The University of New South Wales

MEMBRANE STRUCTURES:

DESIGN, ANALYSIS AND CONSTRUCTION

THE FIRST AUSTRALIAN SEMINAR
ON MEMBRANE STRUCTURES
HELD AT THE
JOHN CLARKE DEBATING GALLERY
STAGE 3, UNIVERSITY UNION
UNIVERSITY OF NEW SOUTH WALES

3 SEPTEMBER - 5 SEPTEMBER 1981

LSRU THE LIGHTWEIGHT STRUCTURES RESEARCH UNIT

GRADUATE SCHOOL OF THE BUILT ENVIRONMENT,
FACULTY OF ARCHITECTURE

DAY 1 : THURSDAY 3rd September 1981

APPLICATION AND CONSTRUCTION:

0830 Registration, John Clarke Debating Gallery,
Stage 3, University of New South Wales Union,

0930 OPENING OF THE SEMINAR
Professor Eric Daniels, Head, School of Architecture,
The University of New South Wales

1000 THE ROLE OF MEMBRANE STRUCTURES IN AUSTRALIA

Vinzenz Sedlak,
Lightweight Structures Research Unit (LSRU),
Graduate School of the Built Environment,
The University of New South Wales

1045 Tea

1115 MEMBRANE STRUCTURES FOR ENERGY AND INDUSTRY

Jurgen Hennicke,
Institute for Lightweight Surface Structures,
University of Stuttgart (IL) and
Architects and Engineers Co-operative (AIC),
Stuttgart, West Germany

1200 CONSTRUCTION ASPECTS OF RECENT MEMBRANE
STRUCTURES IN AUSTRALIA

Peter Kneen,
Department of Structural Engineering,
The University of New South Wales

David McCready,
Geodome Spaceframes Pty. Ltd.,
Melbourne, Victoria

1245 Luncheon, Dining Room, Stage 3, University Union

1400 WORKSHOP DISCUSSION ON APPLICATION,
FABRICATION, MATERIALS AND CONSTRUCTION

Chairman: Jurgen Hennicke

Panel:
Bert Bilsborough, B W Bilsborough & Sons Pty. Ltd.
Bob Anderson, Geo. Pickers (Brisbane) Pty. Ltd.
Bernard Davis, McWilliam & Partners, Brisbane
Leslie Thorogood, Environmental Structures (Aust) Pty. Ltd.
Gordon Smith, B J O'Neill & Associates, Melbourne
Bob Barrow, Geodome Spaceframes Pty. Ltd., Melbourne
David McCready, Geodome Spaceframes Pty. Ltd.
Peter Kneen, Dept. of Structural Engineering, UNSW
Robert Hutton, Nylex New Zealand
Vinzenz Sedlak, LSRU

PROJECT PRESENTATIONS BY:

1410	Bert Bilsborough,	B W Bilsborough & Sons Pty. Ltd., Sydney
1445	Bob Anderson, and	Geo. Pickers (Brisbane) Pty. Ltd.
	Bernard Davis,	McWilliams & Partners, Brisbane
1530	Tea	
1600	Leslie Thorogood,	Environmental Structures (Aust) Pty. Ltd., Sydney
	and Gordon Smith,	B J O'Neill & Associates, Melbourne
1630	Bob Barrow, David McCready	Geodome Spaceframes Pty. Ltd., Melbourne
	and Peter Kneen,	Dept. of Structural Engineering, UNSW
1700	DISCUSSION	
1800	Close	
1900	RECEPTION AT LSRU Architecture Laboratory, King Street, Randwick (next to Randwick Technical College) (Tel: 662 3765)	

PRESENTATION:

A CASE FOR AN EFFECTIVE RESEARCH AND INFORMATION CENTRE ON LIGHTWEIGHT STRUCTURES IN AUSTRALIA

Vinzenz Sedlak
Director, LSRU

Presentation of films and slides on Lightweight Structures by:

LSRU

Institute for Lightweight Structures,
University of Stuttgart

B W Bilsborough & Sons Pty. Ltd.

Geodome Spaceframes Pty. Ltd

Geo. Pickers (Brisbane) Pty. Ltd.

Nylex Corporation Ltd.

Birdair/Chemfab

Hoechst Australia Ltd.

Refreshments served.

DAY 2 : FRIDAY 4th September 1981

DESIGN AND ANALYSIS:

0900	FORMFINDING, PATTERNING AND DETAILING OF MEMBRANE STRUCTURES Jurgen Hennicke, IL, AIC, Stuttgart
1030	Tea
1100	SHAPE DETERMINATION AND ANALYSIS - A COMMENT Peter Kneen, Department of Structural Engineering, UNSW
1145	PHYSICAL MODELLING FOR LOADING AND PERFORMANCE EVALUATION OF MEMBRANE STRUCTURES John Howell, Vipac & Partners, Melbourne Former Lecturer, School of Architecture and Building Engineering, University of Bath, UK.
1245	Luncheon, Dining Room, 4th Floor
1400	COMPUTER-AIDED DESIGN AND ANALYSIS OF LIGHTWEIGHT STRUCTURES USING THE PAM-NL/LISA PROGRAMME PACKAGE Eberhard Haug, Engineering Systems International, Rungis-Silic, France
1530	Tea
1600	WORKSHOP - DISCUSSION ON DESIGN AND ANALYSIS Chairman: Eberhard Haug Panel: Bernard Davis, McWilliams & Partners Jurgen Hennicke, IL, AIC, Stuttgart John Howell, Vipac & Partners, Melbourne Peter Kneen, Dept. of Struct. Eng., UNSW Vinzenz Sedlak, LSRU Gordon Smith, B J O'Neill & Assoc., Melbourne
1800	Close

Change of Conference Room:
Private Dining Rooms, 1st Floor, Stage 3, University Union

DAY 3 : SATURDAY 5th September 1981

MATERIALS, PROJECT MANAGEMENT, ENVIRONMENTAL CONTROL, STANDARDS AND GUIDELINES:

0900	DEVELOPMENT OF A PVC-COATED POLYESTER FABRIC FOR AUSTRALIAN CONDITIONS Robert Hutton, Nylex New Zealand
0945	DISCUSSION
1000	ASPECTS OF CLIMATE CONTROL IN MEMBRANE STRUCTURES John Ballinger, SOLARCH, Solar Energy Research Unit Vinzenz Sedlak and Stuart C Smith, LSRU Graduate School of the Built Environment The University of New South Wales
1045	DISCUSSION
1100	Tea
1130	EXPERIENCES IN MANAGING CONSTRUCTION PROJECTS INVOLVING LIGHTWEIGHT MEMBRANE STRUCTURES Robert Barrow, Geodome Spaceframes Pty. Ltd., Melbourne, Victoria
1215	DISCUSSION
1230	Seminar Course Summary Vinzenz Sedlak
1300	Luncheon

1400 A CASE FOR CONSOLIDATION:
DESIGN AND PERFORMANCE CRITERIA
FOR MEMBRANE STRUCTURES

FORUM DISCUSSION

Chairman: Vinzenz Sedlak

Panel:
Bob Anderson, Geo. Pickers (Brisbane) Pty. Ltd.
Bert Bilsborough & Sons Pty. Ltd., Sydney
Bob Barrow, Geodome Spaceframes Pty. Ltd., Melbourne
Bernard Davis, McWilliam & Partners, Brisbane
Serge Fijac, Department of Services
Eberhard Haug, ESI, Rungis-Silic, France
Jurgen Hennicke, IL, AIC, Stuttgart
Robert Hutton, Nylex New Zealand
Peter Luzinat, Fire Safety Advisory Committee, Building Regulations Committee of Victoria, Local Government Department
Gordon Smith, B J O'Neill & Assoc., Melbourne
Peter Kneen, Dept. of Structural Engineering, UNSW

TOPICS: MATERIALS, DESIGN AND ANALYSIS, FABRICATION, ASSEMBLY AND MAINTENANCE, SAFETY

1700 Close and Tea

DISPLAY

A membrane structures and materials display is mounted in the Conference Foyer.

MEMBRANE STRUCTURES FOR ENERGY AND INDUSTRY

Jürgen Hennicke
Institute for Lightweight Structures, University of Stuttgart

Synopsis / Abstract

The possibilities of application and utilization of membrane structures of all types are exceptionally wide and of a great variety. That for what we are using them already today, is in all probability only a small share of that for what we could use them. Above all, this is true for tents and cable nets. In case of pneus obviously the palette of applications hitherto existing is already larger. But anyway, it seems to be for sure that the possible avenues are not explored at all - as permanent, temporary or convertible buildings, individually planned or serially mass produced, for sale, for rent or for leasing.
In the light of a number of selected examples the spectrum of possibilities will be shown. Thereby the fields of energy and industry are to be consciously taken very wide-ranging to make recognizable the outlines of the total scope of applications.
In the examples not only executed buildings will be presented. An emphasis will be on ideas for some particular possibilities and on specific proposals of use which partly are in research, in model investigation or in full scale testing already.
Prestressed membrane and net buildings: e.g. shade roofs, large size halls for offices, building in winter, harbours, universities, department stores, exhibitions, sports grounds, aviaries, airports and multi-purpose use, dismontable and transportable unit structures, cooling towers, wind energy structures, upwind power stations, solar energy structures, climate control facilities, under water structures, noise and emission protection, storage dams, acoustic insets, interior walls, and others.
Pneumatic buildings: e.g., large size halls for antennas, storage facilities, green houses, sports grounds, exhibitions, building in winter, research laboratories and multi-purpose use, high pressure tube structures, multi-storey structures, city envelopes, tube bridges, canal barriers, high water emergency dams, weir gates, groynes, dirt water and oil barrages, pipe lines, breakwaters, air ships, advertising facilities, tanks and containers for gases, liquids and bulk materials of all kinds, embankment and storage dams, lifting and floating bags, protection coverings for construction, conversion and historical restoration, floating cities, wave power stations, form works for concrete and plastic structures, rescue equipment, lightning fixtures, and others.

CONSTRUCTIONAL AND DESIGN ASPECTS OF SOME RECENT MEMBRANE STRUCTURES IN AUSTRALIA

Peter Kneen
Senior Lecturer
Department of Structural Engineering,
University of New South Wales.

David McCready,
Geodome Spaceframes Australia Pty. Ltd.
Melbourne.

1.0 INTRODUCTION

This paper will examine some of the constructional and design considerations that can influence the development of a membrane structure solution in a given situation. It also discusses factors that were considered in the execution of a few recent membrane structures erected in Australia. It should however be noted that to date only a limited number of significant fabric membrane structures have been constructed from which to draw directly on local experience.

We are dealing with "lightweight" structures in which the self weight is extremely small both compared to conventional structures and also compared with the imposed external design loads. Whilst conventional systems generally have elements which transfer loads via flexure to supporting elements of compression or combined compression and bending less frequently tension elements are utilized, except perhaps for diagonal wind bracing and some suspended solutions. In membrane structures all the surfaces are preloaded in tension either directly by stressing or by deliberate internal pressure. These surface stresses must be counterbalanced by compression in supporting masts or concentrated into edge cables and hence to large anchorages. These anchorages are designed to resist primarily horizontal and vertical uplift forces. In some cases by continuous attachment to the foundation the self weight of a floor or ground slab may be sufficient anchorage.

Consequently, whilst the roof surface itself is lightweight, the footings and other supports may be substantial. Furthermore, for architectural structures of a semi permanent or permanent nature we will be considering fabrics which are not necessarily lightweight in cost particularly when the costs of design, cutting patterns and fixtures are included.

It would seem important some brief general discussion should be presented covering the following structural considerations:-

a) Functional aspects of the structure.
b) Size of required surface.
c) Site shape and height restrictions.
d) Material characteristics.
e) Erection procedures.
f) Maintenance and operational aspects.

2.0 STRUCTURAL DESIGN CONSIDERATIONS

2.1 Functional Aspects

The end use of the proposed structure usually dictates whether the type of membrane solution is a tension structure or is of a pneumatic type. Pneumatic structures generally fully enclose a space and offer an opportunity to be able to control the internal environment in an integrated fashion with the support system. Tension structures on the other hand, are generally more suited to cases in which a limited environmental protection is sought such as from rain or direct sunlight where side "walls" can be omitted. (See Figure 1).

There are obvious exceptions to the above statement - for example, pneumatic "cushion" structures have been constructed which can allow open walls and alternatively, tension structures may have independent or integral walls, or roof surfaces anchored directly to the ground to totally enclose a given space. (See Figure 2).

