WIND LOADING ON TENT STRUCTURES

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Introduction

Most studies of wind loading on membrane structures refer to problems in which the membrane is highly prestressed (as in tension and pneumatic structures), so that the loading results in small deflections about an equilibrium shape. However by far the most common membrane structure is the ordinary tent in which prestress is generally small or absent, and deflections are subsequently large. Two questions of interest in the design of such tents are as follows:

(i) To what extent is the nature of the wind loading influenced by the consequent changes in tent shape?

(ii) Are tent structures prone to dynamic amplification of wind loading?

Both these questions were addressed by the author in a study which was carried out at the University of Western Ontario (Jackson, 1982), and which forms the basis of the discussion below.

Mean Loading

One obvious effect of wind loading on a flexible tent is that the loading distorts the tent to a new shape. It is useful to know the extent to which the pressure distribution on the loaded shape resembles that on the original shape, since if the differences are insignificant the loading can be estimated from measurements on a *rigid* model of the initial, known shape.

To study this question tests were made on a series of idealised tent models. The basis model was a 1:25 scale model of a triangular tent of length 3.0m, width 2.0m and height 2.2m. Two further models were constructed with one face distorted in a manner characteristic of panels under load (as shown in Figure 1), and on a further model one face was a flexible membrane. These were tested in a flow representing flat, open terrain with a full-scale roughness length of 4mm and turbulent intensity near the ground of 10%. Because of the large model size it was not possible to scale the large eddy structure correctly – the power spectrum peaked at a length scale of around 0.6 m in the tunnel, well below the corresponding full-scale value. However since gusts of this scale were much greater than the model size it is believed that this mismatch does not have a significant effect on the comparisons between models made below.

At most of the pressure taps the mean, rms and maximum and minimum pressures were measured. In addition the pneumatic averaging technique was used to find the same statistics for the overall instantaneous load on each face, the total forces acting on the tent and the generalised forces for the first and second mode of vibration of one panel. Pressures were converted to coefficients using the free-stream static pressure and incident mean velocity at tent height as reference values. The mean

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pressure distributions on the basic model are shown in Figure 2. They do not show any surprising features, and the range of values is similar to that obtained for other highly 3-D shapes.

To determine whether the differences in C_p between models were significant it was necessary to compare them with the magnitude of error inherent in the measurements, this error being determined by repeating the entire sequence of measurements for the basic model (removing the model in between). The standard deviation of the differences between experiments was found to be 0.013 for mean values and 0.074 for peaks. Comparison with the typical values shown in Figure 2 indicates that in fact these measurements are highly repeatable. Under the hypothesis that there is no difference in point pressures between models of different shape, the ratio of the sum of squares of differences *between* models to the sum of squares of differences *within* models (between tests on the same model) has the F-distribution whose likelihood of exceeding any value is known. This test showed that the differences between models of different shape which were statistically significant were concentrated in a narrow region near the tent ridge on upwind faces. It could be concluded only that the distribution of pressure on downstream faces was insensitive to panel shape, whereas that on upstream faces may not be. The total force acting on a tent panel is arguably more useful for design, and the results obtained for this force coefficient are shown in Figure 3. It can be seen that while there *are* differences between models, they are generally small enough to be ignored. The modal forces for the first and second modes of vibration, and the X,Y,Z components of the total force on the tent were also measured, and these showed differences between model shapes which were no greater than those of Figure 3. One can conclude that area-averaged wind loads on tents can be adequately estimated from tests on rigid models. The worst loading cases are clearly obtained by assuming that the internal pressure is vented to the maximum or minimum external pressure.

