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MOBILE STAGE FOR OPEN-AIR PERFORMANCES, SYDNEY, N.S.W.

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## MOBILE STAGE FOR OPEN-AIR PERFORMANCES, SYDNEY, NSW

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### Summary

Design, Analysis and Construction of the "Mobile Stage", a large, demountable prestressed tent structure commissioned by the NSW Government is described.

Covering an area of 815 m<sup>2</sup> the membrane canopy provides shelter for performers during outdoor events such as concerts, theatre, opera and ballet.

### Introduction

Since January 1984, the public of New South Wales has been provided with a new demountable stage covered by a large, sand coloured prestressed tension membrane. The building is a further addition to facilities provided for cultural activities and forms part of an ambitious cultural expansion programme currently pursued by the NSW Government under Premier Neville Wran. The new "Mobile Stage" was first erected in the historic Domain Park, close to the City Centre, for the now well established and popular annual "Opera in the Park" performances and forming one of the main events of the Festival of Sydney.

Held during the Australian summer in January the festival, first introduced in 1978, encompasses a variety of cultural events and social entertainment for a wide range of age groups and, annually, attracts large numbers of visitors and resident Sydneysiders alike.

### Design

The design/construct tender called for a roof canopy which would give protection to performers and equipment underneath against sun and rain while completely covering stage and overhead lighting structure.

The audience's view of the stage should not be obstructed and the building should have an attractive appearance.

Structurally, it was to be designed for high windloads, while being readily demountable. Its components were to be readily stacked, transported and erected.

The Client plans to establish several sites in and around Sydney, possibly exposed to onshore winds, where the structure will be used for outdoor events such as concerts, theatre, ballet etc.

It was further specified, that the overall scheme was to be composed of 3 separate components:

A Stage (18.5x12m with 2.5m side-extensions), an Overhead Lighting Structure (18.7x12,7m and 11m high, above the stage), and the Roof canopy.

The components were to be designed as individual units in order to allow for anticipated flexibility in the choice of components for different events.

The design of the canopy was based on the above brief in the following order of priority :

1. Cover the Overhead Structure as efficiently as possible integrating all user requirements with regard to protection and sightlines.
2. Design a structurally stable membrane surface in order to cater for high windloading involving adequate curvatures while minimising the number of supports and anchorages in order to reduce installation time.
3. Design the membrane shape to be visually attractive and aesthetically pleasing resulting in a building which, through its unique appearance would enhance the environmental setting it was to be placed in and provide the organisers and sponsors of events with an attractive feature to maximise on spectator participation.
4. While maintaining all the above, keep the structure as light as possible and its components simple in order to facilitate transport, storage and erection.

Soon after design commenced it became clear that some of the tender requirements were contradictory and compromises had to be made in order to obtain a product that would satisfy the requirements as closely as possible.

The contradictions were :

Lightness against Size

Lightness against Structural Loading Requirements

Size resulted from the fact that the shape of the canopy had to be designed to accommodate the 11m high steel frame of the overhead lighting structure while allowing for adequate clearances in anticipation of large deflections of the membrane under high windloads. (Integration of canopy and lighting structure by suspending a rigid steel lighting grid from four, internal masts was suggested in order to alleviate the problem but was not permitted)

The structural loading requirement which specified Category 2 wind loading in accordance with Australian Standard 1170, Part 2 was high and resulted in weight penalties for masts, cables, anchorages and fittings thereby making speedy handling and erection more difficult to achieve.

The design developed from these parameters was an anticlastically shaped membrane surface, supported by an internal, diagonal cable system, composed of two intersecting main cables which are supported by four internal masts (Fig.1). A central "flying strut" at the intersection of these cables - connecting the four masttops - was used to maintain membrane curvature in this area. The membrane is tensioned by the perimeter edge cables over the main support cables which include the diagonal corner cables to ground anchors. - Resulting overall dimensions were 35.9x26.1m, 13.7m internal height at the centre, 19.5m front mast height and 16.9m rear mast height.

Initially, an alternative design utilising an external cable and mast support system to suspend a membrane surface at four high points was investigated, - point support from internal masts was also considered.

The internal cable support system was chosen because it enabled tighter control of deflections within the surface and flatter entrance curvatures at the high points (see Fig.2). It was therefore possible to minimise the overall surface area required for stage coverage to 815 m<sup>2</sup> by keeping the membrane surface closer to the overhead lighting frame (Fig.3) and to reduce overall mast heights as well as overall ground coverage. Due to maststays being integrated in the cable support system for the membrane - with the membrane surface itself providing lateral stability - reduction in the number of

perimeter anchorages was achieved.

Furthermore, by tilting the entire membrane surface back-wards, the necessary central height for the large, 42m long edge cable over the front of the stage and unobstructed sightlines could be achieved. The backward slope of the roofplane of the lighting frame allowed reduction of the overall height at the rear of the structure. (see Fig.).

During the various design stages the membrane roof was modelled from 1:200, 1:100 up to 1:25 until a satisfactory balance between design and structural requirements was achieved.

Wind tunnel tests were then carried out on a 1:100 model by John Howell at Vipac & Partner's laboratory in Melbourne and combined wind pressures were established for internal and external surfaces.

The shape of the membrane surface was optimised on the 1:100 design model after preliminary stress calculations based on experimental windloads were carried out and the geometry of the surface, initially obtained by measurement from the 1:100 design model by co-ordinate measurement of salient points along cable catenaries and principal curvatures, was checked against a minimum energy soap-film shape by computer. This shape generation process by computer was carried out on one half of the surface (axial symmetry) by isolating the half surface into three individual anticlastic surfaces bordered by common (internal) support cables and edge cables which were measured from the model. - While the common support cables between two adjacent surfaces were assumed to be rigid boundaries for the purpose of obtaining the soapfilm shape the edge cables were fixed in their length with their curvature left to adjust (see Fig.4).