2.2 Size of Membrane Surface

The proposed function will largely dictate the size of the membrane required. Applications such as enclosing Olympic sized swimming pools are in the range of structural possibility of both tensioned structures and pneumatic structures and both have been done in Australia. A tensioned structure consisting of a series of circular trussed steel arches with a structural outer membrane and a non structural inner liner for insulation was used to permanently cover such a pool at Corio in Victoria. A standard pneumatic structure which is intended to be demountable covers the North Sydney pool and another pneumatic is currently being erected in Clarence, Tasmania for the same purpose.

It would seem that structures much smaller than this, where functional requirements allow, are perhaps better suited to tension structures where the added costs of mechanical air handling plant including back up facilities and regular inspection and monitoring would not be required. Rather dramatic free-form surfaces associated with tension structures add a great deal of excitement to these projects and they can best be appreciated in the small to medium sized structures.

On the other hand, very large structures have been realized with pneumatic (air supported) structures. The Silverdome in Pontiac (Detroit) is a cable restrained pneumatic roof which covers an indoor stadium capable of seating 80,000 people and has an area of some 40,000m^2 (10 acres). Numerous other pneumatic forms have been constructed of the order of 15,000m^2 and up.

It would be reasonable to say that for very large clear spans (say greater than 150m), and suitable boundary conditions that pneumatic cable restrained roofs come into their own. Smaller structures are not necessarily cheaper but may be the only way of achieving the desired effects economically. Quite small structures probably are not cheaper than conventional construction but the architectural quality of the end result will be dramatically different which by itself often warrants a membrane solution.

2.3 Site Shape and Height Restrictions

a) Pneumatic Structures

Whilst it would be possible to erect a pneumatic structure over an irregular boundary this has been quite rare. Indeed most pneumatics have extremely simple, regular and symmetric boundary shapes and generally the larger the structure the more regular and symmetric it becomes. The large indoor stadiums in North America have the boundaries consisting of an edge beam of polygonal form in a horizontal plane. At each vertex a restraining cable is anchored and this force is counterbalanced by thrusts from the different angles in the self balancing edge or ring beam. The large horizontal forces are all self contained and the small downward vertical forces are easily carried. Potential uplift forces can utilize some of the weight of the remaining structures.

These large structures have a fairly low rise of roof relative to the spans but the roof itself starts at a considerable height. Earthern berms have also been used to gain height cheaply at the boundaries and the resulting overall shape is very effective in resisting the strong wind forces as discussed in more detail in a separate paper.

Smaller structures such as those over Olympic pools will have a much higher rise to span ratio in order to achieve height clearances at the sides of the pool. The potential behaviour under wind loads is considerably different for these situations. Many circular dome structures have been built both as semi permanent structures and as demountable projects.

b) Tension Structures

These offer perhaps the greatest scope for architectural imagination (and sometimes frustration and considerable challenge) to arrive at a suitable form to suit the site. Very irregular boundaries are common including gentle and steep slopes to the site. Often anchorage points for supporting masts or surfaces are finally located well away from the edge of the covered area.

With a membrane structure covering a large percentage of a restricted site it may be necessary to anchor points into adjacent existing buildings which could prove to be an interesting problem in itself. Normally, and perhaps fortunately, adequate surrounding space is available.

As distinct from pneumatic structures whose shape is described as being "synclastic" - the centres of curvature for surface curves in any two perpendicular directions being on the <u>same</u> side of the surface - tensioned structures are "anticlastic".

This requires the presence of alternating relative high and low points to provide the desired control of membrane curvatures. High points usually involve either a mast element as a point support, or a rigid frame, truss or curved arch as a line support. Low points are often achieved by a tension anchorage to the ground or by a restraining cable pulling the membrane down along a line.

Functional requirements may suggest the perimeter of the structure be low and the internal region to be high. Further, if a clear span is required then internal masts become a problem and suspended short masts can be introduced. In such a case the provision of appropriate "skyhooks" dramatically alters the external appearance and the site size requirements in order to anchor these necessarily high "skyhooks". Well known examples are the Munich Olympic Stadium and The Haj Terminal in Jeddah.

Alternatively where rigid frames or arches of steel, concrete or laminated timber can span the complete space these can be used very effectively to provide the desired double curvature. The main concern in these cases is to allow for the possible uneven horizontal tensions created when uneven loads occur on adjacent membrane panels or where one panel is damaged, deliberately removed, not yet installed, or of a different size and shape. The frames thus need to be stabilized by guying or bracing between adjacent frames or by techniques such as diagonal arches intersecting.

For the reverse case with high perimeters then obviously drainage can be a problem for multipanelled surfaces with clear spans.

2.4 Membrane Material Characteristics

It is not the purpose of this paper to discuss the detailed material properties of the various fabrics that are available. However some generalizations are certainly in order since the choice of material greatly influences the detailed design.

There are a wide range of materials from numerous types of "shade cloth" consisting of uncoated synthetic threads through nylon and polyester base cloths coated with PVC to fibreglass fabric that is teflon coated. There is a corresponding wide range of costs and properties to be considered. It should however be noted at the outset that the raw cost of the fabric "off the roll" may only be a relatively small percentage of the finished structural cost.

Other important items include design cost, (which could well be higher than normal for tension structures), expensive fittings, masts, anchorages, fabric cutting and joining.

The cheaper cloths generally are more flexible and continue to creep with time. Because of the weaving process, the properties in the warp and weft directions usually differ particularly with respect to the elongations. Since tension structures need to be prestressed this requires that some means of readjustment has to be incorporated into the design details. Small structures may only need rigging screws whereas larger surfaces may need to use hydraulic jacks. It is desireable to have these points of adjustment easily accessible at anchorages or inbuilt jacks in the base of supporting masts. When adjustments are made there will be a corresponding change of surface shape. These changes are most critical near more rigid elements where the fabric may be less able to accommodate the movements and secondary means of tuning may be required. Figure 3 suggests some areas requiring special consideration.

Fortunately, with many fabrics the creep characteristics will tend to relieve highly stressed areas to a certain extent and of course the shape of edge cables can vary from the intended shape due to irregularities. The creep characteristics can well be expected to be dependent on the biaxial stress state - the relative magnitudes of the principal stresses and the orientation with respect to the warp or weft direction. Whilst some tests have been done overseas there does not appear to be very much direct local knowledge in this area.

With nylon or polyester based fabrics used in tension structures the pretension would decrease with time and consequently a higher proportion of the design wind load may be carried by one direction than anticipated. Masts need to have end details allowing some degree of pivoting to reduce bending due to eccentric loads. Using these fabrics, minor wrinkles can often be pulled out.

For pneumatic structures the problem of creep is not usually of direct concern since the internal air pressure can maintain the same state of prestress. Minor edge wrinkling which can occur along the base is normally of no concern.

Under uniaxial testing elongations at failure for these materials can be as high as 15-25% in the warp/weft direction and considerably more at 45^{0} to these. Under normal preload conditions in a structure the stress levels may only be in the order of 5-10% of the ultimate strength of the new fabric. Short term stresses under design wind loads may reach (by calculation at least) 20-33% of the U.T.S.

The more elaborate material - teflon coated fibreglass by the very nature of the base fabric - is much more dimensionally stable and it is claimed that once installed and pretensioned there is usually no further adjustments required. However, it is also a fact that the shape determination, or form finding, needs to be performed with considerably more care. Consequently the suppliers of these structures carry out their own independent form finding exercise.

All fabric structures can be easily damaged by acts of vandalism and offer no resistance to a sharp knife. A normal tear is often not propogated due to the adhesion and strength of the coating. Obviously the best design approach is to avoid the problem by making the fabric surfaces as inaccessible as possible. Permanent pneumatics could start from elevated earthern berms or be contained behind a wire fence or be supervised adequately. For portable structures, the pneumatic is an ideal solution except for this major concern and the operation of such structures should be organized so as to safeguard against damage.

Another design aspect to consider is the expected life of the membrane and its performance during this life. One function of the coating is to protect the base fabric from degradation due primarily to the ultraviolet radiation of the sun. PVC coatings can be varied in content and number of layers on either side of the base cloth. Normally the fabrics are translucent and can come in a wide variety of colours. Carbon black can be used as an inner coating as added UV protection but this makes the surface opaque. Most PVC coated fabrics contain fire retardants.

Common forms of degradation of PVC coated fabrics are delamination of the coating, the coating (in particular) becoming brittle, the fabric could become quite dirty and there is a gradual loss of strength. This loss of strength needs to be considered when deciding on design stress levels. A loss in the order of 15-20% over a period of 8-10 years may not be unusual. The loss of tear resistance and elongation may be more but the general dirty appearance of the material may suggest even greater loss than actually recorded. Once again there is little local direct experience with these aspects of the material behaviour in service. The life of PVC coated fabrics may be extended by occasional painting with specially developed lacquers.

Consideration should be given to the short and long term costs of the project and whether it is more economical to replace the fabric skin at regular intervals. For demountable structures PVC coated materials are better able to resist the rough handling, folding and abrasion during erection.

Teflon is a very inert material and offers excellent long term protection. It initially has a rather bland colour but quickly bleaches to a brilliant white after a few months exposure. Many structures have remained very clean in appearance compared to comparable PVC coated fabrics, but others become rather dull due to industrial pollution etc. A disadvantage of TCFG (teflon coated fibreglass) is that it needs to be handled on site with kid gloves. It is very prone to damage due to careless handling, creasing, abrasion by dragging over concrete on dirty sites. Design consideration should allow for a suitable construction sequence and allow a clean unobstructed site to be available for handling fabric structures. Manufacturers need to carefully roll (preferably) or fold (with perhaps layers of felt) and crate the fabric. Mobile cranes may be needed to handle the large panels of fabric (e.g. $60m \times 30m \times 1000gm/m^2 = 1800kgs$).

2.5 Erection Procedures

Some aspects of site preparation and construction sequence planning have been mentioned above as a means of protecting the material. Careful detailed planning is required since it is generally necessary to completely erect and make secure whole structures or large panels in a continuous uninterrupted operation. These large surfaces if exposed to strong winds before being properly inflated or tensioned can flap vigourously and easily tear (e.g. $60m \times 30m \times 0.2kPa = 360kN$!) Each group of workers needs to be self contained with the necessary tools. An early start may be desirable to avoid weather changes and sea breezes for example. Working platforms need to be considered attached to masts to speed the process.

Heavy steel fittings and edge cables should be able to be attached to the fabric without completely unfolding the surface. Once unfolded these fittings should be tied to convenient anchor points to prevent them being blown back onto the fabric. Temporary pulling lines or webbing should be bundled up with the main panels ready to use. Perhaps a net of webbing can be used around a panel being lifted by crane to safely contain the loose fabric in the air until the last possible moment.

2.5 Maintenance and Operational Aspects

Regular inspection of these structures is obviously required since any defects in the prestressed surface may well have detrimental structural consequences. Particular attention to fittings, anchorages, regions where contact with rigid elements such as doors will greatly help in maintaining a practical structure.

For pneumatic structures, the air inflation system is also the means of maintaining structural integrity and must be regularly maintained and monitored. All valves, backflow dampers and air ducts must be checked regularly. The back up unit needs to be started and run occasionally and fuel levels maintained in case of primary power failures. An operator should be in attendance in cases of adverse weather in order to increase the pressure if necessary (mainly for high rise to span ratio structures) to resist strong winds. He must be able to override any automatic control system which may well malfunction due to sudden changes in pressure.

If pneumatic structures are used for storage of goods then care needs to be taken to ensure that adequate clearance to the membrane is maintained to allow for the deflection under winds.

A number of construction and design aspects have been discussed in more general terms and it would be of benefit to examine some examples of recent structures built in Australia.

3.0 DEAN PARK SOUND SHELL ROOF

Principal: Council of the City of Townsville (TCC)
Location: Dean Park, Townsville

Initial contact was made by TCC for a scheme to roof the stage area and provide shade protection and prevent dew settlement on instruments during night performances.

The site is essentially an open air theatre in a region where temperature is generally in the region of 20°C upward but where there is a long wet season (summer). Winter temperatures are moderate so use during March-November is fairly consistent as is fine weather. It is part of the Cyclone belt and the site is close to the ocean with a fairly open aspect. A basic wind of 55m/s on a 50 year return is required with multipliers in the usual fashion plus a mandatory cyclone multiplier. Townsville averages about two close passes per year and a direct pass of a cyclone every 5-15 years.

