THE INFLUENCE OF GEOMETRY ON WIND PRESSURE COEFFICIENTS ON CONICAL STRUCTURES

(Research study undertaken by MSAA Technical Subcommittee)

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1.0 Introduction

This paper describes a series of wind tunnel experimental tests which measured pressure coefficients for a single cone fabric structure model. The study was commissioned and directed by the MSAA Technical Subcommittee and form part of what is hoped will be a more extensive testing program. The objective of the study is to provide wind pressure coefficients for a number of commonly used fabric forms since this data is not generally available in the literature. The model shapes selected were derived from a study of constructed fabric membrane structures. Several parametric studies were performed to determine the influence of these variables.

The wind tunnel testing was carried out by VIPAC Pty Ltd with input from Connell Barrow McCready Pty Ltd and Connell Wagner Pty Ltd. The efforts and contributions of various individuals of the companies involved are fully appreciated and listed in the acknowledgements.

2.0 Literature on Wind Pressure Studies of Fabric Structures

Membrane structures can be divided into two main categories comprising either
- (a) synclastic surface (for example. a hemisphere), or
- (b) an anticlastic surface consisting of opposing positive and negative curvatures.

Anticlastic forms can be generalized into:
- (a) freeforms,
- (b) conics, and
- (c) barrel arches.

The Australian wind code (AS1170.2 1989) does not have specific provision for membrane structures except for the use of wind tunnel simulations to obtain the appropriate loadings. To date, most designers derive pressure coefficients by either
- (a) interpolation of previous wind tunnel results,
- (b) approximation of pitched roofs coefficients provided in AS1170.2, or
- (c) conducting a full scale wind tunnel.

The latter method is not usually justifiable for small scale projects. It is interesting to note that wind tunnel tests generally provide wind coefficients which are lower than the Code resulting in cost savings. This indicates the conservativeness of present methods of estimations from monoslope or pitched roof models for a doubly curved surface.

Literature on wind loading of synclastic surfaces are well documented from the work conducted during the early 70s in Europe and the United Kingdom. These forms basically cover all the pneumatic air supported structures.

Literature on anticlastic surface structures is sparse and usually conducted on a project requirement basis.

3.0 Conical Form Design Variables

A conic form was selected for this initial series of experimental tests since it represents one of the most commonly used fabric tension membrane schemes in Australia dating back to the tent cities of Ballarat. For further simplification the study was limited to square base plan cones.

As a first step, it was necessary to define a typical conical form and then to decide which variables should be investigated as a parametric study. The characteristics of several fabric tension conical structures designed by Connell Barrow McCready Pty Ltd and Connell Wagner Pty Ltd in recent years were studied to establish the principal variables. These are summarized in Table 1 below.

Table 1: Survey of existing Fabric Conic Projects

Project	l(m)	b(m)	h(m)	d(m)	h: half base diag.	d: base diag.	Comments
Bicentennial Theatre	38.0	36.0	13.20	10.00	0.5:1	0.19:1	Large tent
Arcade	17.5	9.0	5.8	0.8	0.6:1	0.04:1	Dual cone canopy
Portiere	20.4	24.0	10.5	3.6	0.7:1	0.11:1	Dual cone canopy
Preston Market	6.75	6.875	2.0	0.7	0.4:1	0.07:1	Cone structures
M.V.R.C.	8.690	8.750	4.335	0.7	0.7:1	0.06:1	Cone
Keysborough Golf Club	15.0	15.0	8.7	1.5	0.8:1	0.07:1	Dual cone
Pavilion Hotel	25.0	26.0	8.20	5.0	0.45:1	0.14:1	Large cone
Keysborough Entrance	6.9	5.0	2.5	0.7	0.58:1	0.08:1	Cone

3.1 Curvature Variable

The most important structural characteristic of a fabric structure is its curvature since this determines not only the fabric forces but also the fabric's stiffness. Referring to Figure 1, for a square base plan cone, the curvature is related to two main geometrical ratios:-

(i) height:half base diagonal = 2h:diagonal = c

(ii) ring beam diameter:base diagonal = d:diagonal = k

For a conical form of constant base dimensions, the curvature increases with height and decreases with the ring diameter. This is demonstrated in Figure 2.

From a design viewpoint, low curvatures can lead to rainwater ponding problems and should be avoided.

A limited range of model shapes and configurations were investigated due to time and economical constraints. On studying Table 1, the most practical situation to take into account the high and low bounds of the curvature are as follows:

(a) high curvature h:half base diagonal = 0.8:1, and

(b) low curvature h:half base diagonal = 0.4:1

3.2 Central Ring Beam Size Variable

Both the Bicentennial Theatre and the Pavilion Hotel projects consist of cones having large base dimensions with large rings and give figures of 0.19:1 and 0.14:1 respectively. These are classified as large cone structures.