The resulting shapes were then used to obtain developed cutting patterns employing a program developed by Dr. Peter Kneen at the University of NSW. The patterns, which had been compensated for expected fabric elongation obtained from information on biaxial stress/strain behaviour of the chosen material, - were then checked for fit by construction of a 1:25 scale model of one half of the structure and membrane connection details were finalised.

### Structural Design

The main loading on the structure is that from wind. The unusual shape is not adequately covered by the wind loading code and wind tunnel testing carried out on the scaled model had turbulence length scale matched to model scale and surface roughening applied to the skin to achieve Reynolds number scaling. Pressure tapping was automatically recorded to provide details of pressure coefficients with varying wind directions. The mean pressure coefficients for internal and external pressures were summed vectorially for calculation of nett pressure.

The variation of nett internal and external pressure coefficients with wind direction is shown in Figures 5 to 8. In all cases some areas of the canopy model were measured to have pressure coefficients greater than 2.0, and large areas had nett pressure coefficients of the order of 1.5. The wind forces act normal to the fabric surface at all points.

The average maximum free stream dynamic pressure (approximately 3 second gust) of 1.2 kPa was used with the pressure coefficients. This corresponds to Category 2 loading in the Sydney area with a 50 year return period.

The magnitude of these pressure coefficients together with the requirements for design to Category 2 wind loading resulted in forces considerably larger than those anticipated at the time of preparation of the original tender. The wind pressures thus estimated were applied as average values over appropriate areas of the membrane for calculation of membrane and cable forces by cable

theory and approximate calculations to ensure static equilibrium. Following assumptions of design loading on the membrane, the analysis was essentially an iterative and approximate process. Firstly, calculations were made as to the load path through the membrane by strip analysis and edge cable equilibrium. Then calculations were made for anchor forces to satisfy equilibrium and overturning. These forces were then taken back through the structure to find membrane stresses.

These steps are listed as follows:

1. Establish a range of membrane stress values by applying appropriate wind pressures on membrane strip profiles.
2. Calculation of edge cable forces to be in equilibrium with the average membrane stresses.
3. Static equilibrium checks in x,y and z directions to ensure stability of structure.
4. Estimation of main support cable forces from maximum membrane stresses.
5. Estimation of how the primary mast/cable system readjusted under load.

The canopy structure is designed to redistribute wind forces by moving into a position of equilibrium between edge cable tensions, the main diagonal cable tensions and mast compressions.

Essentially, any high membrane stresses tend to be shared throughout the structure by large deformations resulting in load shedding or redistribution. It can be seen that any increase in edge cable forces (and hence anchorage loads) is balanced by a combination of wind uplift and mast compression.

The main generation of the relatively high mast compressions found in the structure is the wind load on the steep corner areas of the membrane directly loading the main mast cables.

The estimated maximum fabric stress of 12.5 kN/m under Category 2 wind loading leaves a factor of safety of 6 on ultimate strength.

The cable sizes provided allow a factor of safety of 2.25 at Category 2 wind loading based on a UTS of 1770 MPa.

For installation, initial membrane prestress forces of 1.5kN/m were proposed to maintain the anticlastic shape wrinkle free in its 'unloaded' state.

#### **Membrane**

The material specified was a PVC coated polyester fabric, 2/2 (panama) weave construction, 900g/m<sup>2</sup> overall weight, colour sand, flameretarded to AS1530 and stabilised for high UV exposure. Initially the fabric was to be supplied by a local coater, unfortunately the base cloth could not be woven in time and the material had to be imported from overseas. The final material was "Duraskin B127235" by Verseldag Coated Fabrics of West Germany.

The material was joined by double row stitching with carbon black thread and overwelding (high frequency) with a protective, clear PVC strip (40mm seam). At stress points the membrane was reinforced. Tangential stressing reinforcement along edge cable pockets is provided by 75/5mm Polyester webbing sewn onto the underside of the fabric.

#### **Membrane connections and Fittings**

In order to permit ease of handling during fabrication and erection/- dismantling the membrane surface (total surface area 1340m<sup>2</sup>) was subdivided into four individual panels which were joined on site by aluminium plate clamping joints located alongside the ridges formed by main support cables. All support cables are carried in sleeves to restrict movement.

At the rosette points used to hold the upper areas of canopy around the masts, the membrane edges are bordered by cables which are clamped to four galvanised

steel clamping plates fastening the membrane corners and providing attachment for four support cables to the masttop.

Circular corner cut-outs terminate the membrane at the intersections of edge cables at the membrane perimeter, while the edge cables are continued to common galvanised steel clamping plates which provide connection to the anchorage cables. Three types of corner plates occur (Fig.9). Tangential stressing cables connect the webbing reinforcement which terminates at the membrane edge to corner plates.

#### **Cables**

The cable sizes provided for diagonal central support cables and edge cables were 26mm diameter and for the front edge cable, main corner cables and all anchorage cables were 36mm diameter. This allows for a factor of safety of 2.25 (based on a UTS of 1770 MPa) at maximum design wind loading.

In order to allow sleeving of edge cables with relative ease during erection and dismantling and to provide effective length adjustment with available fittings a cable clamping joint was introduced at cable ends in the vicinity of each corner plate. It utilises two galvanised steel "double base grips" fastened by eight high tensile bolts each and spaced apart to interconnect the edge cable to a short cable section attached to the corner fitting. This economical connection was developed after consideration of alternatives such as large turnbuckles and high strength U bolts and was satisfactorily load tested to full design loads.

#### **Masts**

Design compression loads of 60 t for the front masts and 50 t for the rear masts were established including an allowance for possible future suspension of a lighting grid from the masts. The masts are galvanised mild steel built up struts from three circular hollow tube sections (140 x 4,9 CHS) battened apart and spliced for transport and storage (Fig.10). Mastfootings are bored piers and the base plate has universal joint action to allow unrestricted mast movement during wind loading to allow stress redistribution in cables and membrane. Ladder rungs were added to D.L.I. (Department of Labour and Industry) requirements.

