WIND LOADS ON CANOPY ROOFS

J.D. Ginger, Department Of Civil Engineering, University Of Queensland, 4072.

Introduction

Most wind loading codes (eg AS-1170) [1],prescribe a quasi-static design approach for determining peak wind loads on low rise structures. In the quasi-static approach the fluctuating surface pressures depend entirely on the fluctuating wind velocity in the atmospheric boundary layer. This approach has been shown to be satisfactory for regions, where the flow impinges directly [4]. However it is not suitable for determining pressures, where flow separation and vortex formation takes place. The shape of the structure (or structural element), it's dimensions and the characteristics of the flow mechanisms over the surfaces will determine the pressure field.

The fact that local pressures depend on the area under consideration and flow characteristics is accounted for in wind loading codes [1], by use of local pressure factors. These local pressure factors are used to magnify the mean pressure in regions of flow separation, to take account of the larger mean pressures and the highly intermittent nature of the pressure fluctuations. Area reduction factors are also used to account for the spatial distribution of the wind loads. Typically a range of values for the factors are provided depending on the dimensions and the location of the area of interest. For simplicity, the areas for which these factors apply are usually squares whose side length is some fraction of the dimensions of the structure.

The magnitude of these pressure factors and the area over which they apply is important, particularly on roofs which have been shown to be the most likely component of low rise structures to suffer wind induced damage. Wind loading studies, on various roof forms have shown that the largest pressures are experienced at oblique wind orientations close to leading edges and ridge lines, where flow separation and consequent formation of stable conical or delta wing vortices takes place.

The cause of very high negative pressures under the separated / reattaching shear layer from a sharp edged flat plate placed parallel to the flow has been studied by Melbourne et al [6]. They established that very large negative peak pressures were experienced in the separation bubble when very short reattachment of the separated shear layer occurred. Furthermore, with increasing freestream turbulence intensity, progressively earlier shear layer reattachment occurred, along with larger negative peak pressures. These large negative pressures occur with the intermittent roll-up of the shear layer to form a vortex, which then convects downstream producing large negative pressures on the surface beneath it. They also established that the pressure fluctuations are highly intermittent in the reattachment region and that the peak pressures are spatially correlated over a significant length in the lateral direction.

A wind tunnel test program investigating wind loads on canopy or free standing roofs is presently underway at the Department Of Civil Engineering, University of Queensland. This study is aimed at providing a better understanding of the pressure distributions over canopy roofs and identifying regions most vulnerable to wind induced damage and the flow mechanisms that cause these loads. Tests were carried out to determine area averaged pressures on sections of the roof and individual pressure measurements were carried out to determine the pressure distribution from which regions experiencing large pressures were identified.

Wind loads on roofs

Stathopoulos et al [7] and Kind [5], carried out series of tests on various roof forms of closed low rise buildings. The results showed that the largest local mean and peak pressures were experienced close to the leading corner at oblique wind orientations. The influence of the delta wing vortex is felt over a considerable area as the vortex expands and spreads downstream over the roof surface. Kind, obtained mean and peak pressures significantly larger than values obtained in previous studies, and reasoned this to the scarcity of pressure taps close to roof edges, in the other studies.

Kind,[5] hypothesized that for flat roofs of simple rectangular shaped closed buildings the largest pressures occur close to the leading corner at a wind orientation ~ 45°, due to formation of a highly stable conical vortex similar to that which forms over a delta wing aircraft at moderate angles of attack.

Gumley [2, 3] published a series of studies on the wind loading of free standing canopy roofs, typically used in the Agricultural Industry in England. Wind tunnel tests were carried out on a variety of canopy roof forms and the area averaged mean pressure coefficients on various sections were determined. Design wind loads using the joint extreme value approach were also obtained. Again the largest pressures were experienced close to the leading edges and behind the ridge line of pitched roofs, at oblique wind orientations.

Experimental technique

Tests were carried out in the Boundary Layer Wind Tunnel which is of the recirculating type with a working section 3m wide x 2m high, and a length of 11.5m over which boundary layer development occurs. In this study the boundary layer was simulated at a length scale (L_r) of 1/100, terrain category 3 (AS-1170) [1], conditions. The velocity scale (U_r) was ~ 0.5, resulting in a time scale (T_r) of ~ 1/50.

A 7mm thick, 300mm x 300mm rigid canopy roof model, of a sandwich construction with pressure tappings directly opposite on top and bottom surfaces and variable height and pitch was constructed. Pressures were measured by connecting the surface pressure tappings through a tubing / manifold / restrictor system connected to Honeywell 160PC pressure transducers via a Scanivalve switch. The system had a good frequency response up to 100 Hz, at which the signals were lowpass filtered. The mean, standard deviation, maximum and minimum pressure coefficients were obtained using a PC controlled data acquisition system, at a sampling frequency of 250 Hz over a time period of 60s. Spectral measurements were obtained using a Bruel and Kjaer 2034 spectrum analyzer. The pressures are defined positive downwards perpendicular to the roof surface and the mean, standard deviation, maximum, minimum pressure coefficients are defined as

$$C_{\bar{p}} = (\bar{p} - p_0)/q, \qquad C_{\sigma p} = \sigma_p /q,$$

$$C_{\hat{p}} = (\hat{p} - p_0)/q, \qquad C_{\check{p}} = (\check{p} - p_0)/q$$

where $q = 1/2\ \rho\ \bar{U}_h^2$

$\bar{p}$, σ_p, $\hat{p}$, $\check{p}$ - Mean, standard deviation, peak positive and peak negative resultant (top-bottom) pressure

p_0 - Freestream static pressure

$\bar{U}_h$ - Mean wind speed at eaves height h

ρ - Density of air = 1.2 kg/m^3

The zero wind orientation is when the flow is perpendicular to the ridge line. Tests were carried out on 30m x 30m roofs with eaves heights (h) of 7.5m, 10m and 12.5m and roof pitches (α) of 0°, 5°, 10°, 15°, 22.5° and 30° over wind orientations (β) of 0° to 360°.