For the smaller size cones the range of ring diameter to diagonal is from 0.06 to 0.08. This range covers high curvature conics to flat conics.

A constant value of ring diameter:base diagonal equal to 0.07:1 was adopted for the study.

3.3 Design Variable

From a designer user viewpoint, the following configuration variation were considered important for a limited parametric study:

(i) height of the membrane above ground (i.e. height of the supporting columns)

(ii) presence of building blockage or open space under the structure

(iii) capping of central ring beam or open ventilation

A summary of the conical shapes and configuration variables is listed in Table 2 (see below) and Figure 3.

Table 2: Summary of the Conical Shapes and Configuration Variables

	High/Low	Building blockage	Ring Cap	5m/12m height to perimeter base
Tent 1	Low	No	No	5m
Tent 2	Low	Yes	No	5m
Tent 3	Low	No	Yes	5m
Tent 4	Low	No	No	12m
Tent 5	High	No	No	5m
Tent 6	High	Yes	No	5m
Tent 7	High	No	Yes	5m
Tent 8	High	No	No	12m

4.0 Model Configuration

The wind tunnel study utilized rigid fibreglass models on a 1:50 scale.

The use of rigid modelling for wind tunnel testing of fabric structures is a relatively common technique as opposed to aeroelastic modelling. Whilst tension membrane structures are prestressed into a relatively rigid surface, the surface responds to external loads by a change of geometry such that the forces can be transferred by pure tension stresses.

Comparative tests have been carried out by various researchers (Ref. 4, 5, 6) into the use of rigid modelling techniques. Based on this information and literature, the technique was considered to be sufficiently accurate for our study.

For the model making process, an innovative approach was employed whereby 1:50 scale lycra models of the conical shapes were developed by Connell Barrow McCready Pty Ltd and these were then used as a mould for the fibreglass models.

Firstly the lycra fabric forms were coated with a thinned epoxy fibreglass resin to stiffen them and then coated with a release agent. The models were then covered with several layers of finely chopped mat fibreglass and resin coatings until a sufficiently stiff mould was formed. At all times the thickness was kept to a minimum (approximately 3 mm).

Upon setting of the fibreglass coatings, the models were removed from the lycra form and reinforced where necessary. The outer surface of the fibreglass models were then sanded smooth prior to installation of pressure taps on both inner and outer surface of the model.

The supports for the cones consisted of 3.5mm diameter wires and attached to the perimeter edge.

Building blocks were simulated using styrofoam and the central ring beam cap was made up of fibreglass resin and hemispherical in shape.

5.0 Pressure Test Procedure

The aim was to develop a series of pressure coefficient diagrams which could be readily available for use by designers and in accordance with AS1170.2 1989.

Two distinct pressure measuring techniques were carried for each configuration and are as follows:

(a) spatial/pneumatic averaging (patch averaging), and
(b) discrete pressure tap measurements.

For rigorous structural analysis, the conical surface would be divided up into a finite element mesh similar to Figure 4 involving a series of fabric panels which are bounded either by cables or edge supports. Often the designers/analysts are more interested in the average pressure acting on a panel section rather than the peak pressure distribution over the surface. This further simplifies the wind tunnel testing and analysis procedure and provide an accurate assessment of the global fabric stresses, boundary cable forces and support reactions.

5.1 Patch Averaged Pressure Tap Measurements

The technique of spatial or pneumatic averaging of pressures on wind tunnel models is a well established technique used to estimate pressure values representative of specific areas on the surface of a structure.

Referencing to wind tunnel studies conducted on past fabric structures projects, it was decided to divide each quadrant of the surface into four equal area pressure tap zones. This provides an independent patch zone adjacent to each support boundary and 45 degrees ridge line. This also provides separate pressure at the base of the cone where the fabric is near horizontal as opposed to the central ring beam where the membrane is near vertical.

Each patch consisted of manifolded pressure taps on the outer and inner surfaces. Within each patch, there are 7 brass tubing pressure taps (0.8mm internal diameter) flush mounted in the location as shown diagrammatically. [Figure 5(a)]

Each tap on a patch meets at a manifold consisting of a capped plastic tube section epoxied onto the inner surface of the model near the centre of the patch. This manifold is further connected to a pressure tubing to obtain spatially averaged pressures.

As the models were only instrumented on one quadrant only and thus a combination of data from each azimuth (i.e. at every 22.5 degree rotation) was required to provide results on the wind distribution.