#### **Anchorage**

Grouted high yield "Tempcore" reinforcing bars into bedrock were used for all ground anchors. The anchors are similar to large, 10m long split pins with a 100 mm dia. loop above ground grouted into a 120mm dia. hole drilled at the angle of the anchorage cable. Maximum design load was 240 kN for Category 3 loading in the Domain.

Anchorage cables are connected to the anchors via twin galvanised steel anchorage plates which provide for incremental adjustment during stressing and allow for limited variations in ground levels between different sites.

#### **Erection**

Once the anchor and mast positions were confirmed and constructed, the masts were erected by crane and stabilised by temporary guying cables to temporary peg anchors. The membrane was unfolded, interconnected, cables were drawn through sleeves and all fittings were attached. Connected at the four high points to pulley and lifting cables trolley-hand winches were used to simultaneously lift the membrane into position. Stressing was introduced through perimeter anchorage cables with adjustments made at tangential stressing cables and rosette support cables. The structure was dismantled after 2 months with geometry spot-checks made to be re-erected on the same site later in the year. At this occasion it is proposed to make final adjustments to the membrane shape to eliminate minor wrinkling and to obtain stress measurements on the anchorages.

Client: New South Wales Premiers Department, Division of  
Cultural Affairs (project administered by the Public  
Works Department, Special Projects Section)

Designer: Surface & Spatial Structures  
(Vinzenc Sedlak Pty.Ltd.)

Engineer: George Clark & Associates

Specialist Consultants: Peter Kneen Pty.Ltd.(Cutting Pattern)  
Unisearch Ltd.(Model construction and testing)  
Vipac & Partners (Windtunnel tests)  
Stromeyer Ingenieurbau GmbH (Detailing and erection  
check)

Fabricator/Contractor: B.W. Billsborough & Sons Pty.Ltd.

Material Supplier: Rheem Ltd., Woven Products Group for Verseldag, Krefeld

Cable and Fittings: Bullivants Pty.Ltd.(NSW)

Steel work: Simonsen & Edwards Pty.Ltd.

Main Contractor: Brakeil Products Pty.Ltd.