Results and conclusions

The largest pressures were experienced at a wind orientation (β) of ~ 30° for all pitch angles investigated. Large positive pressures were obtained close to the leading edges of the windward half and large negative pressures close to the leading edge of the leeward half and close to the ridge line. The pressure contour plots follow a similar pattern in all the roof forms. The results obtained for the roof of 22.5° pitch and h = 10m, at a wind orientation of 30° are presented. The area averaged pressures on the six (A-F) 15m x 10m sections are given in Figure 1. The mean pressure coefficient contour plot is given in Figure 2. The largest point positive $C_{\bar{p}}$ is ~ 2.1 close to the leading edge corner on the windward half, and the largest point negative $C_{\bar{p}}$ is ~ -2.8 close to the leading edge corner on the leeward half. Peak pressure coefficients as large as 10.3 and -9.8 were obtained at these two points respectively.

Area averaged pressure coefficients on regions of high pressure on 13m x1m leading windward and leeward side strips and 10m x 1m windward leading front and windward and leeward ridge strips of the roof are presented in Figure 1. These regions are associated with high suction pressures found under separated shear layers. At $\beta = 30^0$ the wind flow will be such that delta wing vortices form close to the leading edges of the underside of the windward half and the leading edge and ridge line of the topside of the leeward half.

References

(1). Australian Standard, SAA loading code part 2: Wind loads AS 1170.2- 1989
(2). Gumley, S. J. 1981. Panel loading mean pressure study for canopy roofs,Univ. of Oxford, Dept. of Eng. Sc. OUEL report 1380/81
(3). Gumley, S. J. 1982. Design extreme pressures - a parametric study for canopy roofs,Univ. of Oxford, Dept. of Eng. Sc. OUEL report 1394/82
(4).Kawai, H. 1983, Pressure fluctuations on square prisms - Applicability of strip and quasi steady theory, JWEIA, Vol. 13 (197-208)
(5). Kind, R. L. 1986, Worst suctions near edges of flat roof tops on low rise buildings, JWEIA, Vol. 25 (31-56)
(6). Saathoff, P. J. and Melbourne, W. H. 1989, The generation of peak pressures in separated/reattaching flows, JWEIA, Vol. 32 (121-134)
(7). Stathopoulos, T. and Mohammadian, A. R. 1986, Wind loads on low buildings with mono-sloped roofs, JWEIA, Vol. 23 , (81-97)

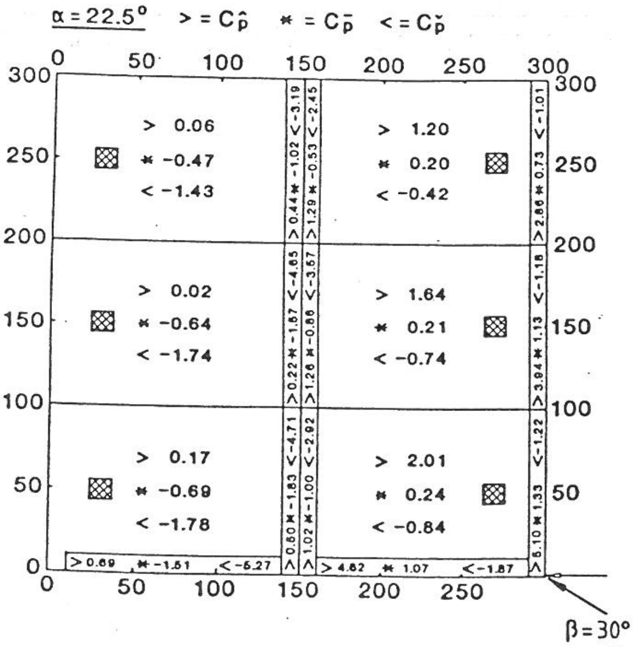

Figure 1. Area averaged pressure coefficients on sections of the roof. ($\alpha = 22.5^\circ$, $\beta = 30^\circ$)

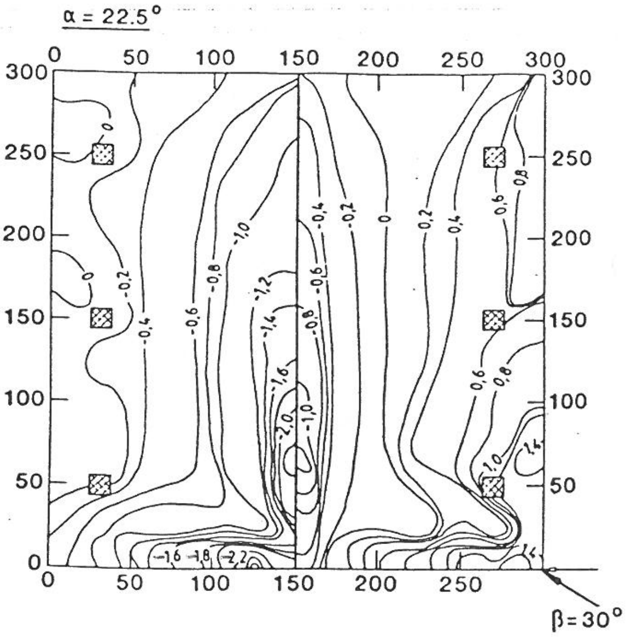

Figure 2. Mean pressure coefficient ($C_{\bar{p}}$) contours. ($\alpha = 22.5^\circ$, $\beta = 30^\circ$)