Two main wind directions have been analysed in detail, i.e. wind normal (0 degree rotation) and at 45 degree rotation. Since data were accumulated at 22.5 degree movements, the variation in the direction of the approaching wind can be accounted for by considering the extreme value obtained at ± 22.5 degrees. For example, the normal wind (0 degree) will account for values within the range of 337.5 degrees, 0 degrees and 22.5 degrees rotation.

5.2 Discrete Pressure Tap Measurements

The second quadrant that was to be instrumented consisted of 47 taps installed on the outer surface and a similar number on the inner surface. The taps consisted of 0.8mm (internal diameter) brass tubings approximately 20mm long bent at 90 degree and filed flush with the model surface. The taps were connected to 1.6mm (internal diameter) plastic tubing and bunched up together directly underneath the central ring beam. The tap locations are as shown diagrammatically. [Figure 5(b)] The inner surface of the mould was further coated with fibreglass resin and chopped mat to obtain a consistent inner surface.

5.3 Wind Simulation

The VIPAC Boundary Layer Wind Tunnel (BLWT) measures 14.9 metres in length, 2 metres in height and 2 metres in width. This tunnel normally simulates wind at 1:200 and 1:400 scales. In order to simulate a Terrain Category 2 wind for a 1:50 scale model, a modified technique suggested by Holmes (Ref 3) was adopted.

6.0 Discussion of Spatially Averaged Results

Eight models were tested with the varying configurations as discussed. The peak positive and negative pressures for the two main wind directions (0 degrees and 45 degrees) were measured and tabulated for Tent 1 to Tent 8.

As an example, Figure 6 shows the peak positive and negative pressure coefficients for Tent 1 and Tent 2. All coefficients relate to the design mean hourly wind speed as defined in Clause 4.2.2 of AS1170.2 1989 referenced to the height of the central ring beam from ground level.

All pressure values are net pressures acting across the fabric surface. The sign convention acting across the fabric surface is positive pressure acting inwards from the outer to inner surface, whilst the negative pressures act outwards (suction).

From the experimental data obtained, several observations are worth noting. Large pressure variations were found over the surfaces of all tent configurations. The highest positive pressures were found in the zones along the upwind edge and sides of a cone. The worst suctions were found in the zones to the side and immediate lee of the central ring beam. Increasing the height of the cone produced higher pressures in the zones immediately in front of the central ring beam. The addition of the ring beam cap and the increase in the column supports did not have a significant effect on the pressures on both the low and high curvature cones. However building blockages under the models changed the surface pressure significantly. Lower peak pressures and higher suctions were found in the zones along the upwind edge of the tents and higher pressures occurred on the zones immediately in front of the central ring beam. This is because the building blockage restricts airflow under the cone, directly resulting in stronger flow separation from the leading edge and subsequent reattachment higher up on the surface. The building blockage also resulted in slightly reduced suctions in the zones to the side and immediate lee of the central ring beam.

It should also be noted that due to the minor model inaccuracies and minor variations of the experimental data extraction procedure, the coefficients are not truly symmetrical. (Figure 6) This applies typically for wind tunnel testing and the actual test results have been presented to give designers an indication of the accuracy and allow them to select the worst case.

7.0 Discussions on Discrete Pressure Results

Due to the constraints of time and equipment, the recordings of instantaneous pressure across the tent surface were not measured but the results are based on a very conservative upper and lower limit approximation. The peak positive pressure for the upper tap was combined with the peak negative pressure of the lower tap to provide the peak net inward acting pressures at a particular point. The above pressures do not necessarily act instantaneously and hence provide an upper bound limit.

The results of the discrete peak pressure measurements are presented in contour form, an example of which is shown for **Tent 1** on Figure 7.

Comparison between Figure 6 and Figure 7 for **Tent 1** configuration, there is a significant difference between the contour plots with the patch averaged values especially in the windward edge region.

The contour plots indicate that the local peak positive pressures along the windward edges of the tents can be much higher than corresponding patch averaged values. Similarly, local suctions in the lee of the central ring beam are generally more severe than the corresponding patch averaged values. The relative effects of building blockages, central ring beam caps and column heights on the net pressures noted earlier are also shown in the corresponding pressure distribution contours. Again it should be noted that the net pressure values on these contours are conservative, but they do point out pressure hot spots which may be important factors in fabric design and attachment considerations.

8.0 Experimental Conclusions

This paper has described a series of wind tunnel test on rigid fibreglass models of simple conical forms (namely a low and high curvature shaped cone). Typical pressure diagrams are presented which have been extracted from a more a comprehensive report by VIPAC Pty Ltd (Ref.2) which will be made available to MSAA members shortly.