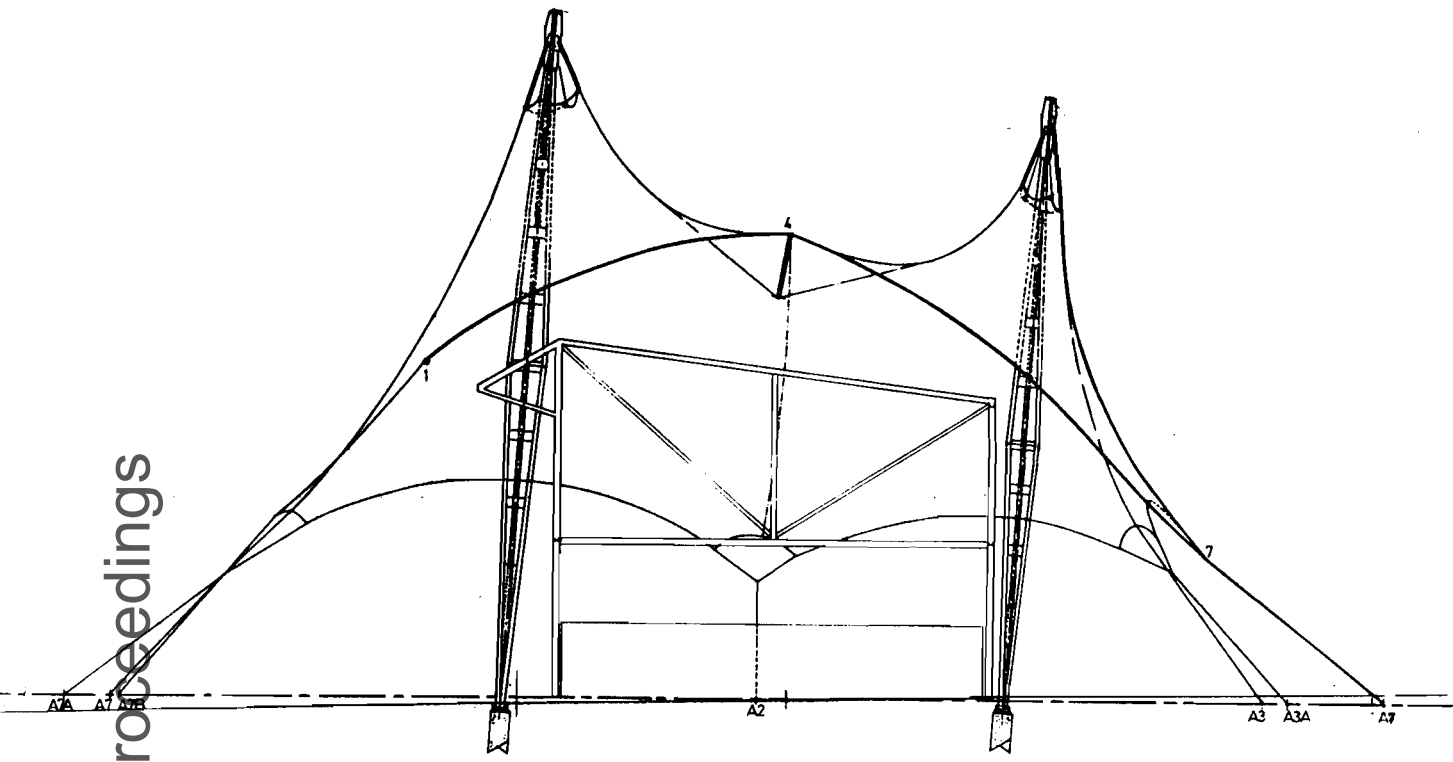
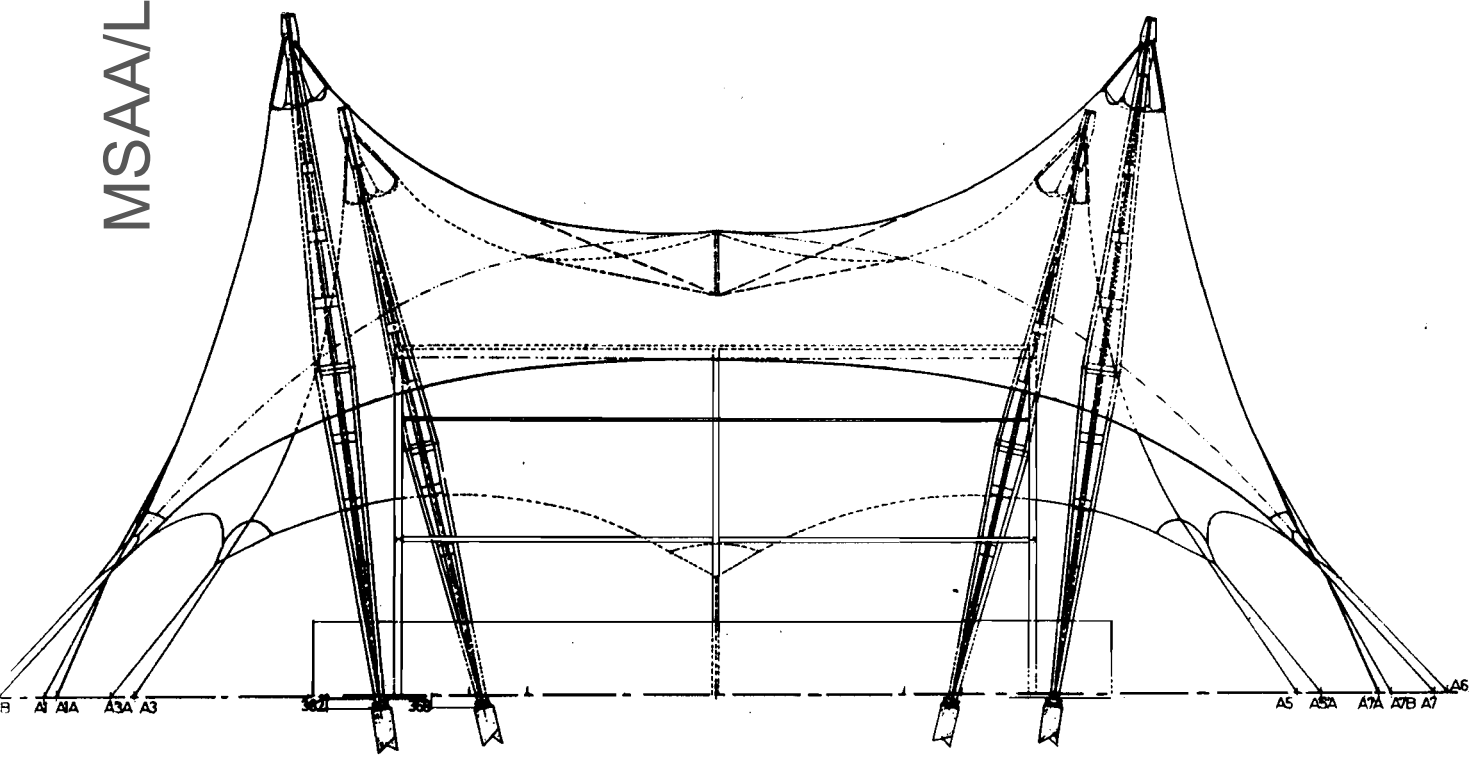