The site is on a reclaimed mangrove wet land which latterly was used as a rubbish tip and has received a large amount of fill to prepare the site for recreational use and accordingly the ground conditions are not ideal, the stage structure and its sound reflectors being founded on a floating raft slab. The existing raised concrete stage, a segment of circle, of 20m diameter, is attached to a performers changing room and toilet block in the rear plus a series of free standing, precast concrete uprights in a circular array, fanning out from either side of the stage. The uprights are folded in plan providing passageways between each, and their height increases from the edge to centre from 3.5 to 6m. These form a rear wall to the stage and surround and act as sound reflectors to the front region which had been filled to form a circular mound to provide a tiered effect for seating.

The original drawings received detailed a largely planar canvas awning style of roof, attaching to various locations on the uprights and prestressed via two guyed pylons at front of stage. The TCC admitted some concern about the design in that the roof transmitted overturning loads to the uprights and would be difficult to remove in a gathering wind. They considered removal would be necessary. Part of the preliminary design requirements was to examine alternative forms of construction, principally space frames. An exercise was carried out totest the feasibility of various forms of space frames but results indicated that the combination of costs, site constraints, aesthetic factors and configuration of existing works, pointed to a membrane structure as the best solution.

In looking at shape the following aspects were considered to be parameters for successful design:

1. the front and rear should have good access for transport vehicles,
2. the audience region should be relatively unencumbered to prevent sight line blockage or obstacles which might cause accidents during night use,
3. the roof should assist acoustics if possible but not have deleterious effect on the existing successful reflectors,
4. moisture should be channelled from the roof to a minimum number of collection points away from audience and stage,
5. the entire stage region plus at least 2 metres all round should be covered,
6. the membrane should not interfere with existing lighting arrangements which were pylon mounted in front of stage,
7. there should be no attachment to existing buildings and an adequate clearance should be allowed to prevent contact during high wind defelc-tions,
8. there should be a minimal use of pylons and tie downs to limit hardware as much as possible,
9. no part of the membrane should be lower than 3 metres to eliminate potential vandalism,
10. the structure would be manufactured in Melbourne and must be able to be readily transported by truck to site as no high frequency welding faci-lities existing in Townsville,
11. the region is readily visible from the newly developed heart of the city and accordingly should be aesthetically excellent,
12. budget constraints precluded large scale coverage of the region and called for efficiency of form,
13. it was considered that a reasonably large structure would result that could not easily be demounted in cases of cyclones and consequently a fail safe design needed to be evolved,
14. the level of expertise at the time suggested a simple symmetric structure of reasonably high curvatures.

With regard to points 1, 2 and 6 it was apparent that a form which used a parallel line of support either side of the stage would best conform with the requirements. Accordingly several combinations of high/low undulating forms were considered and eventually produced a shape which took account of these parameters. This took the form of a structure with four high and two low points, the latter being close to the raft slab and seemed to gain some advantage from being tied into this existing footing.

The line of high points front and rear satisfied the lighting and viewing criteria and the developing shape also satisfied the sound performance requirements. Further points 7 and 8 seemed to be solveable with suitable shaping and the line between opposite low points across the stage provided a suitable channel to two points for drainage. Work proceeded on the relative curvatures to attempt to make these equal in opposite directions and to determine the relative positions of footings and pylon tops. A model study revealed appropriate positions for the high and low points whereby the distance between the low points is less than the similar distance between high points giving a better relative curvature over the surface.

Several working form finding models were made for this process and the results of a final accurate 1:100 scale model were presented to the client. The TCC in turn decided to tender based on the projected costs and details submitted.

Following the award of the contract to Geodome to design, fabricate and install the membrane, efforts were directed towards finalizing the cutting patterns and hardware details. This was based on a combined computer and model approach whilst the order for the fabric was being filled.

The fabric used was a special run done by Hammersteiner Kunstleder in Germany according to the following Geodome specifications. Polymar 6303. 8800 to be used with an all up coated weight of 1400gm/m^2 containing a carbon black inner lining and outer coats of white flame retardant PVC with a heavier outer coat. The polyester weave was a 2/2 panama weave with an ultimate uniaxial tensile strength of 600kgs per 50mm width in the warp direction and 550kgs/50mm in the weft with elongations of 14 and 20% respectively.

A substantial testing procedure was conducted at the University of New South Wales to determine the influence of jointing methods. Samples of welded, stitched and combined welding plus stitching joints were tested and from these minimum weld widths and procedures determined. Some test strips of the fabric have been attached to the structure and it is planned to test these at regular intervals to ascertain any loss of strength.

A computer program developed by the writer was used to generate the surface from a knowledge of the x,y,z coordinates of a limited number of salient points. This program was able to produce crude fabric cutting patterns but, at that stage, could not optimize the alignment of the strips on the surface. As a result, a 1:10 model was built from the computer produced strips and this was carefully measured to give the final fabricating dimensions. In this way an efficient patterning resulted.

It was decided to fabricate the structure in one piece although the weight of membrane was fairly high and the fabric became fairly unmanageable. A seam line (field joint with plates etc.) was considered but this pointed to discontinuities in the edge cable sleeves, sealing problems for water penetration, and an un-aesthetic break in the flow of the fabric. Fabrication difficulties were overcome and the membrane was completed fairly swiftly. All seams were high frequency welded with a 50mm seam overlap and also were sewn with polyester thread (double stitch). The thread was a carbon black heavy duty (Sinton 11/3) 100% polyester, imported from Germany. The middle joining seam was HF welded only with a 75mm weld. The assembly was carried out by dividing the structure into its 4 symmetrical parts and individually welding these together then joining the four pieces last. Finally cable sleeves were attached to the perimeter. The structure was packaged and shipped to site, to await the hardware.

Edge cables were all of fixed length with sockets as were the upper ends of the pylon guying cables. The tie down ends of the guys were designed for fixing with multiple grips to enable adjustment of the top of pylon position. In this case the cable passed around a pulley at the footing cleat and turned back on itself to be fastened via grips. Pulling equipment could easily be attached to assist the process. Generally it was planned to fix the correct position of top of pylons in the initial stage and prestress the surface via the assembly at the two low points, and this in fact occured without any need to alter the length of guys. All fittings at pylon tops and tie downs had full three dimensional movement capability to enable free movement under load and to take up construction inaccuracies if they occurred. The low points also provided prestress ability by two opposing plates connected by threaded prestressing rods. A VSL hydraulic jack at each point was used to obtain the required prestress levels in accordance with the planned procedure and design stress.

The pylons were fabricated in halves and shipped to site wher they were assembled, final coat painted and erected first with cross cables holding them in position. The cross cables served as a fail safe mechanism if membrane tearing should occur. The fabric was delivered, laid out, cleaned and cables were inserted in relevant sleeves and plate fittings at each attachment point were located and fixed. The plates fixed to a region of reinforced fabric via bolting and also were cable grip fixed to the edge cables. Provivison was made for pulling the plates toward the fixing points to allow adjustment to membrane stress along the region between the cables at each point.

Mobile cranes and pulling equipment were used to hoist and fasten the high point attachments to pylon tops and the process of low points tensioning began. Following the final stage of prestress a survey was done to check pylon tops and centre of fabric and the results were nearly perfect.

Three days later the first concert was held in the new facility and complaints to authorities from residents at a distance (several kilometers) from and in front of the stage area regarding noise,point to the success of the acoustical performance. All steel work was sand blasted and primed with two top coats of polyurethane paint. The 28mm diameter galvanised steel cables were encased in rubber hoses in the sleeve regions. All bolts were galvanised and prestress hardware was wrapped in a protective coat of Densotape followed by alum sealing tape to protect the threads.

4.0 COMMAND PERFORMANCES TRAVELLING DOME

Principal: Command Performances Educational Enterprise Australia:(CPA)
Location: Melbourne, Exhibition Gardens: Sydney, Hyde Park.

The brief developed for this project with the client over a protracted period of time as the requirements for expansion of their facilities became clear. The troupe is a travelling company which performs for children at schools in association with the Dept. of Education. Previously they had a small high pressure tube geodesic membrane structure and developments lead them to require a larger and more sophisticated facility. As the project developed the requirement changed from one to two structures.

The brief was not well defined but contained reference to the need for a structure which needed no fixed footings, but relatively easy to move from location to location, was relatively fast in this process and could be packaged into the smallest feasible area. Additionally it should comply with regulations as provided by the principal resulting from his negotiations with authorities. The structures were planned for erection in all states and in a variety of locations which provided obvious problems in satisfying all codes. The occupancy was variable as the design developed but was from 600-1000 children depending on seating etc. The structure was to be used for a musical performance complete with a laser light show and accordingly was to be opaque or nearly so. Finally the structure was to resemble a flying saucer if this could be achieved. A tension structure of some form was initially considered, but it was swiftly realised that this involved substantial forces at few points or required a significant frame which involved expense for which the brief was not providing. Accordingly the final solution was a pneumatic as the forces at anchors could be divided around the perimeter and might be achieved by anchor stakes driven into ground.

A general spherical shape was chosen with an upper section of a smaller (10m) spherical segment to give more of the appearance required and also served to improve the acoustics inside the structure. The base diameter was 27m.

As the structure was to be used on lawn surfaces it was planned to seal the pressure differential by a long skirt on the inside working against the ground surface and fastening points at the perimeter. The pressure inside was assumed to hold the skirt with no further fixing and also provide apertures for passing equipment through (cables etc.) and in operation this was found to be successful.

Around the perimeter the forces from the membrane were transferred into a catenary cable near ground level forming a series of arcs from seam point to seam point. At entry and exits the cables became more substantial and arched over the door penetration to remove forces from rigid elements and provide a flexible torus region to allow for movements in winds.

The membrane was cut in the classical orange peel pattern from 2m wide rolls of Polymar 6301.8605, Polyester 9/9/ standard weave with PVC coated on both sides. The coated weight was 870gm/m^2 and the fabric was produced with a carbon black liner to be nearly completely opaque. Outer and inner surfaces were white in colour. The fabric had a tensile strength of warp 300kgs/5cm weft 300kgs/5cm and elongation of 15% & 20% respectively, and contained flame retardants.

The upper spherical section contains a small manually (from ground) adjustable butterfly valve to control exhausting of hot air build up at higher regions. The junction of the two spherical segments contained a perimeter cable in a sleeve to take the forces developed at the interface.

Door elements required varied in number and were eventually set at 8 exits and one revolving entry door. These were designed to be as light as possible for portability and were fabricated from fibre glass and resins (flame retardant). The exits are outward opening conventionally hung doors fitted with panic hardware and the four leaf revolving door also from fibre glass was centre pivotting in the usual manner.

All doors contained floors and were built as cabinets which reduced dimensionally toward the front to allow stacking together for space efficiency. Exits were box like to provide provide protection over the door swing against membrane collapse. Each was built complete with a flange all round for fastening the membrane to the door. This was achieved by a reasonable fast and efficient aluminium section on a roped edge at the door flange. No bolting through the membrane was required as a result.

Considering the application of the structure for erection in varying conditions and with relatively unskilled workers we were concerned about the seal which could be achieved so it was decided to provide excess capacity of air supply to take up expected leakage during use.

A basic internal operating pressure of between 250-270 Pa was determined and fan size was chosen to provde this level with great volume of air. In fact up to 17 changes per hour are achieved during correct operation. An axial fan was chosen for economics and an attenuator at the fan cut sound levels down to acceptable levels. A manually controlled flow adjusting damper assembly was attached to the outlet end of the fan assembly to control flow as required. This unit also contained snap shut dampers for prevention of pressure loss during power outage of the unit. The unit was designed to be fitted onto a truck or trailer which were not available at time of first inflation so skids were provided to enable the unit to sit on ground. The fan type was Buffalo 38G½ 4P Axial with 16 degree pitch containing a 6KW three phase motor.

Inlet fittings were bolted to the membrane wall and a flexible duct connected the fan unit to the structure. Adjacent to this unit was a Diesel powered 300CP centrifugal back up fan which was wired to start automatically if the main fan cut out in any way. This smaller fan had the capacity to provide normal operating pressure on its own while the structure was closed.

Air was exhausted from the structure through the top vent and an additional ground level vent which was equipped with a manual flow control and also a solenoid controlled damper which shut if power loss occurred. This unit was also connected to the structure by a flexible duct. Power supply for operations was to be arranged by the CPA at each site.