The relative effect of the cone height, building blockage, central ring beam and support column height on the net surface pressures have been investigated. Of these variables, the presence of building blockage has the greatest effect on the surface pressures.

9.0 Acknowledgements

The paper would not have been possible without the valuable contribution and assistance of the following individuals:

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- Dr John Howell, ETRS (formerly of VIPAC)
- Mr Ron Dutton, VIPAC
- Dr Saman Fernando, VIPAC
- Dr John Holmes, CSIRO
- Mr Malcolm Barr, CONNELL WAGNER

Special thanks also to all involved in the model making and research.

10.0 References

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APPENDICES

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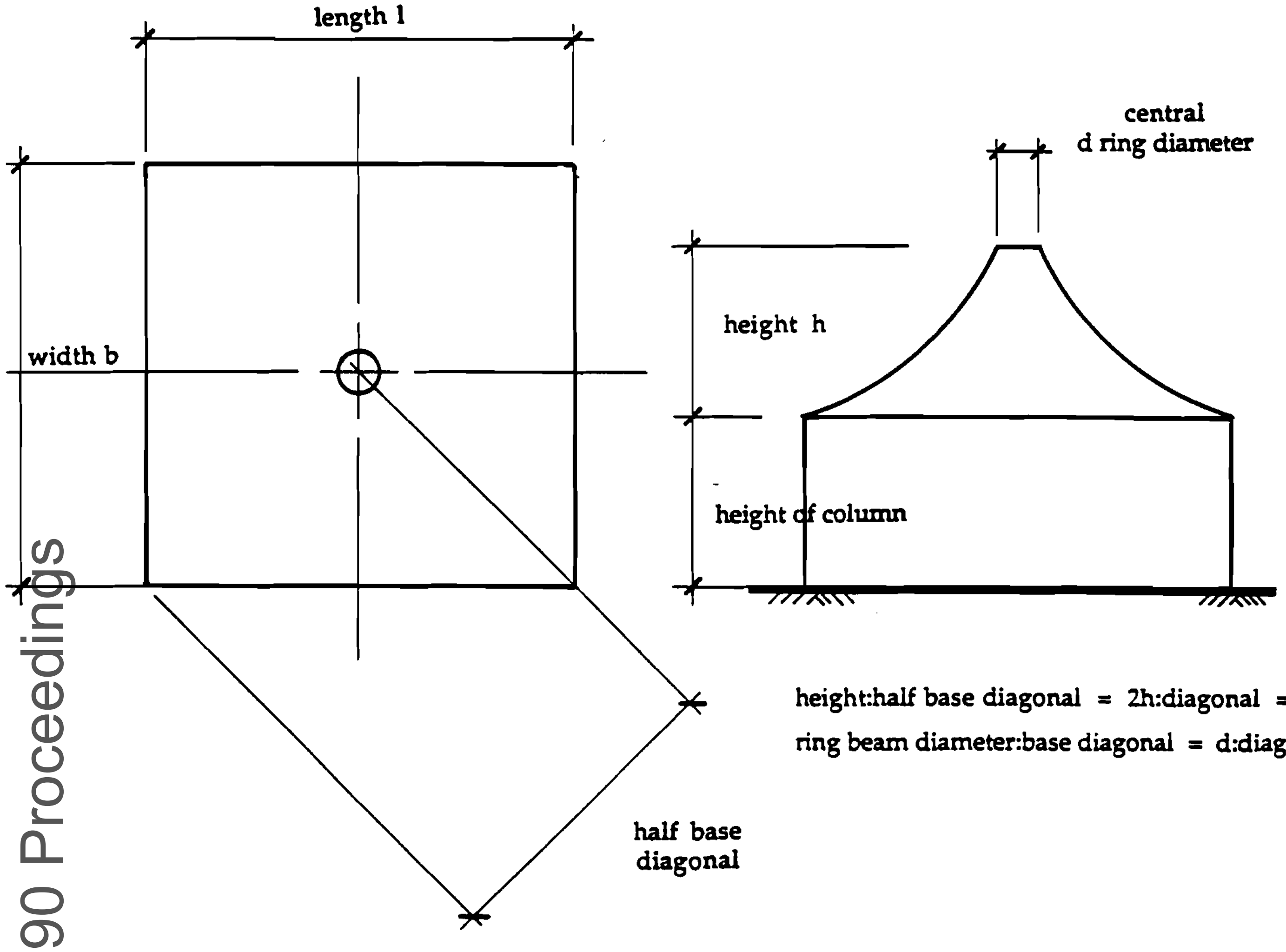
Figure 1 **Cone Geometry Variables**