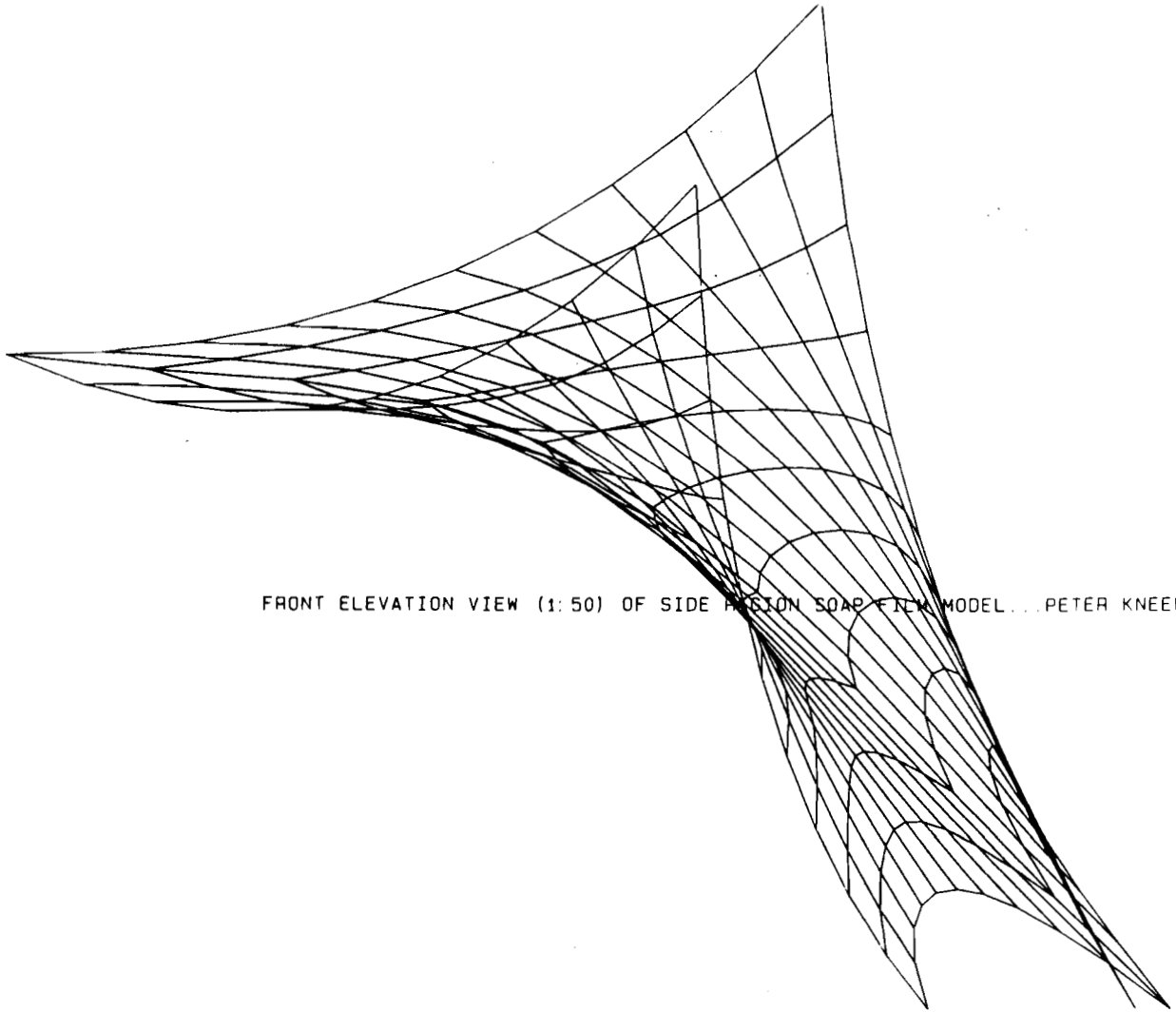