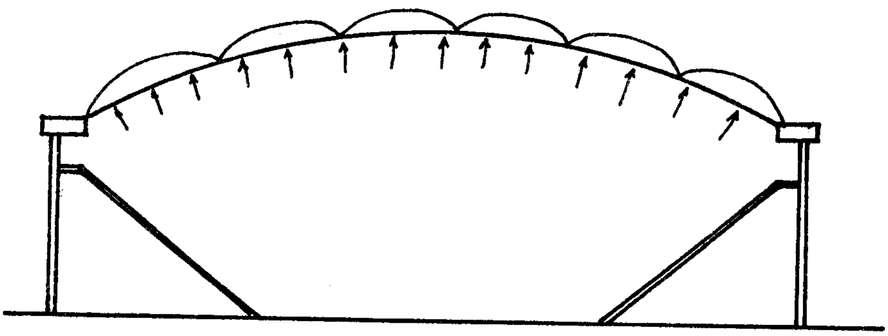
All seams were high frequency welded with a 30mm wide seam and at cable sleeves these were 50mm and double sewn with 100% polyester thread. The cable sleeves were sewn and welded on as separate elements and reinforcing patches were applied in crucial areas to prevent wearing on fastenings etc.

In designing the anchor spikes, due allowance was made for the variation of soil conditions and the location of the structure. Long C36 reinforcing bars with side fin plates welded on were used and were to be driven into the ground so that the fins could engage a wedge of overlying soil. Peak loadings on anchors were averaged out before applying the normal factors of safety.

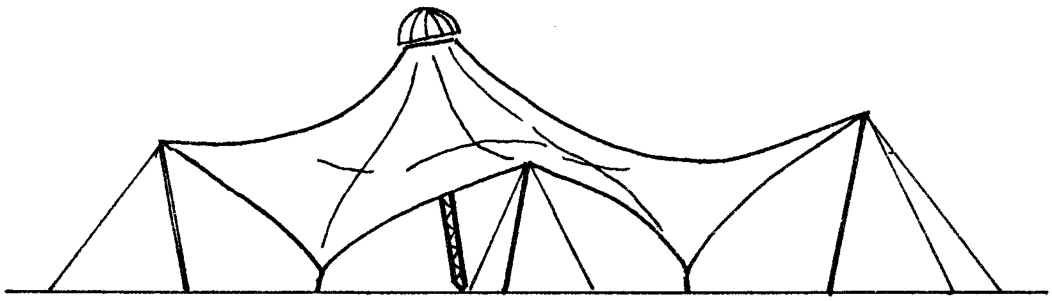
The anchors were found to be difficult to hammer in as expected when done with sledges but the planned technique for a mechanical device to assist was not realised prior to inflation. Alternatives e.g. augers were discarded due to cost and lack of recoverability. The first inflation contained some elements of the finishing processes as the schedule was extremely tight but it is expected that the time to inflate from first arrival on site should be no more than 1-1½ days with 4-6 men.

5.0 CONCLUDING REMARKS

This paper has endeavoured to present some of the design and constructional factors to be considered when a membrane structure is contemplated. These were presented in a general fashion and then reinforced with more detailed descriptions of two recently completed local projects.

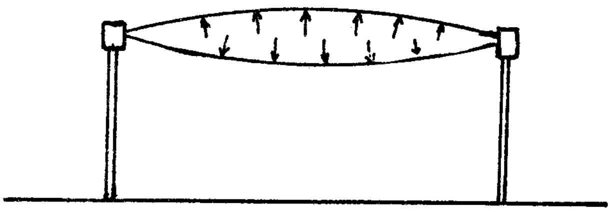


Pneumatic cable restrained
air supported stadium.

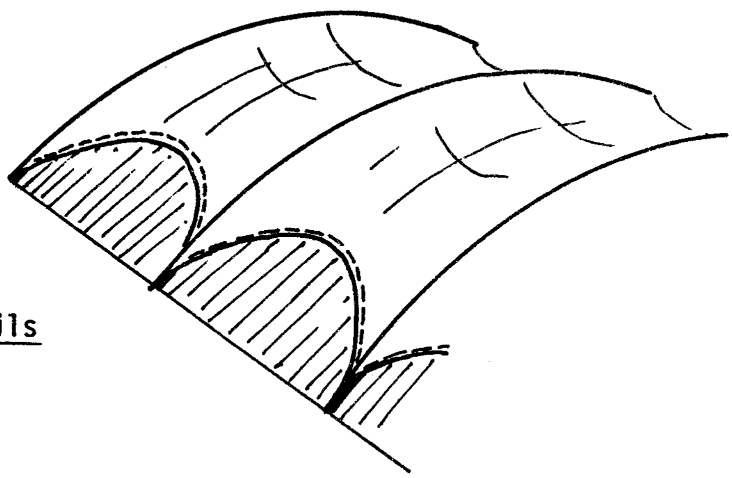


Tension structure with internal
and edge masts, open sides.

Figure 1. Basic forms of Membrane Structures



Pneumatic "cushion" structure
with open sides



Tension structure with
side walls (low prestress)

Figure 2. Alternate Edge Details

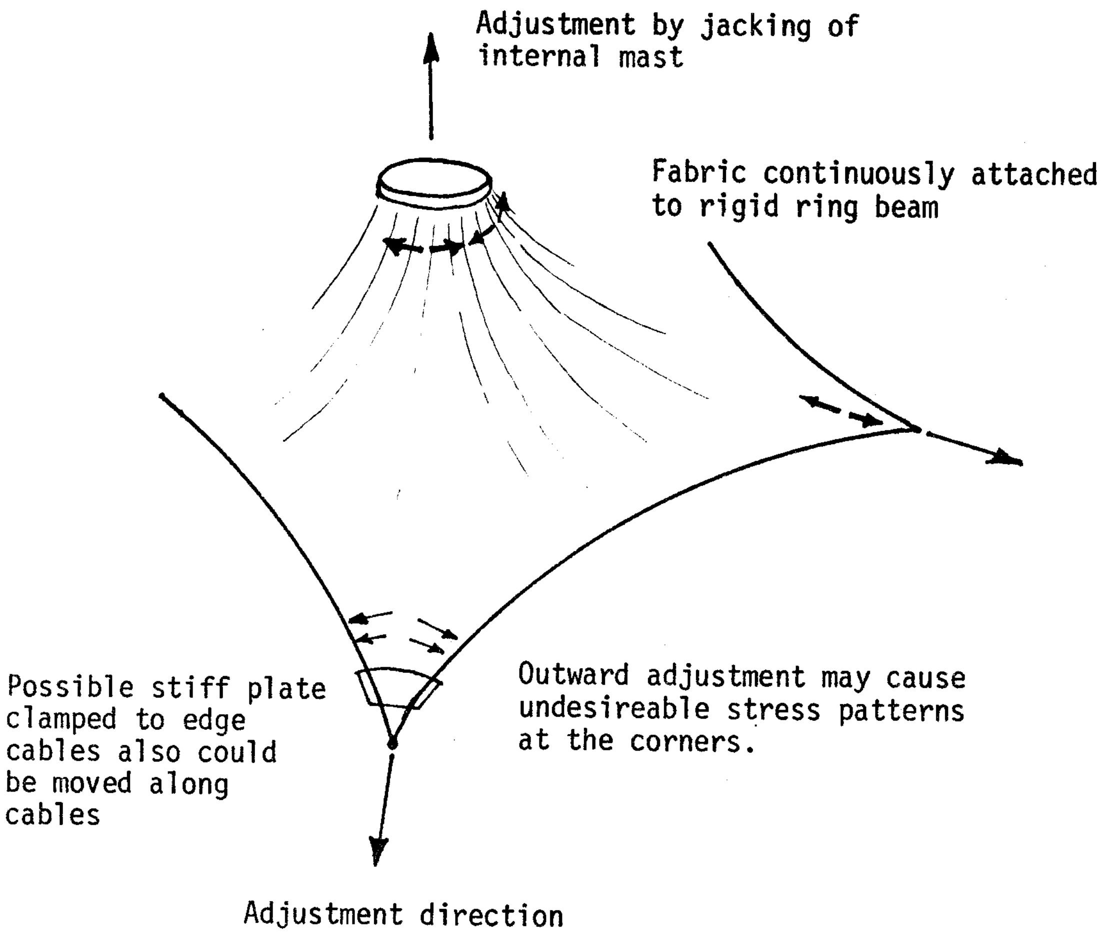


Figure 3. Regions requiring special care.