height:half base diagonal = 2h:diagonal = c

ring beam diameter:base diagonal = d:diagonal =

Figure 2 **Curvature Relationship for Cone Geometry**

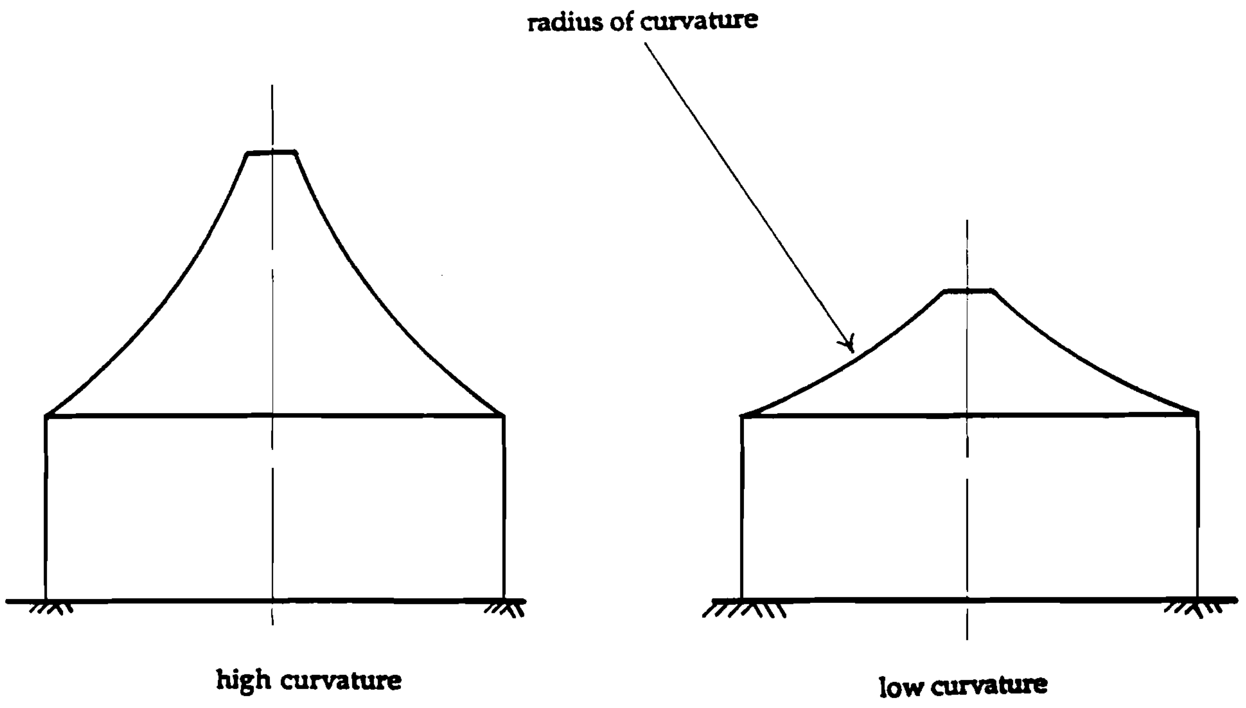


Figure 3 Model configuration of Tent 1 to Tent 8