Fig. 3 Section and side elevation.

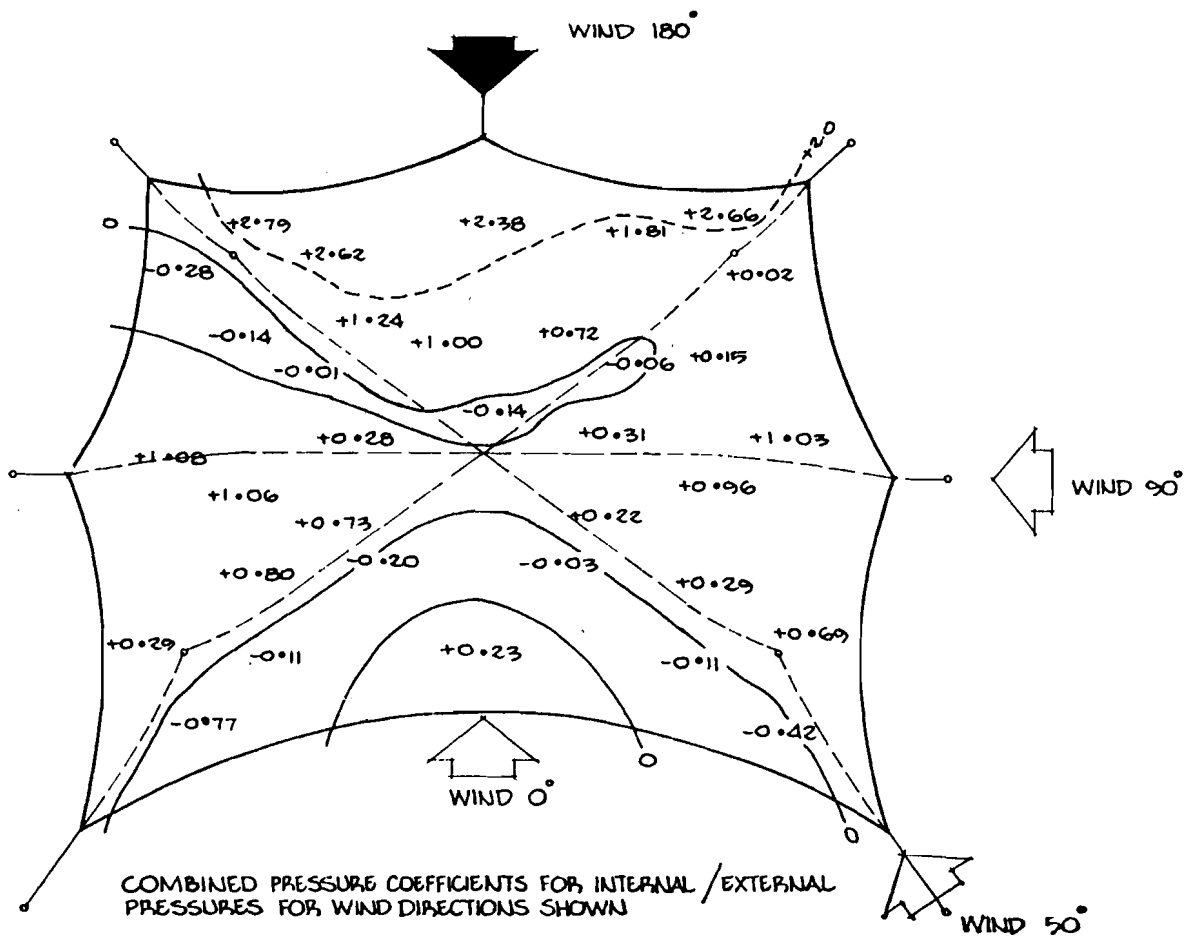
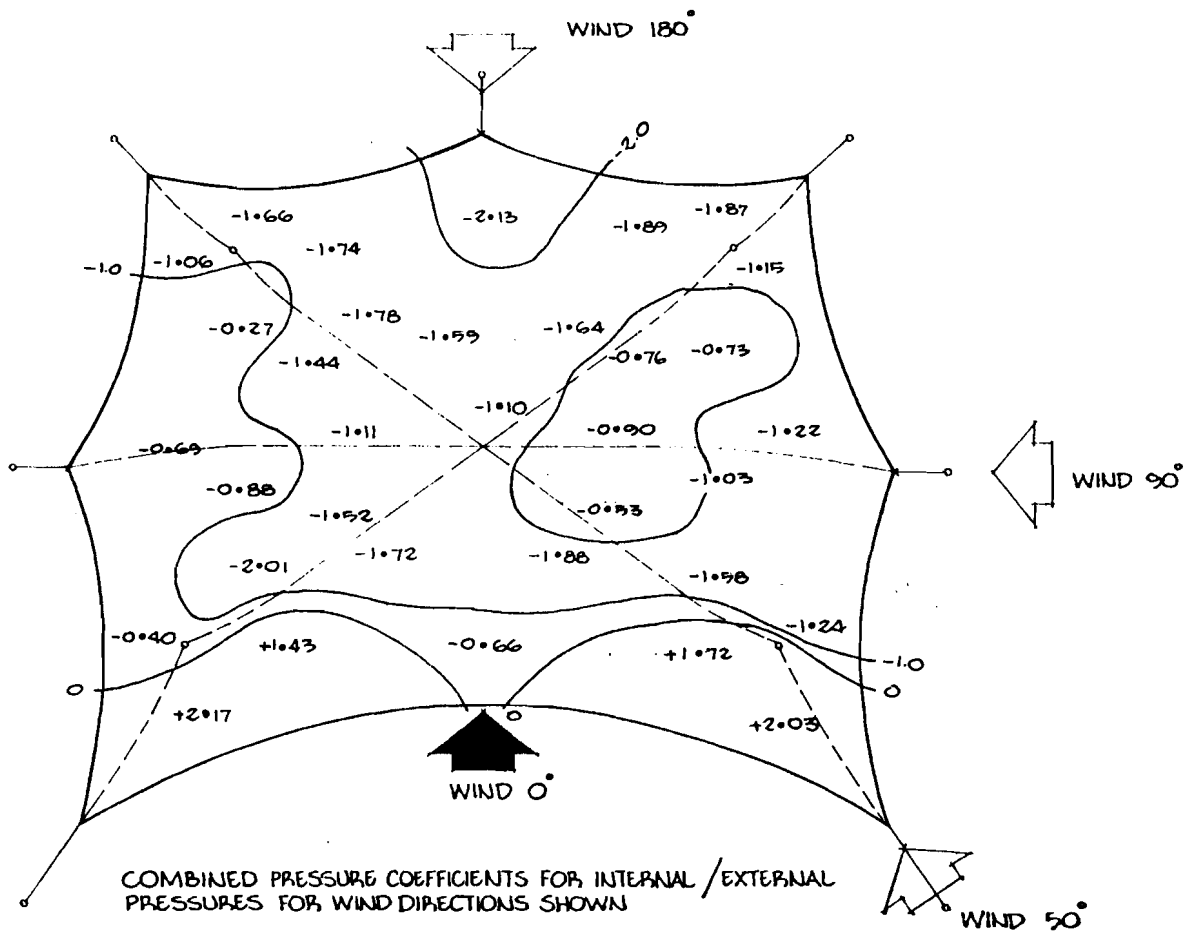
Fig. 2 Front elevation showing overhead lighting structure.