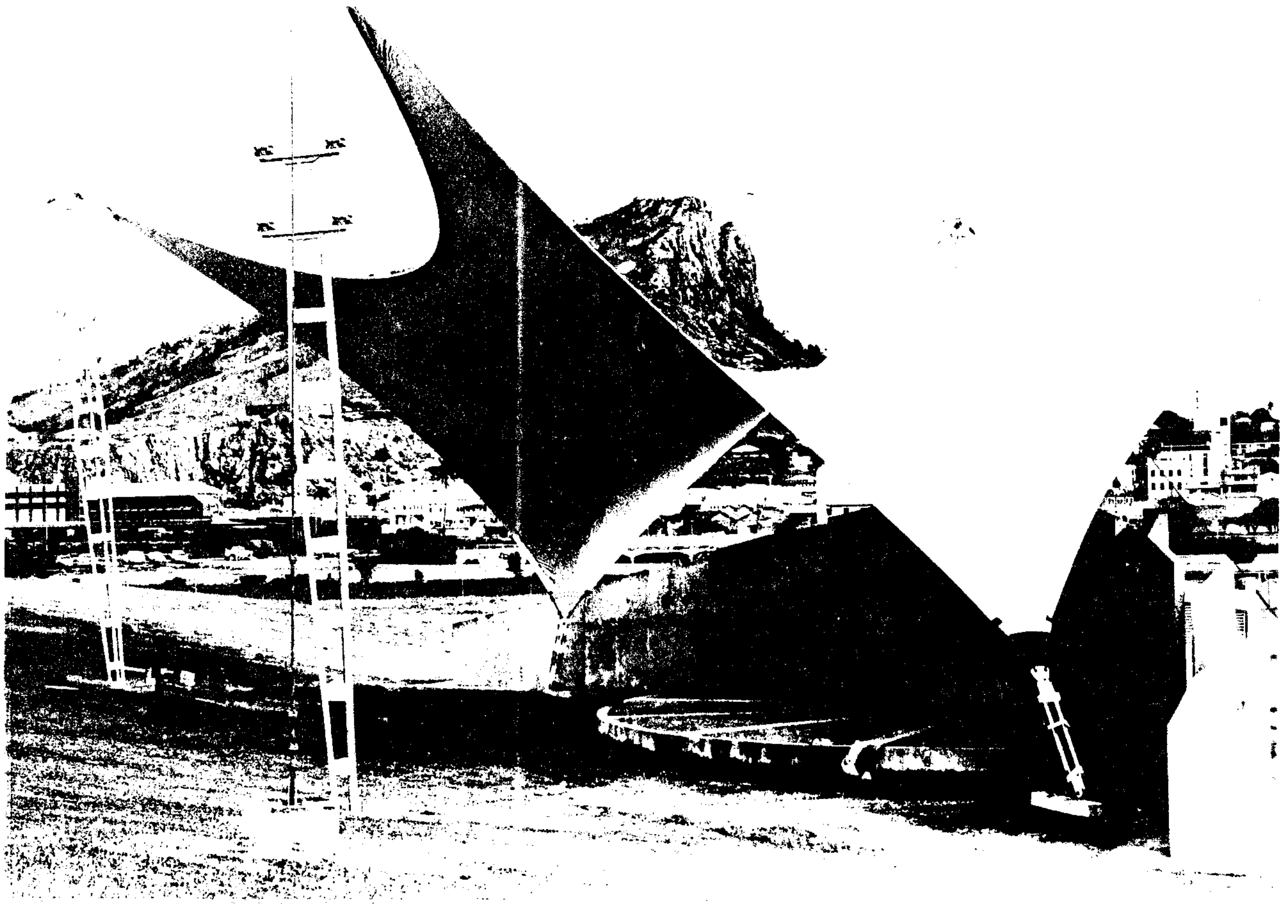


Figure 4. Dean Park Sound Shell, Townsville

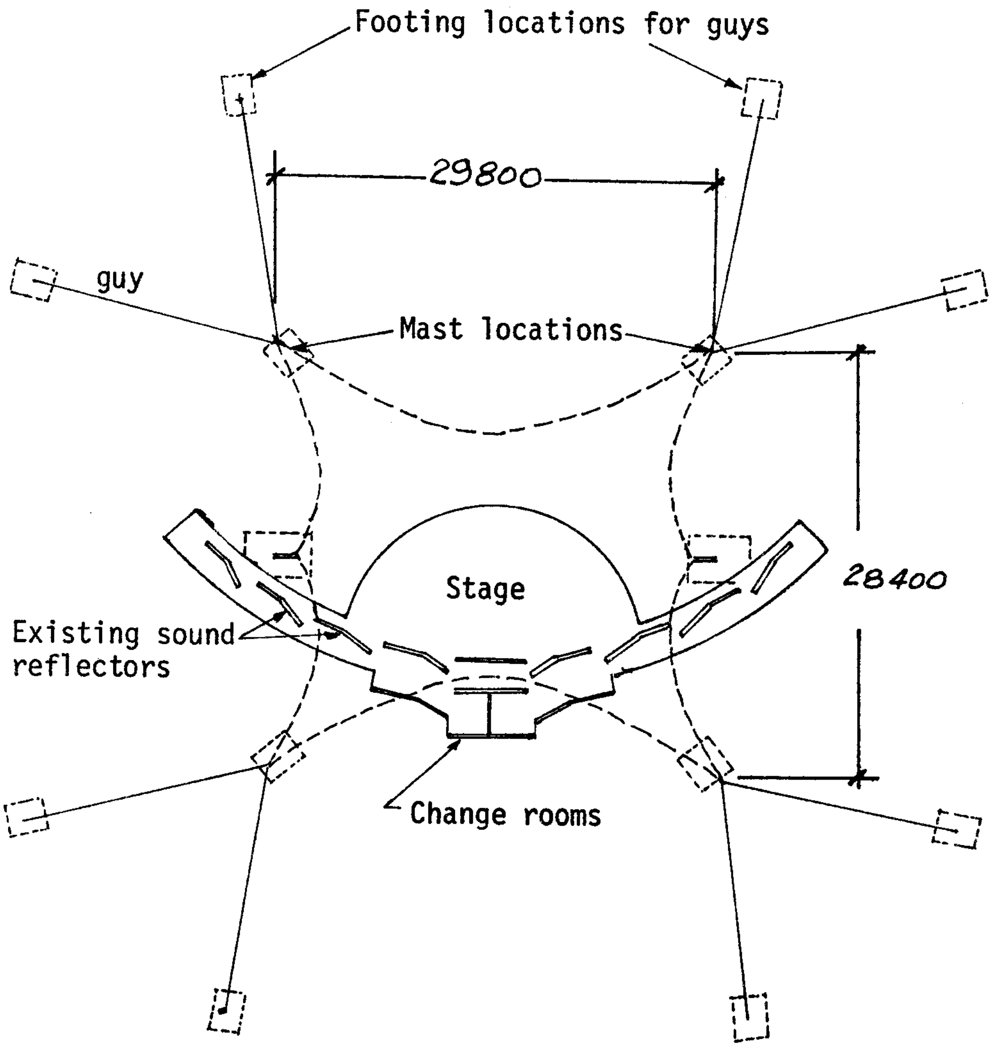


Figure 5. Dean Park Sound Shell
(showing existing conditions and outline of membrane structure)

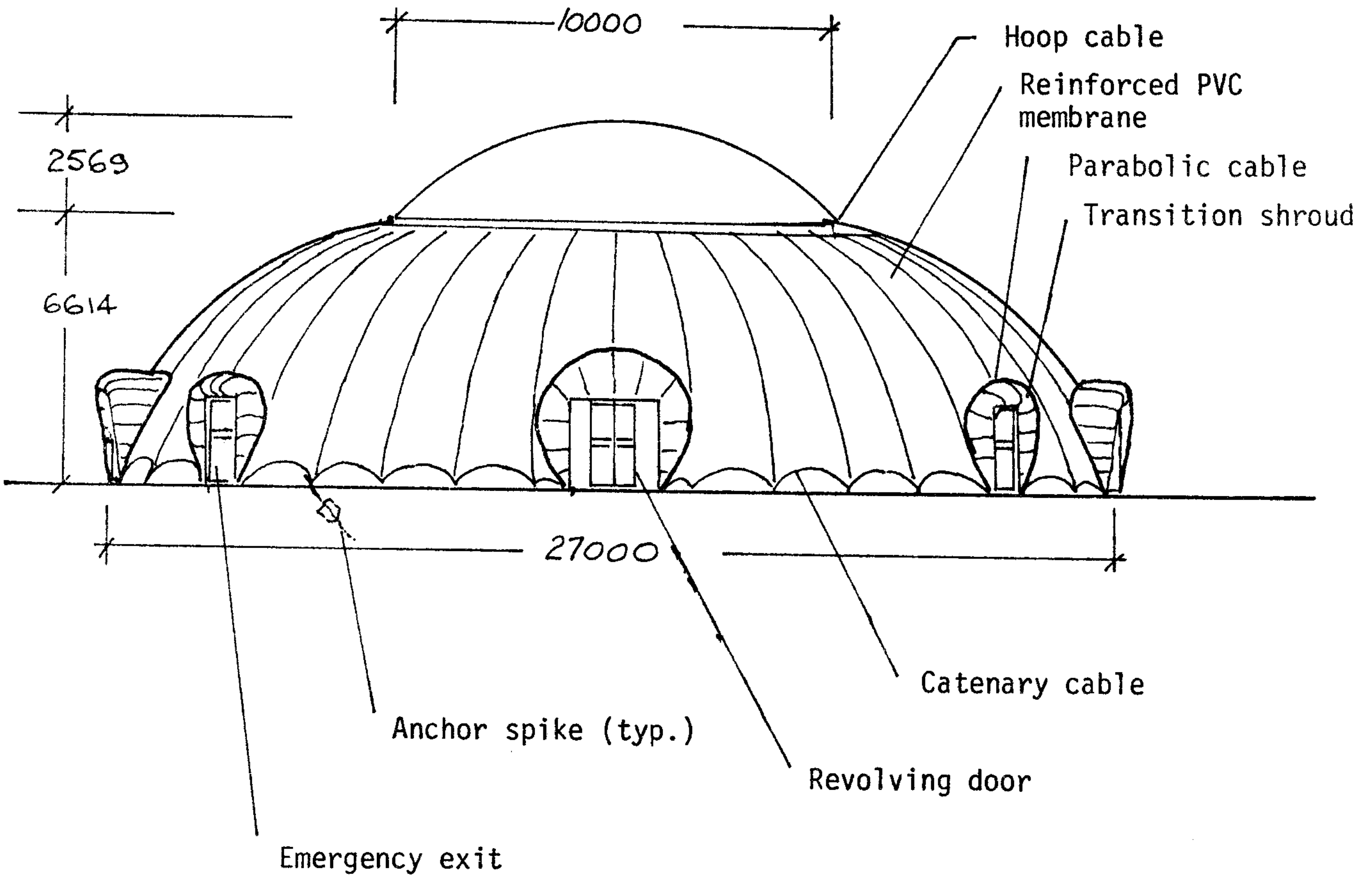


Figure 6. Command Performances Travelling Dome

Note- Air handling plant not shown.

FORMFINDING, PATTERNING AND DETAILING OF MEMBRANE STRUCTURES

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Synopsis / Abstract

Form finding is the fundamental and most essential phase of work in the planning process of a membrane building - no matter if it is a tent or a cable net stabilized by prestressing, or a pneu supported by interior pressure. Form finding can be conducted empirically with models or mathematically on computers or both together supplementing each other. Here, the empirical form finding methods are to be brought to the front, completed by some references to the possibilities of the mathematical form finding.

Plastical substances, soap films, rubber skins, hardening and solid materials, textile tissues, wire nets, stiffening of elastic models, movable and convertible models, size and scale, accuracy and value of statement, representation of structural details, evaluation and measurement of models: geometry, forces and deformations, load tests, model statics.

The pattern is the most important result of the form finding: it is the basis for the manufacture of a membrane in unstressed state and at the same time it is fixing beyond recall the final spatial form of a membrane structure.

Methods for the determination of pattern, pattern position on spatially curved surfaces, directions of membrane strips and web fibers, presentation of pattern as a workshop drawing, pattern manufacture, influence of short and long time behavior of fabrics, compensation factors, prestressing of membranes: geometrical-similar stretching and stress center, measurement of membrane forces on site, control of built form, creeping and poststressing, pattern quality and service life.

A well reflected design and a careful manufacture of the structural details are decisive factors for the architectural and engineering quality of a membrane building. In particular these factors have an essential influence on the service life and the long-term stability of the building.

Seams and other connecting technics, influence of seams on stress distribution and built form, releasable and fixed joints,membrane edges and corners, high and low points, eyes, rosettes, rings, masts and guyings, comparisons of bad and good details, protection against corrosion.

THE NEED FOR AN INDEPENDENT LIGHTWEIGHT STRUCTURES RESEARCH AND INFORMATION CENTRE IN AUSTRALIA

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JUNE 1981.

TOPIC: LIGHTWEIGHT ARCHITECTURE

Lightweight structures has been an established area of Architecture and Engineering since ancient history. Lightweight structures such as tents and vaults were used to cover small and large spans. In order to span over large spaces structures had to use available materials such as poles and skins or canvas, brick and masonry, as economically as possible: the structure had to be lightweight.

With a limited range of materials of given strength a structure can only be optimised through its shape, its form.

The search for the shape most suitable to withstand the applied forces has therefore always been of paramount importance. This principle is reflected in nature: with the available limited choice of the materials protein and calcium and through a single principle of fabrication and assembly: the growing cell, living nature achieves an incedibly large variety of different shapes and structures, each and everyone providing an individual solution to an individual problem: nature constantly optimises its structures towards minimal weight and minimal effort.

Developments of Lightweight Structures during the first seven decades of our century were rapid. Pioneers such as Gaudi, Torroja, Nervi, Candela, Fuller and Otto pushed the limits of span further and further, based on a range of new high strength materials and by intricate manipulation of the shapes of their daring structures. Lightweight structures during this period gained considerable publicity through their innovative aspect and challenging appearance, incorporating both a sense of beauty and a high level of engineering achievement.

Since then modern lightweight structures have gained their share in building and in other areas of technology.

It has been recognised that structures, that are economical for large spans can also be applied to smaller spans, with similar economy. Thus the range of potential uses and application has multiplied rapidly and there are few ares in building where a suitable alternative based on lightweight structures cannot be developed.

Lightweight building, because of its light material weight and its elemented construction is generally adaptable to its environment.

Lightweight architecture does not aim at replacing traditional architecture, but through its adaptability seeks to enhance the environment by either complimenting existing architecture or by providing an individual architecture ot its own.

Most lightweight structures can be adapted to almost any arbitrary boundary and support condition and cover any conceivable surface and space.

Lightweight buildings are of considerable interest and importance to Australia: its considerable resources in energy, mining, settlement, agriculture, breeding and tourism which need to be developed require spaces for the protection of people, animals and goods from the sun and the elements.

Increased human activity in zones with adverse climatic conditions such as arid, wet and arctic zones requires increased control over the environment.

If these challenges are to be met by economical means new approaches and utilisation of latest technological advances in building are needed.

Lightweight construction is synonymous with economical use of resources in terms of material, energy, manpower and environmental impact.

Applications are wide and varied, a few examples are given:

Inner City: shading and weather protection of pedestrian areas and shopping malls, restaurants, cafes, children's playgrounds, open air entertainment and exhibition, facilities for a wide range of indoor sport and entertainment, winter roofing for public swimming pools, tennis courts etc;

Commercial: department stores, storage;

Industrial: large and medium span cover for mining, manufacture and bulk storage, containers;

Agricultural: large and small shading roofs over nurseries, pastures and in arid areas; greenhouses, wheat and grain storage etc; equipment storage, animal and food protection;

Other: touristic facilities, energy generation and storage such as large solar collectors and cooling towers, wind generators; sewage plants; temporary dams for irrigation, maintenance and repairs, large covers for Antartica, providing sheltered environment for accommodation, mining and agricultural use.

LIGHTWEIGHT ARCHITECTURE IN AUSTRALIA

Although lightweight structures is not an entirely new area of research for Australia, which is reflected in a respectable number of buildings constructed here, the main thrust of development sofar has occurred overseas (W. Germany, U.K. U.S.S.R., U.S.A. and Japan).

Over the past two years interest in lightweight structures has consistently increased in Australia culminating in the recent visit of Professor Frei Otto, one of the pioneers and foremost researchers of lightweight structures, to this country.

The Lightweight Structures Research Unit (LSRU) has provided Australia with a centre for research into lightweight architecture and since its establishment in 1976 it has made substantial contributions to the furthering of interest in and awareness of lightweight architecture, despit its very modest financial means. LSRU cooperates closely with the Institute for Lightweight Structures in Stuttgart, West Germany, Professor Otto's Research Institute.