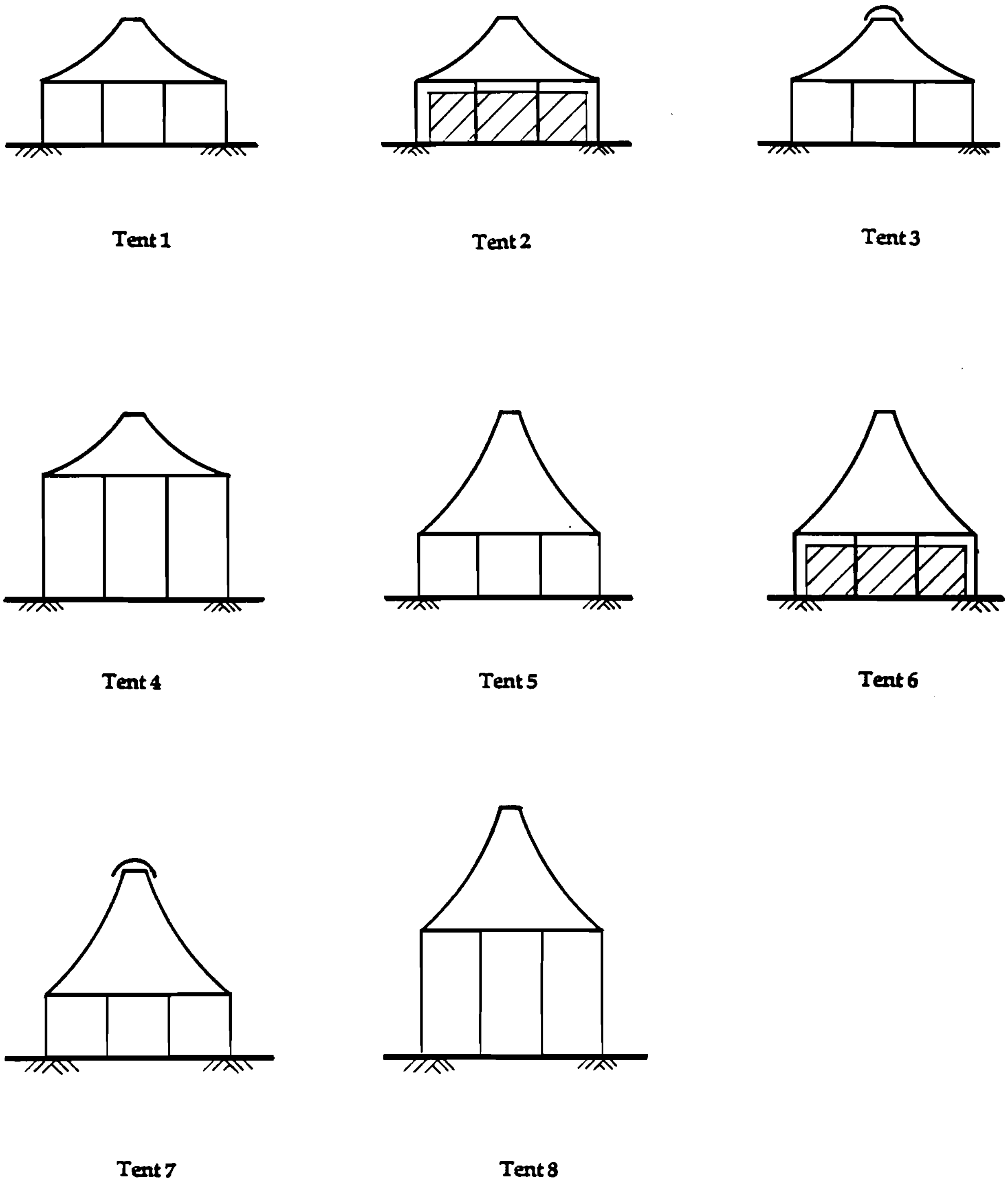


Figure 4 Formfinding membrane elements of typical conical forms

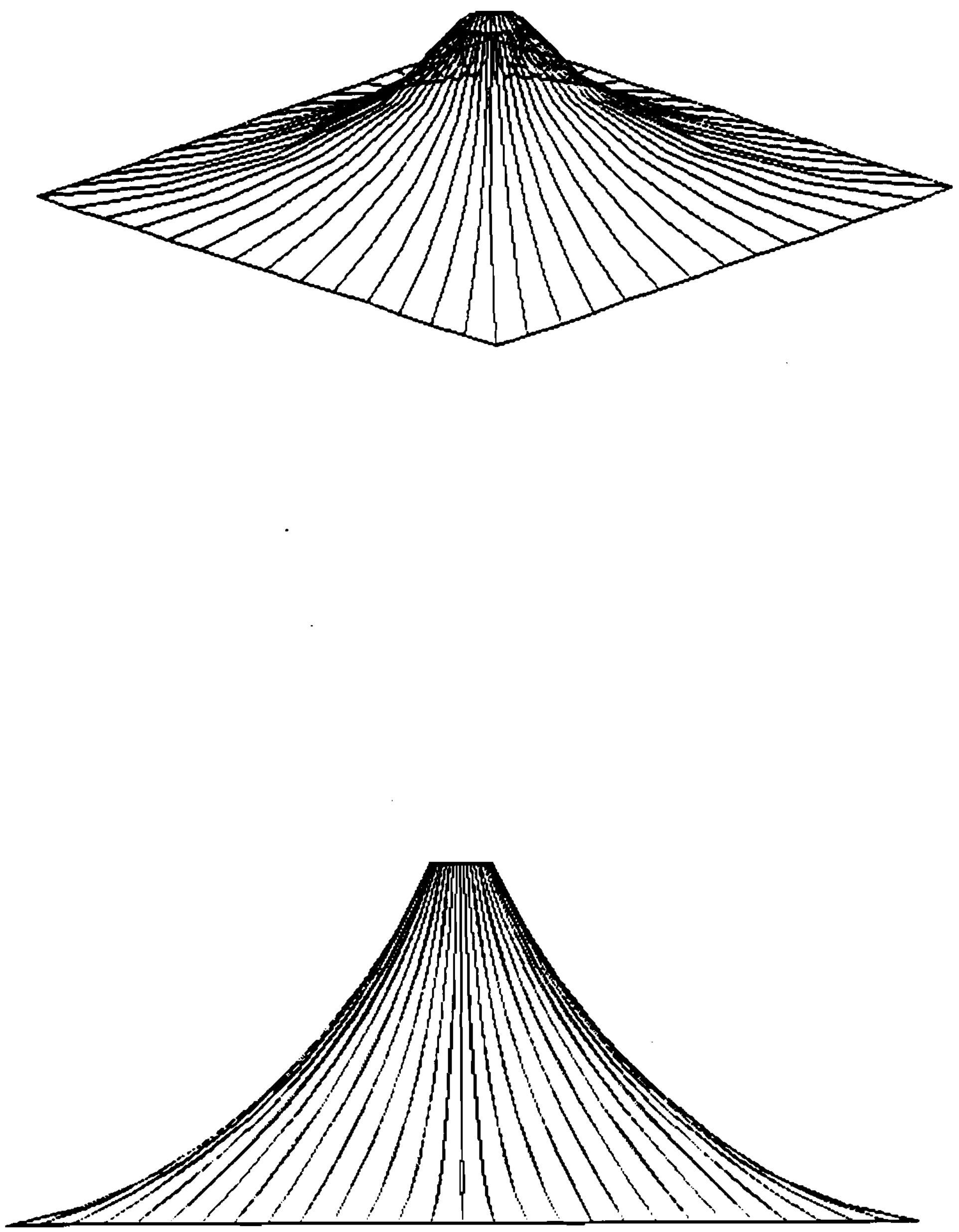


Figure 5(a) Pressure tap location for patch averaging technique

