. It appears that porosity has the effect of delaying the occurrence of the aerodynamic instability. The inviscid flow theory does not accurately predict the real fluid situation for large membrane curvatures where flow separates from the surface of the membrane. The theory is also unable to consider the effects of turbulence in the incident wind flow.

To better understand the wind response of flat porous fabric roofs a series of wind tunnel tests will be performed on sectional models. The main variables to be studied have been identified as the membrane porosity, tension, mass and bending rigidity, as well as the free stream turbulence. The response parameters to be ascertained include the critical conditions for initiation of instability, the mode shape, frequency and amplitude of the instability, and the fluctuating loads on the membrane.

6. CONCLUSIONS

A full scale experimental facility has been successfully used to determine characteristics of wind loading on a porous fabric pitched canopy roof. Results to date indicate that the structure is not susceptible to any aerodynamic instability and can be designed according to quasi-steady theory. A proposed wind tunnel testing program to examine flow-induced instabilities in flat porous fabric roofs is described.

7. REFERENCES

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