Priority in choosing topical research areas are generally linked to social, historical and political trends. Amongst these a range of problems exist which, due to impending necessities, require carefully timed solutions. Energy resources is such an area. Secondly, there is a range of problems of general scientific importance which must be solved. Failure to do so leads to deficiencies and catastrophies at a larter stage. All problems concerned with biology, ecology and environmental impact fall in this category. In addition, there are also questions of vital cultural interest, such as all those related to architectural aesthetics and the arts. Further, there is technological and industrial development and the work of innovators.

For all these tasks the following questions may be asked: Who has the ability and the resources to contribute, and who possesses enthusiasm to contribute, but lacks in resources.

Success can only be achieved when enthusiastic people work in the right place at the right time with a high level of efficiency:

1. Place

LSRU is placed at the University of New South Wales within the largest and potentially the most resourceful Architecture Faculty in Australia, which also has a strong tradition of architectural technology. The Units accommodation requirements are met and space for future expansion exists.

By its very nature, Lightweight Architecture is not only a technological problem, but also a cultural and socio-economic one. This means, that work in the area of Lightweight Architecture is by its very nature inter-disciplinary, it cannot be approached by compartmentalising it into its architectural, engineering, socio-economical and political aspects.

LSRU is a part of the Graduate School of the Built Environment which has been created specifically to concern itself with inter-disciplinary work within the environmental fields.

Finally, Sydney, being a major centre of economic and social development in Australia provides an excellent background for this research.

2. Time

The timing for research into lightweight architecture is certainly right, judging from the level of inquiries LSRU receives at continuously from Government Departments, Architects and from Industry, enquiring into possible solutions and implications of lightweight structure for their relevant field of work. Enquiries included a seasonal cover for a Municipal Swimming Pool in Sydney, in Tasmania and in Jindabyne, demountable exhibition structures for Queensland, covers for existing grain silos in South Australia, stage roofs for an amphitheatre and holiday camp and tourist facilities in the Sydney area and many others.

The need for a substantial increase in research and development has arisen. Recent tendering for several major structures in Sydney, Melbourne and Hobart caught designers and the small Australian fabricating industry largely unaware and a situation resulted with the successful tenders being agents of overseas companies.

This pattern of overseas companies encroaching and beginning to dominate an emerging new market has become familiar now in many fields. It must be halted by consolidating and furthering Australian based development.

In this case the present situation has largely resulted from the fact, that, due to lack of awareness and publicity, potential clients from local government and industry and their professional agents are unaware of the existence and availability of an increasing number of architects and engineers capable of providing a consulting service and of an emerging fabrication industry, as well as the Lightweight Structures Research Unit as a supporting centre for research and development in the field.

If increasing market development should benefit the Australian economy,imminent steps must be taken to consolidate and support ongoing Australian based developments.

Research into form, structure, material and efficiency of lightweight structures in architecture suh as are being carried out at LSRU are prerequisites for future developments.

3. Efficiency

Considering the low level of funding, LSRU so far has done well. Progress in the areas of design and application of lightweight structures has been achieved, (refer to enclosed article: "Membrane and Folded Surface Structures - Recent Research and Development in Australia"), a data and information storage system has been introduced and contacts to professions and industry on a national and international basis have been established.

However, due to lack of adequate resources work cannot be carried out efficiently: the crucial problem is that of staffing. LSRU is presently staffed by a director (part-time) and by a temporary part-time research assistant. The bulk of the work at the Unit is carried out at present by students under the supervision of its director: one PHD student, several thesis and project students as well as approximately 15 undergraduate students enrolled in elective subjects at the Unit, conduct the work. Due to lack of permanent staff a continuity of effort in research projects and in research administration cannot be provided, preventing the Unit from fully utilising its resources for the benefit of the interested community.

If LSRU is to survive and to continue fulfilling its important role in research and development of lightweight architecture in Australia, adequate funding for its programmes is essential.

BENEFITS

It is expected that in the long term increased research and development of lightweight architecture will carry considerable benefit for individual groups, for the public and the Australian society at large.

Architects and engineers will have a larger repertoire of possible solutions in the design of building.

Scholars and students will be provided with a basis of reference from which contributions to future developments in these areas will be encouraged.

Given that the outcome of this research work is being utilised by these parties it can be forseen that:

Lightweight buildings will benefit their clients and users in governments, farming, industry and the public by allowing increased levels of activity and/or by providing additional services and opportunities.

Existing industry involved in the manufacture and fabrication of materials and in the construction of lightweight buildings will be able to increase its output and new industries will be required, because of new demands for larger capacities of material production and fabrication resulting in turn in increasing investment and employment, thus furthering productivity and prosperity.

Australian society at large will be provided with a range of new facilities for sport, leisure, tourism, education, etc. Identification with an aesthetically pleasing built environment will raise the self esteem of the public and contribute to Australia's international reputation.

INTERNATIONAL CO-OPERATION

Basis for the economical utilisation of financial and manpower resources in research is the knowledge that the proposed topic is topical within the international research community. LSRU exchanges information with the major overseas research centres on lightweight structures and participates in staff exchanges and visits.

Following an extended stay in 1979/80 at the Institute for Lightweight Structures, University of Stuttgart, and a subsequent visit of its director, Professor Frei Otto, the major instigator of lightweight structures, to Australia in 1980, Dipl. Ing. Jürgen Hennicke, principal engineer at Professor Otto's institute and Dr. Eberhard Haug, R. & D. director of Engineering Systems International, Paris will participate in LSRU's activities in 1981:

Mr. Hennicke, a long-established co-operator of Professor Otto, is known for his work in the field of Membrane, Cable-net and Gridshell Structures.

Dr. Haug is known for his contribution to the computer-aided design and structural analysis of cable and membrane structures. His programme PAM-NL/LISA is being introduced to the University of N.S.W.

For the benefit of the professionals and industry and for students in architecture and engineering two courses, one on 'Membrane Structures; Design, Analysis and Construction' and on 'Gridshells, a novel method of construction' are being organised involving both visitors.

PUBLICATION

In 1981 LSRU will introduce the first two titles of a series of publications on lightweight structures in architecture. Both titles will be concerned with project overviews in the field of fabric building: 'Circus Tents in Australia' and 'Membrane Structures in Australia'. Future titles on LSRU's work and development in lightweight structures are planned.

A newsletter published on an infrequent basis is planned as well and will contain information of research and development in Australia and overseas. It is planned to distribute the Newsletter to a wide audience.

SHAPE DETERMINATION AND ANALYSIS - A COMMENT

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1.0 INTRODUCTION

This paper makes some comments regarding the form finding or shape determination and aspects of the structural analysis of membrane structures. However it must be stressed that the determination of a suitable shape has far reaching implications in terms of satisfying the design requirements and detailing. Many of these considerations were touched on in an earlier paper. It would seem that throughout the shape determination process that the designer should be constantly aware of whether the evolving form can be analysed to a sufficient degree of accuracy. The normal design process may consist of a feasibility study, often carried out on very limited budget, or even on a speculative basis, which requires an estimate of costs. If successful then the detailed design and analysis can proceed. Some approximate means of analysis is then called for in the initial stages and this paper comments, albeit briefly, on these aspects.

For final design, the correct shape determination is vital for the cases that are using stiff strong membranes such as Teflon coated fibreglass. For other materials with somewhat more "forgiveness" the process is still important and some comments are made in this regard. The material of the membrane is also at the core of the problem and it would be prudent to review some of the material characteristics.

2.0 MATERIAL CHARACTERISTICS

The following aspects are considered important from a shape determination and structural analysis point of view:-

a) limited strength
b) inability to withstand compression

c) potentially non linear stress-strain relationship
d) considerable variation of mechanical properties in different directions
e) potentially important long term loading properties.

2.1 Material Strength

Whilst there are a range of "structural" fabrics available the utlimate strength is limited in the sense that normally only one layer of fabric is used to resist the surface stresses. Internal liners are very lightly stressed. The exception is mainly for PVC coated fabrics and canvas that at concentrated load points such as masts and anchorages, additional layers can be sewn and/or welded on. The range of strength is not comparable to say that of other structural elements such as beams, columns or cables where it is relatively easy to build much larger components.

Consequently, the shape determination process must recognize primarily the limiting material strength. This is achieved principally by controlling the curvatures of the membrane. Thus for example, the covering of an Olympic sized pool, say 60m x 30m can be achieved with a straightforward pneumatic structure of nearly semicircular cross section, it may not be possible to span a distance of 100 metres in the same fashion. Neglecting the fact that it would be undesireable to have a structure nearly 50 metres high, the stresses would exceed those permitted.

A solution could be to use a "cable restrained" form which breaks the surface up into smaller panels which individually have higher curvatures (smaller radius of curvature). The membrane stresses are transferred into the crossing cables and hence to the anchorages. It is the cable-the conventional structural element - that can be made as large as required to resist the forces. Hence the overall curvature can be much smaller but the local curvatures in the panels are large so as to easily satisfy the limiting strength criteria of the fabric material. (see Figure 1).

Tension structures of necessarily low curvature can also be formed using a cable restraint system in one or two directions.

2.2 Lack of Compressive Strength

It is highly desireable to avoid the situation where under dynamic loads due to wind that any portion of the membrane develops or dramatically extend existing wrinkles. On removal of the load the rebounding action of the membrane can produce very severe stresses and may well tear the fabric. There is also the potential loss of stability and large deflections which may cause the fabric to make contact with sharp rigid elements with serious damage resulting.

This criteria determines essentially a required level of prestress to resist later wind loads. For tension structures of low curvature the membrane prestress needs to be higher and due to limiting material strength the form may need to be changed. For pneumatics it may be feasible to alter the internal operating pressure for the duration of a storm.

2.3 Material Non Linearity

Figure 2 indicates a typical uniaxial load-deflection curves for a PVC coated polyester fabric. It is very non linear in nature and one can imagine that quite different stress results could be arrived at in an analysis. However the behaviour after a number of load cycles may change to be stiffer and more linear not unlike that of a cable which is preloaded to remove constructional effects. This may suggest that a preloading sequence may be desireable or at least initial prestressing to be followed by final tensioning at a later date.

2.4 Biaxial Characteristics

Whilst the uniaxial tests indicate one loading behaviour the biaxial stress state may well exhibit quite different characteristics. One factor is termed "crimp interchange". The fabrics are woven and traditionally the yarns in the warp direction are straighter (taut) than in the weft direction due to the weaving process. If a load was applied to the weft direction only it is easy to see that these yarns would straighten out thus crimping the warp yarns. This is crimp interchange and after it has occurred the behaviour under increasing load is normally more linear.

At what point this occurs will depend on the ratio of stresses in the warp and weft direction, the nature of the coating and the weaving process. It is only recently that complex mathematical models relying on powerful digital computers have been devised to incorporate this behaviour.

It has been observed for example that under uniform biaxial tensile stress materials such as teflon coated fibreglass show a tensile strain in the weft direction but often show a negative strain in the warp direction due to this crimp interchange.

2.5 Long Term Loads

As noted in an earlier paper most materials suffer a loss of strength over a period of time and so the load factors should be considered relative to the long term strength. Membranes are pretensioned and it is desireable to adopt a different factor of safety with respect to this long term load compared to a short duration wind load. If the loss of strength of say PVC coated nylon or polyester fabrics is 20% over the useful life then the following minimum factors of safety may be taken as an initial guide:

	PVC coated Nylon or Polyester	TCFG
Prestess loads	12	10
Maximum short duration loads	5 - 6	4 - 5

Sustained high level loads can cause a fabric to fail at levels far below the UTS as indicated by standard testing.

3.0 COMMENTS ON DESIGN LOADING CONDITIONS

In Australia the main design loading conditions would be:-

a) initial prestress
b) wind loads

c) potential water ponding problems.

All these are intimately connected with the shape determination and may be controlled by suitable form finding. For example, the use of a cable restrained pneumatic to increase local fabric curvatures within panels can also be used to produce an overall structure of low profile. For low rise to span ratios the resultant wind pressures produce uplift and as a result the formation of new wrinkles is unlikely. The most likely condition to be aware of, in this case, is water ponding in sudden downpours. It is known that the corners of the panels are "soft" and with sudden heavy rain they could start to fill and spread.

The determination of wind loads can be quite difficult especially for tension structures which have unconventional forms and sometimes allow the wind to impinge on the underside of the membrane. It may be that wind tunnel tests need to be performed but this is usually not possible at the preliminary design or feasibility study stages. Even for definite projects it has not often been carried out.