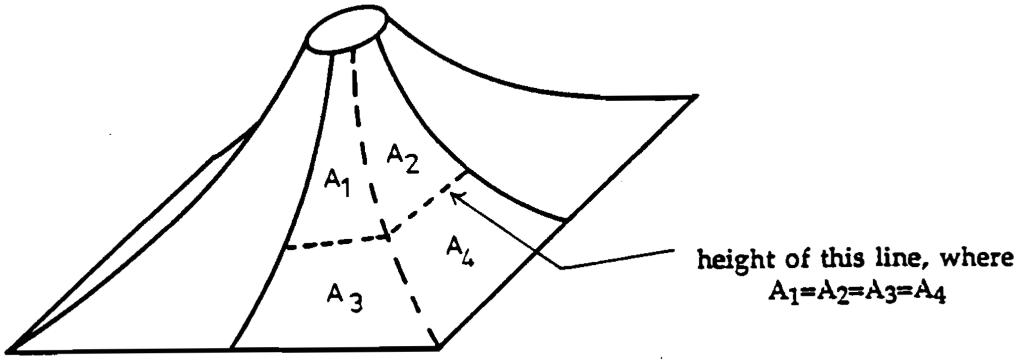


Figure 5(b) Pressure tap location for discrete pressure technique

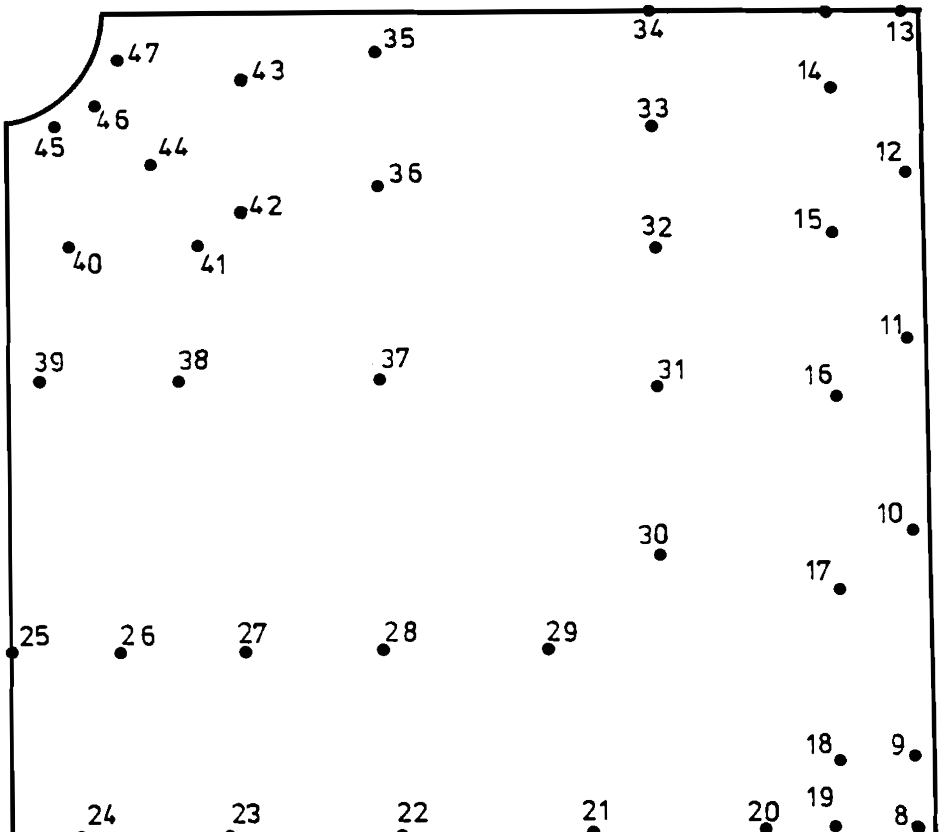
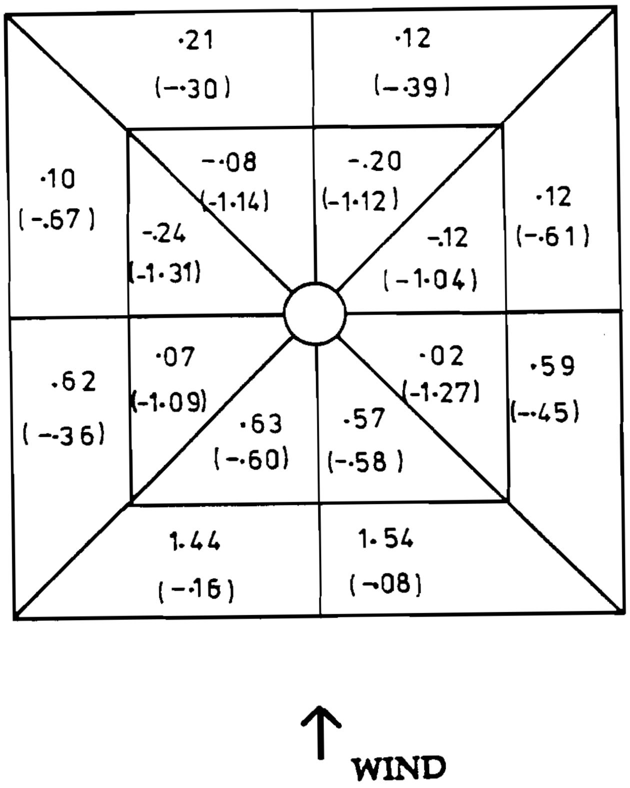