Dynamic Loading

Tent structures are also unusual in that the membrane tension is determined by the wind loading itself. Since the stiffness of the structure is strongly dependent on this tension, it turns out that the stiffness, mass and damping of the tent are all of aerodynamic origin. This is illustrated by the following model for the response of tent volume to unsteady wind loads. If the volume change is V and the tent surface has area A_s, the mean speed of surface normal to itself is $\dot{V}/A_s$. A suitable equation of motion for the external flow is then -

$$M\frac{\ddot{V}}{A_s} + A_s\frac{dp}{dV}V + \rho A_s{}^2\,\omega^2\,C_D\,\dot{V}/c = (p_i-p_e)A_s \qquad (1)$$

where M is the tent mass plus the added mass of the (exterior) air, the third term represents damping by acoustic radiation at frequency ω and sound speed c (Ffowcs-Williams and Lovely, 1975), and $p_i - p_e$ is a weighted average over the tent area of the difference between the interior and exterior pressures. The term dp/dV can be thought of as the 'pneumatic stiffness' of the tent - the tent takes up an equilibrium mean shape under loading, and an increment dp in the internal pressure p_i then causes a corresponding change dV in tent shape. Kind (1984) shows how to estimate this stiffness for pneumatic structures, but here this stiffness depends upon the level and distribution of wind loading itself. For example if all the tent panels are highly loaded one expects this stiffness to be high.

This can be modelled by a square panel of side L, modulus E, thickness d which is loaded by pressure p_o but supported only at two ends (so it behaves as a 2-D structure). It can be shown that if the panel is initially slack with total length $L(1 + \beta)$ then -

$$\frac{dp}{dV} = \frac{p_o}{L^3} K , \quad K = 24 \beta Ed/p_o L \tag{2a}$$

Typical values of K work out to be at least 100 in practice. At the other extreme if just one panel has loading which changes sign along it a small pressure rise over the entire panel can cause a large change in volume, the factor K now being found to be -

$$K = (3/2 \beta)^{\frac{1}{2}} \tag{2b}$$

which is typically only 10 or 20.

Next consider the motion of air near a vent or leak in the tent. If the vent has area A the velocity through it is $v = -\dot{V}/A$, and the difference in pressure between the interior and the exterior pressure (p_v) at the vent is partly converted to a head loss and partly accelerates some mass of air M_i:

$$A(p_i - p_v) = M_i \dot{v} + \frac{1}{2} \rho A v |\dot{v}|$$

Combining this with our first equation gives -

$$(M + M_i A_s^2/A^2)\frac{\ddot{V}}{A_s} + A_s \frac{dp}{dV} V + (\rho L^2 \omega^2 C_p / c + \frac{1}{2} \rho A_s |\dot{V}| / A_s^2)\dot{V}$$

$$= (p_v - p_e) A_s \tag{3}$$

In practice M is dominated by the added mass (approximately $\rho A_s L$) so using equation (2) with $p_o - \frac{1}{2}\rho V_o^2$ leads to a natural frequency of -

$$\omega = \frac{1}{2\pi} \frac{V_o}{L} \sqrt{K/2}$$

This obviously increases with wind speed V_o and is higher for a more highly loaded tent (higher K). Note that $f = \omega L/V_o$ has a minimum value of around 0.4, whereas the energy spectrum of incident turbulence near the ground peaks at a much lower frequency. Treating the forced motion as quasi-static then leads to the tent motion -

$$V/L^3 = (C_{p_v} - C_{p_e})/K$$

with a magnitude increasing as the tent stiffness decreases. Approximating $\dot{V}$ by $V\omega$ then leads to critical damping ratios for radiation and leakage of

$$\xi = \frac{1}{2\pi} Ma \sqrt{K/2}\, C_D/2 , \quad \frac{A_s^2 (C_{p_v} - C_{p_e})}{A^2\ 4\ K}$$

respectively (Ma is Mach number). Since the frequency of vibration is low the radiation damping is not significant, but the leakage ratio can easily exceed unity and therefore represents a very high level of damping. Overall it appears most unlikely that volume changing modes can be excited by turbulence.

Modes which do not cause volume changes are not damped by the leakage term, and so are much more likely to occur (as when an upwind face moves in as a downwind face moves out). Similar calculations can be carried out, giving similar estimates of natural frequency and amplitude, so that dynamic amplification again seems unlikely.

References

Jackson, P.S. (1983) *'Flexible tent structures under dynamic wind loading'*,Boundary Layer Wind Tunnel, University of Western Ontario, Rep BLWT-1-1983.

Kind, R.J. (1984) *'Pneumatic stiffness and damping in air-supported structures'*,J. Wind Eng. & Ind. Aero., 17, 295-304.