4.0 COMMENTS ON FORM FINDING TECHNIQUES

The earlier structures were mainly built by suitably measuring a scale model from which appropriate cutting patterns could be determined. Nowadays this procedure is still used but computer techniques are rapidly making this redundant in terms of engineering design.

4.1 Physical Models

It is often the case that clients and designers inexperienced with freeform surfaces will not appreciate the aesthetic qualities and in these cases it would be worthwhile investing in some form of model. This can be of several kinds. A <u>working</u> model in which the form can easily be changed by pushing and pulling a flexible material over adjustable supports. A <u>presentation</u> model may then be made to incorporate other features of the site but will not allow the structure form to be readily altered. Finally, <u>a structural model</u>, perhaps to a larger scale from which detailed measurements can be taken.

From a structural model it would be possible to arrive at detailed designs for cleats, anchorages, mast heights and included angles between edge cables at critical regions. Curvatures can also be estimated which should enable an approximate analysis to be performed. Such models would need to be to a scale of 1:50 and measurements done on symmetric models should be averaged to reduce the effects of model construction. Such models should feel quite tight to the touch and not have local slack areas. If these exist, (undesireable for the real structure) then the shape is not correct.

Other modeling procedures such as photographing soap film models or making plaster casts can be used to advantage. Photogrammetry techniques either using multiple cameras or altering the position of one camera have also been used. Measurements taken from the photographs can be converted into a three dimensional position through the use of a stereoplotter.

If a computer model was used which gave the fabric cutting patterns, then a physical model constructed from a material that was not easily stretched, to the computer cutting pattern, should give a very similar three dimensional shape.

4.2 Computer Models

Several approaches are possible and will be discussed in a rather brief fashion.

Firstly, measurements taken from a physical working model could define (x,y,z) co-ordinates at a number of salient points such as mast tops, midway along edge cables, low points and a few scattered about on the surface. Some form of mathematical surface could be made to pass through or close to these points. For example, a least squares approach could be used or perhaps an isoparametric finite element type of formulation. Other points on this mathematical surface could then be determined sufficient to use either for an analysis by finite elements and/or the determination of cutting patterns.

Alternatively, the same procedure could be used by scaling off carefully drawn plans, elevations and section of what is thought to be a correct shape. Obviously in this case much depends on the eye of the draftsman.

On a different side, a much simpler shape can be passed through the known, or assumed, boundary points and lines. For example a rectangular pneumatic structure may have a planar grid of lines and nodes described this grid can then be "inflated" mathematically by specifying the internal pressure and allowing the lines to change length but maintaining a constant (or specified) tensile force. The desired shape is when the nodes are all in an equilibrium position with the tensile forces balancing the pressures. We would like to call a shape derived in this fashion a "refined shape" as distinct from an "initial shape".

Of course the same procedure can be done starting from either of the shapes mentioned earlier. As to which shape is correct is a more difficult question to answer. For instance it may not be possible to specify all the tensions correctly in which case a different equilibrium position will result which may in fact be more in error than that obtained by a rough model, scaling drawings or even guessing.

At this stage of the process we may not be aware of which way the fabric is orientated or what fabric properties we should be looking at. Therefore it is unlikely that our tensions specified for a simple line grid will reflect the material characteristics. Given these factors it seems that considerable judgement and care needs to be exercised.

Alternatively, a more elaborate way of representing the surface other than by lines could well give better results. Small triangular or quadrilateral elements have now been developed so that the membrane stresses and different directional properties may be modelled more accurately. This procedure is quite time consuming and requires a powerful computer. It will be left to other speakers to present in more detail.

Quite small computers can be programmed to generate a variety of suitable forms and to perform computer graphic operations allowing the viewer to obtain perspective views from a number of positions thereby enabling the designer to evaluate the surface forms. With such graphics, the computer models can nearly substitute for working models. There is however a limit to the number of forms that can easily be generated.

5.0 COMMENTS ON ANALYSIS

The previous section has suggested that proper analysis for forms of arbitary shape would require a computer program that is based on the finite element technique. Furthermore such analysis must be capable of allowing the structure to deflect to a new position. In most cases it could be said that the majority of the loads are carried by the structure adjusting its shape to accommodate the applied loads. Conventional structures are quite rigid and computer programs normally take the original geometry of the structure for all the calculations.

It is found that an iterative procedure is required to home in on the solution which must indicate that the structure is in equilibrium with the applied loads at the deformed position. Since stress ratios in different directions will change, the biaxial stress-strain curves for the material should be incorporated. This would now assume the direction of the fabric roll was known but this in turn may have little bearing on the gridwork of nodes and lines or elements defined to the computer.

Changes of shape will also influence the applied loads and perhaps some automatic means of re-evaluating pressures is required. Fabric regions going slack should not offer support in further iterations. Furthermore, because of the non linear behaviour it would be necessary to repeat the analysis for each different loading condition. Even if such a program was available it should be noted that these problems require a certain degree of experience to control the convergence of the solution.

Fortunately, not all problems warrant such a solution and many cases can be handled by approximate means. Approximations to membrane stresses can be found from a knowledge of the local curvatures and applied loads.

5.1 Pneumatic Cylinders

Consider the case of a long cylindrical pneumatic having the cross section shown in Figure 3. The associated dynamic wind pressures are shown together with the relevant values of external pressure coefficients. For the case of no wind, the fabric tension is given by $T=p\,r$ where T is the tension per unit length of the cylinder, p is the resultant pressure and r is the radius of curvature. This tension is a constant. Given now a transverse wind is blowing, the structure will change shape and the fabric tension will change. However for any particular shape, the product pr is a constant.

This is the basis for a solution procedure which can be performed graphically or by a small computer or even calculator. The arc is divided into say 10 elements and knowing the internal and external pressures on the first element p_1 we can assume a value of the radius of curvature r_1 for that element. An arc is drawn of the same arc length and the radius r_1. Next, the next element can be drawn tangential to the end of the first of radius $r_2 = p_1 r_1/p_2$ where p_2 is the known resultant pressure for element 2. This is repeated as shown in Figure 4 until we can compare the "span" of the deflected structure. If it is not the same as the undeformed structure we select a new trial value of r_1 and repeat the iterative scheme. The process is easily programmed and can give maximum movements of the structure under various wind speeds. Some typical results are shown in Figure 5.

5.2 Tensile Structures

These structures are "anticlastic" in their shape with two principal curves that oppose each other. Stressing of the surface in one direction automatically stresses the material in the other direction. When an external pressure acts due to the wind as in Figure 6 then the load is shared between the two directions. The stresses in *K1* will increase whilst in *K2* they will decrease.

Assuming that the boundaries are rigid it would be possible to crudely estimate the stresses by using the following outlined steps:

a) satisfy <u>equilibrium</u> by saying that the total applied load $p=p_1+p_2$ where p_1 and p_2 are the portions carried in each direction

b) satisfy <u>compatability</u> at the junction of the two curves. This is done by estimating the change in stress in each curve direction (e.g. by using $T_i = p_i r_i$ where r_i is some estimate of the radius of curvature) and, from a knowledge of the material properties, estimate the elongations due to p_1 and p_2. From these elongations a new position of the common point *A1* and *A2* is found for each curve, and, if they turn out to be the same point then we have chosen a suitable distribution of load p_1 and p_2. If not, then the process can be repeated for new values.

This procedure is similar to that adopted for the grid analogy for the approximate analysis of flat slabs or the trial load technique for analysing such a complex shape as a double curvature arched dam.

The considerations might be, in a crude analysis, - does the additional "compressive" stress in curve K_2 negate the initial pretension in the membrane in that direction? - if all the load was taken by curve K_1 would the fabric be strong enough?

Obviously there are several complications namely:-

a) the curvatures are expected to change along the curves
b) the ratio p_1/p_2 of the loads carried by the two curves is expected to vary as we move *K2* along *K1* or vice versa,
c) the pressure p is not a constant over the length of the curves,
d) the boundaries could well be flexible edge cables and the movements together or apart of opposite boundaries alters dramatically the normal displacements of A.

Local high stresses may occur especially near connections of adjacent edge cables where there may not be the ability of the fabric to allow for changes in shape. An initial design approach is to detail the connections so as not to impart local loads onto the cable sleeves for example.

If the movements calculated are excessive then it may be necessary to increase the level of prestress in the fabric or alternatively to perform a more accurate finite element analysis taking the material properties and the large displacements into account. However for this the careful preparation of the input data - supplying a smooth surface, specifying pretension forces, material properties, defining perhaps largely unknown pressure forces - could be quite an exercise.

6.0 CONCLUDING REMARKS

This paper has discussed the interaction of shape determination, the nature of the membrane material, and some of the requirements of an analysis. It has suggested that because of the limiting strength of the fabric and its inability to carry compression, that correct determination of shape or specifically the local curvatures is important as well as the pretension given to the structure either by internal air pressures or by use of jacks. Several of the complications of mathematically defining surfaces, knowing what might be the "correct" surface and then accurately analysing this under the applied loads have been given. Finally, some guidelines for crude hand analysis of simple pneumatics and tension structures has been presented.