Figure 6 Peak pressure coefficients of patch averaged technique for Tent 1 and Tent 2

Tent 1



Tent 2

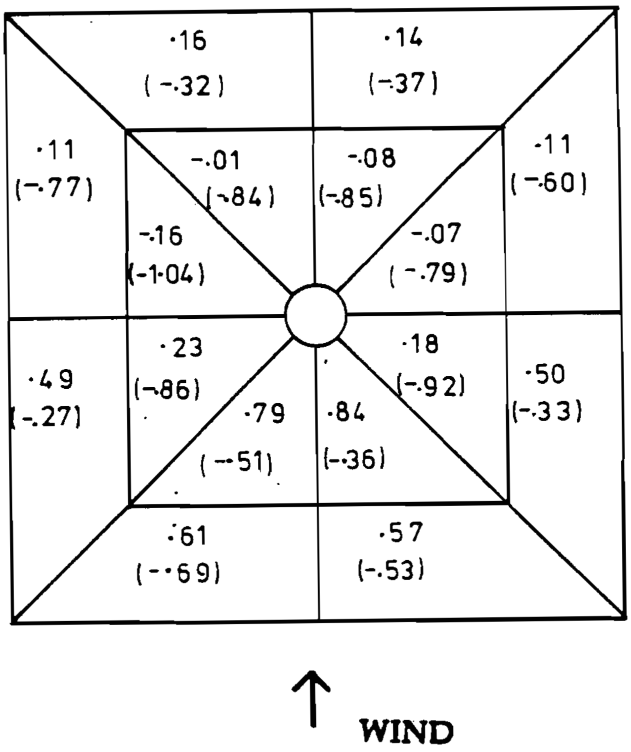


Figure 7 **Contour peak positive pressure distribution for Tent 1 from discrete tap measurements**