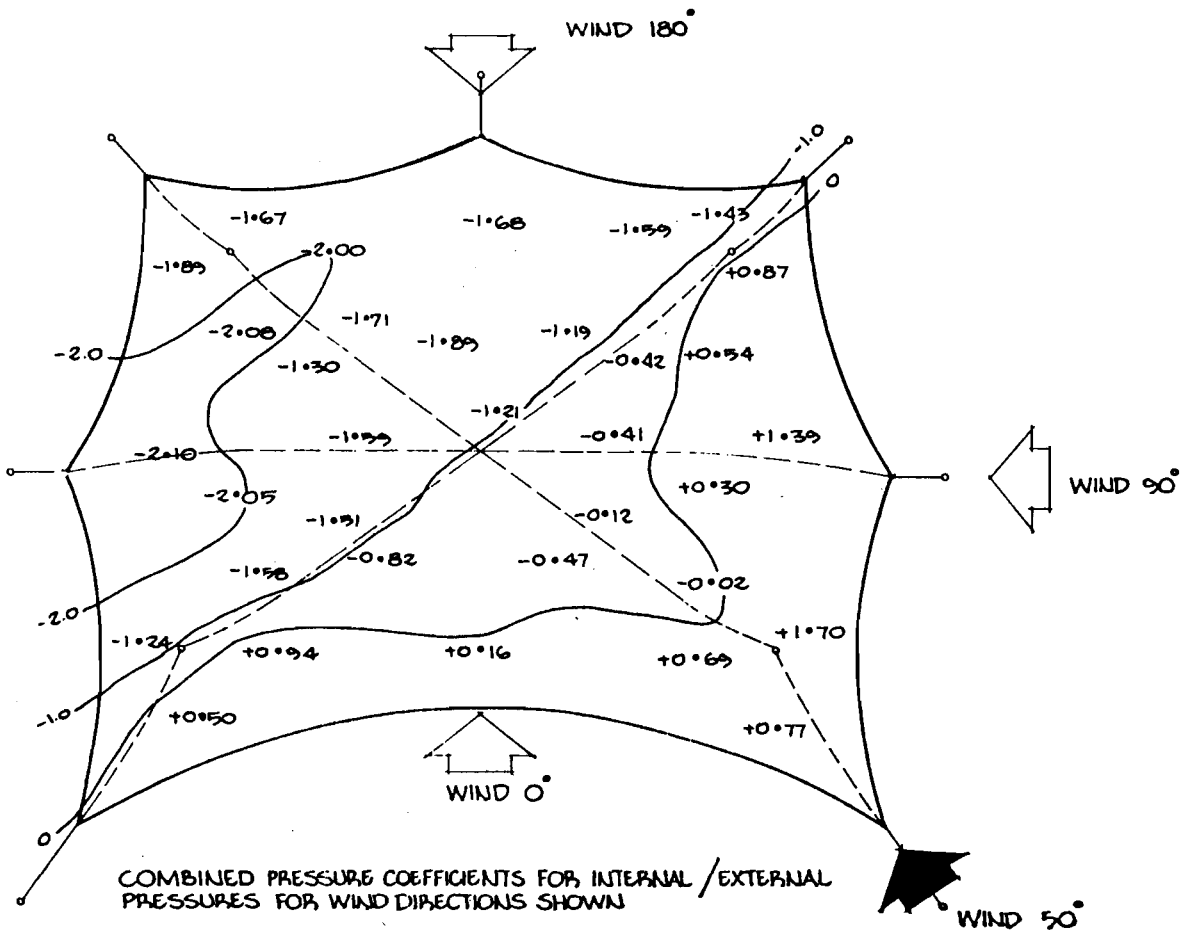
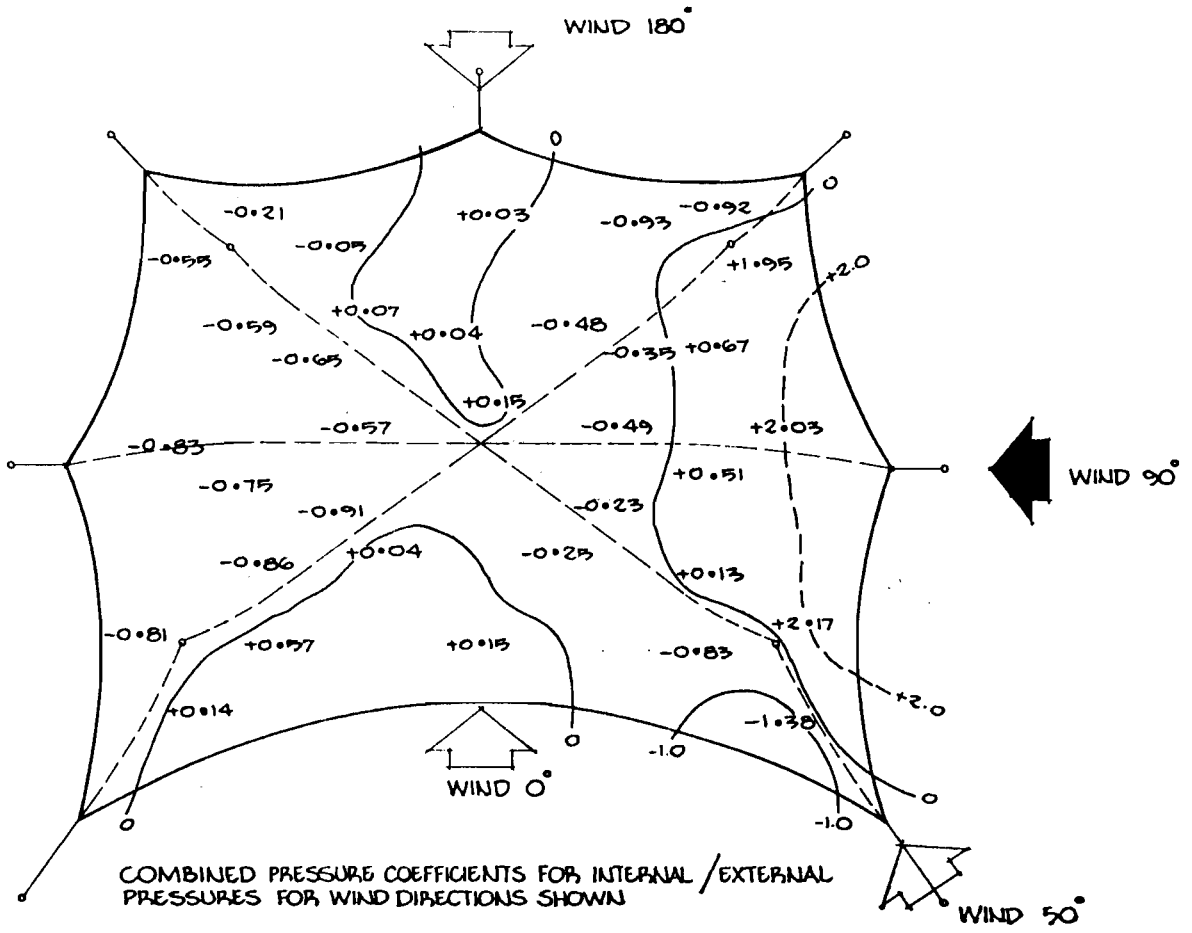