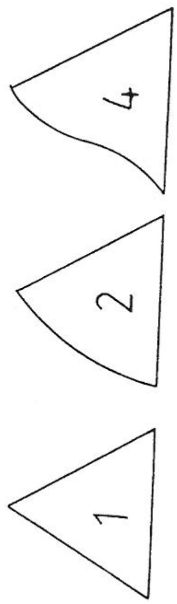

Fig. 1 : Rigid Model Shapes

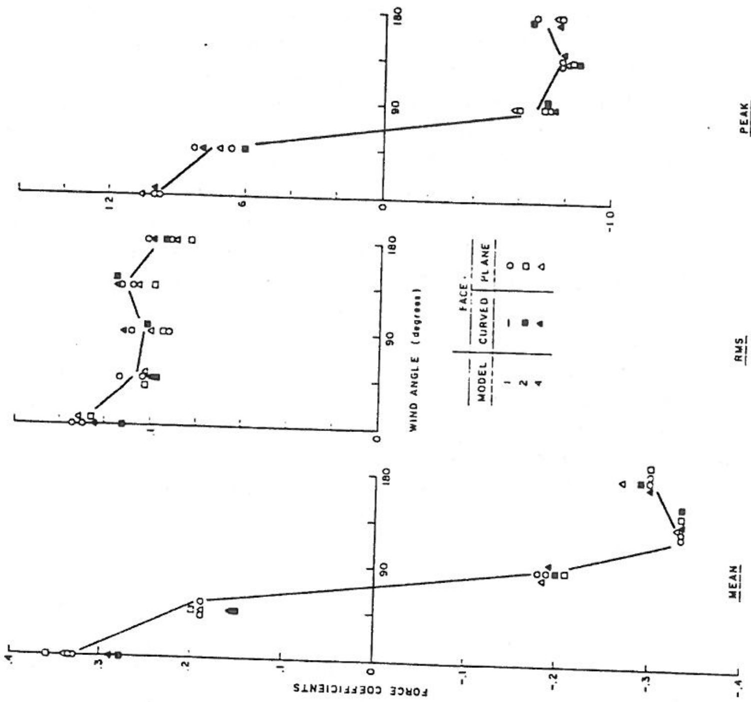

FIG. 3 FORCE COEFFICIENTS ON SLOPING FACES VS. WIND ANGLE TO FACE

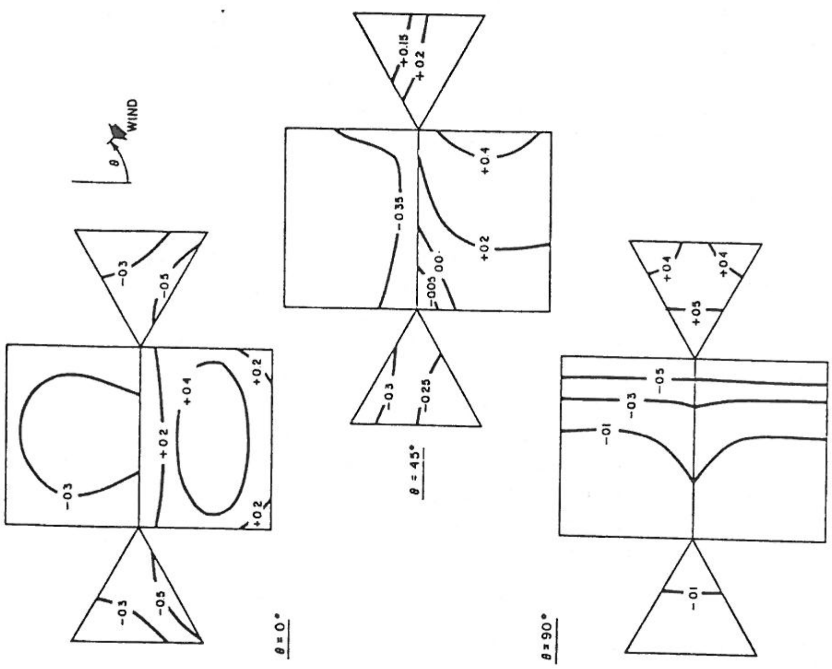

FIG. 2 CONTOURS OF MEAN PRESSURE COEFFICIENTS ON THE BASIC MODEL (# 1)