FRONT ELEVATION VIEW (1: 50) OF SIDE PANEL SOAP FILM MODEL...PETER KNEEN P/L

Fig. 4 Soap film shape of side panel (P. Kneen).





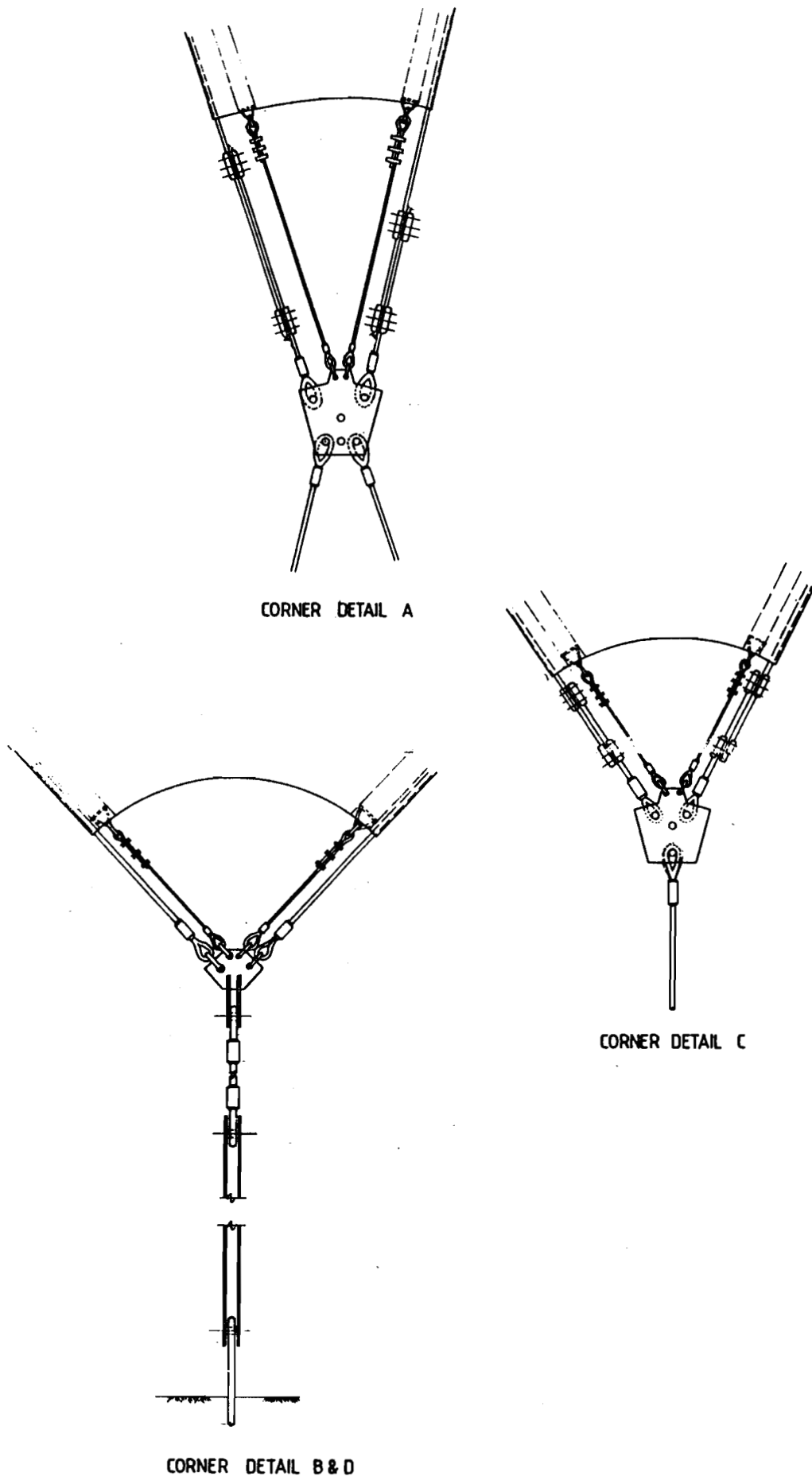


Fig. 9 Corner detail showing edge cable/membrane, tangential stressing arrangement and corner plate.

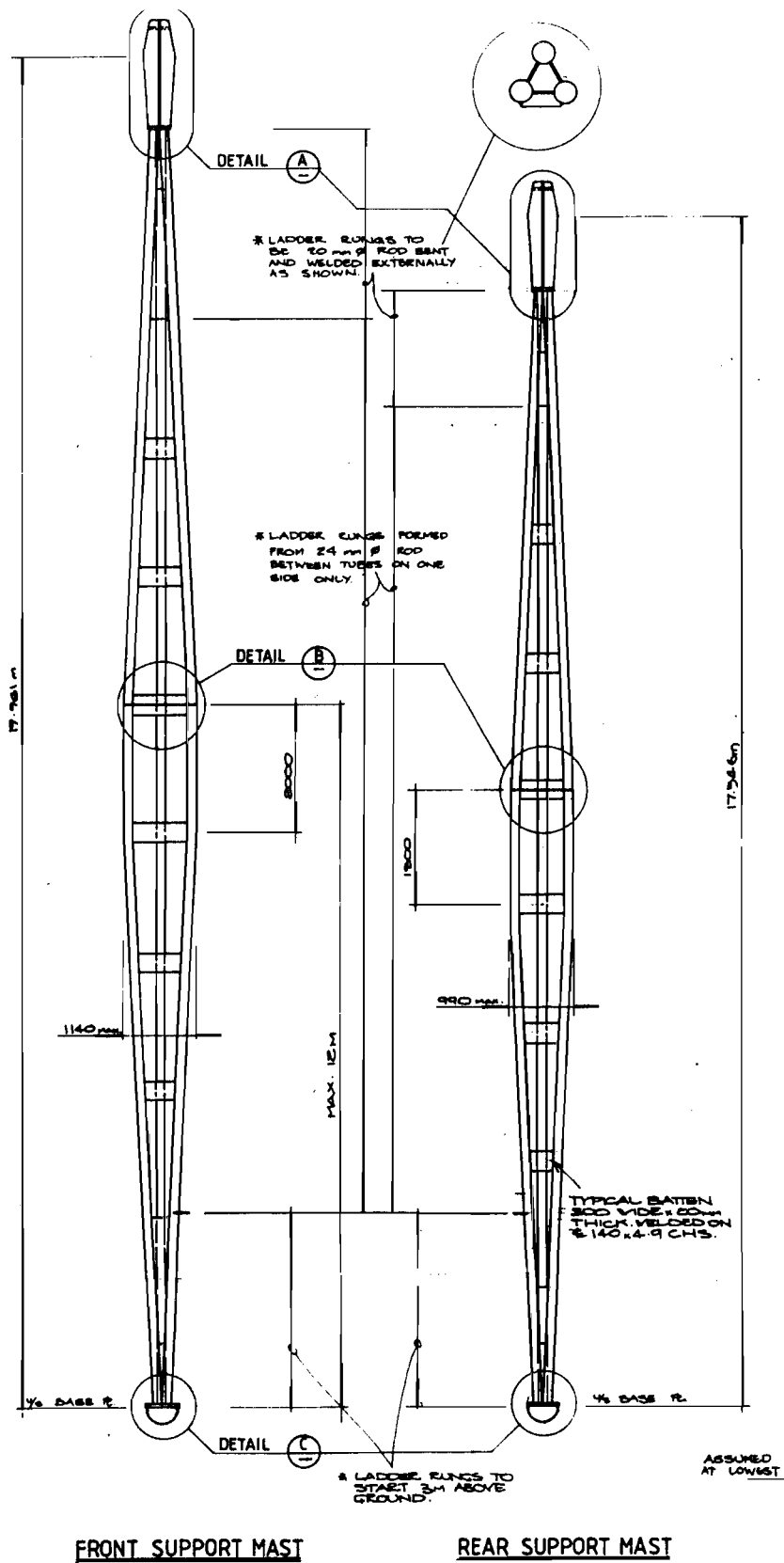


Fig. 10 Masts showing masthead and base