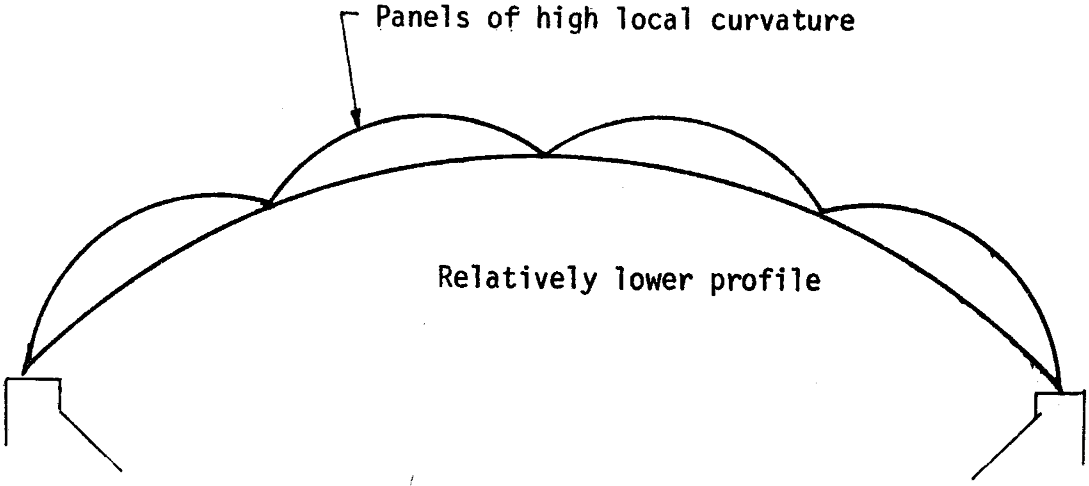


Figure 1. Cable Restrained Pneumatic

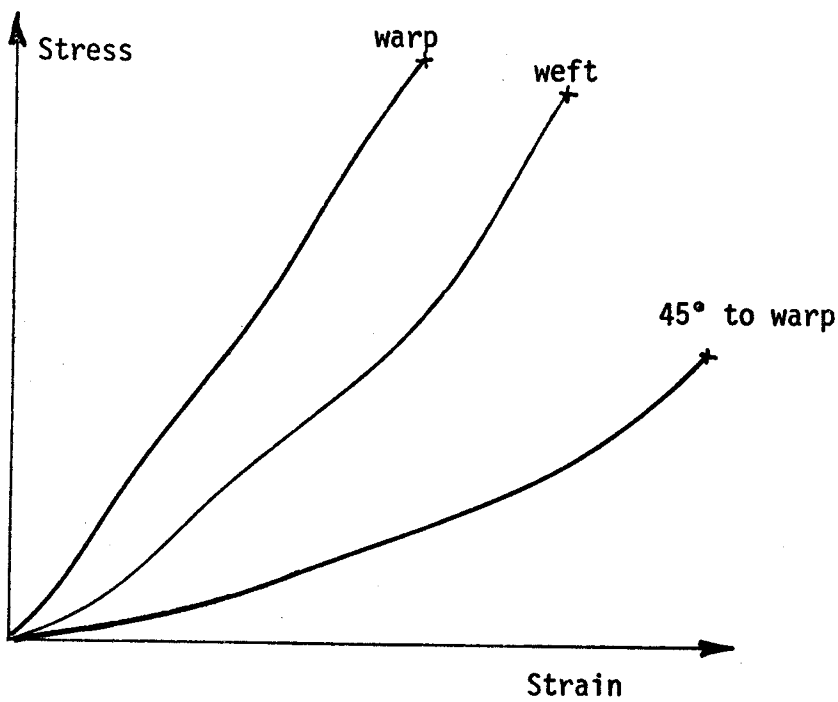


Figure 2. Stress -strain plots for typical PVC Coated Polyester Fabric

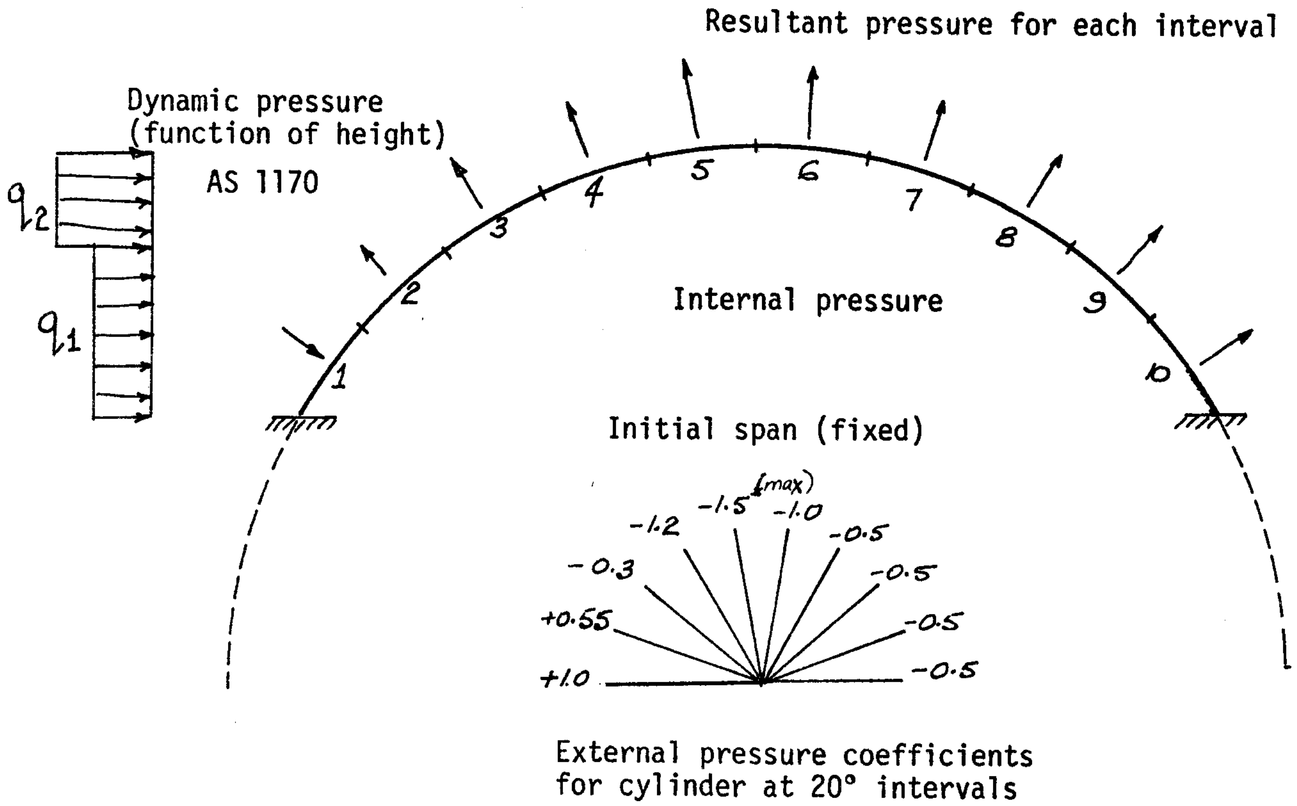


Figure 3. Pressure Distributions for Cylindrical Pneumatic

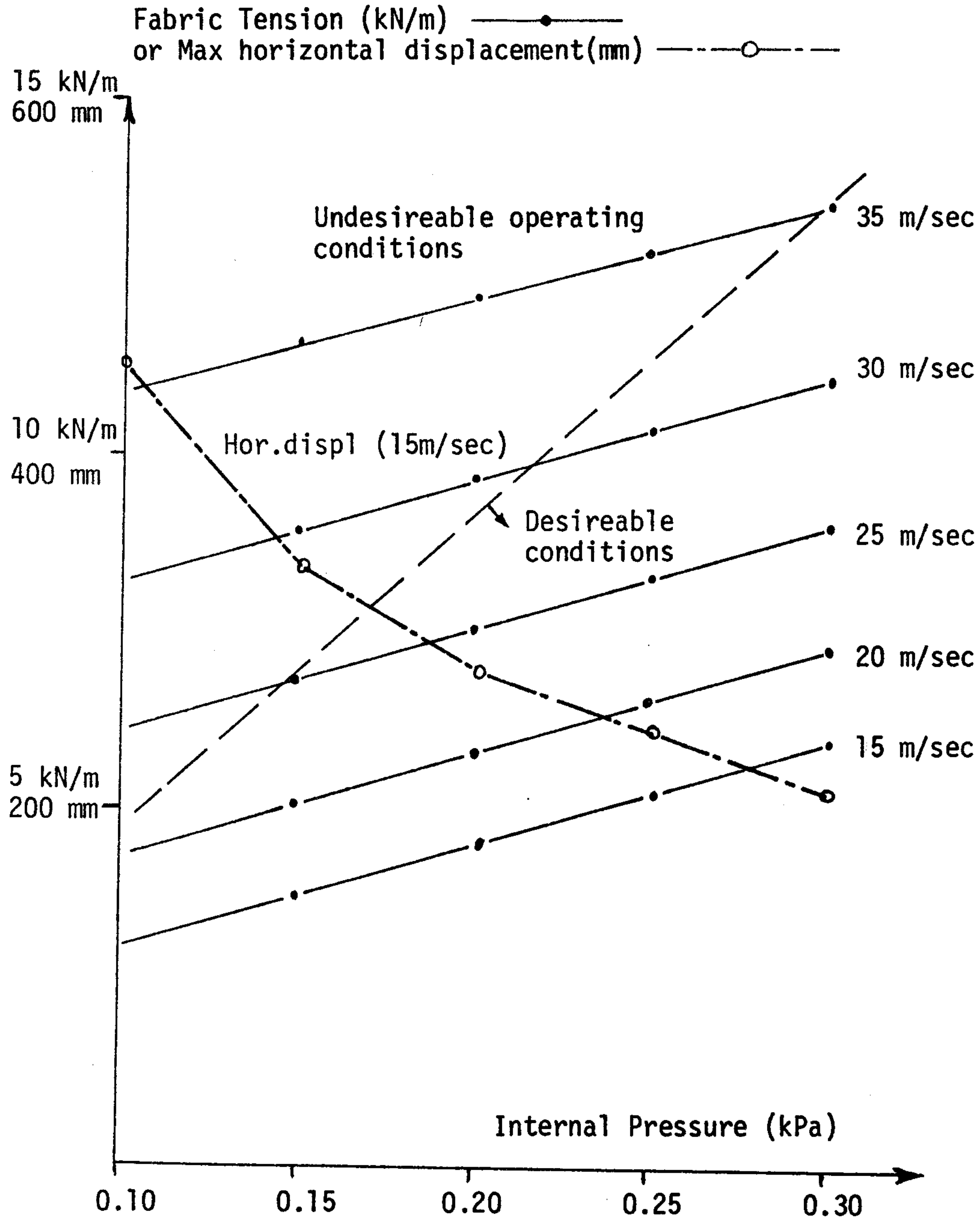
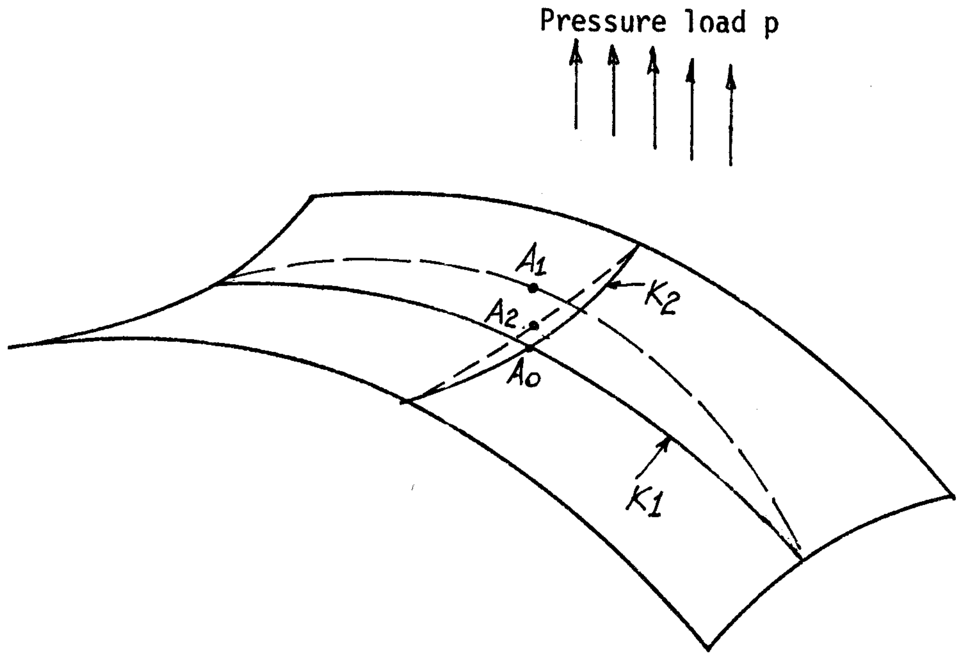


Figure 5. Variation of Fabric Tension and Displacements with Internal Operating Pressure and Wind Speed



Equilibrium requirement $p=p_1 + p_2$

Compatability requires that A_1 and A_2 be the same.

Figure 6. Approximate Analysis of a Tension Structure

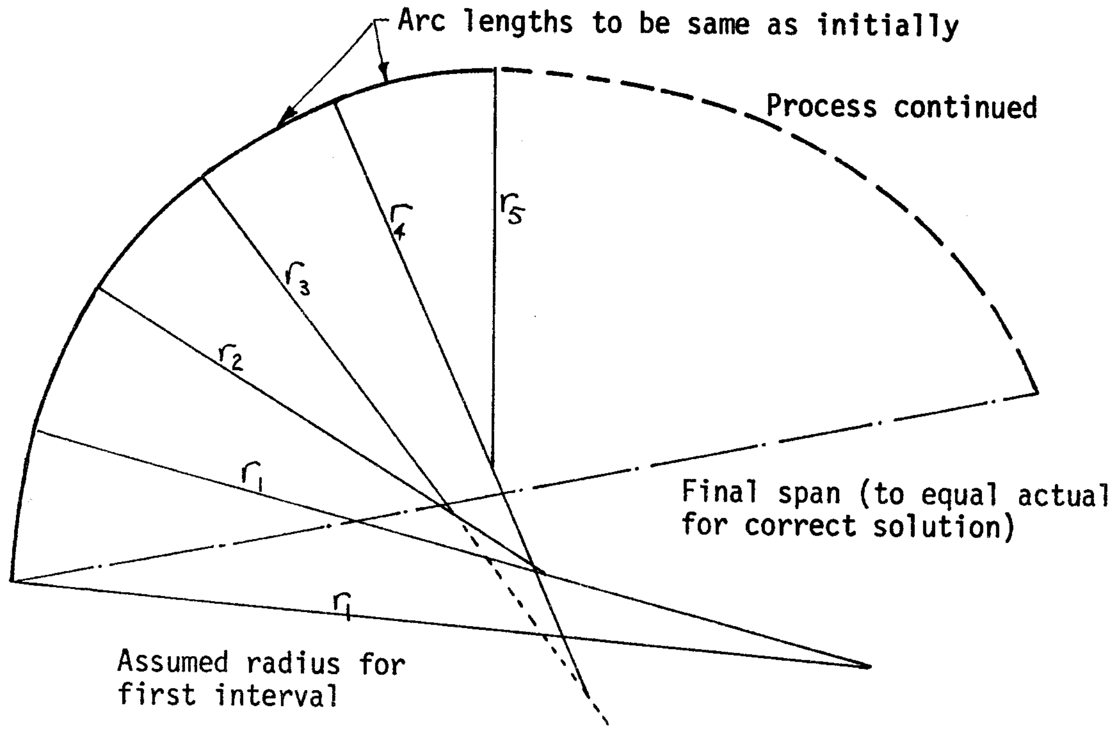


Figure 4. Graphical Analysis for Cylindrical Pneumatic Subjected to a Transverse Wind Load

PHYSICAL MODELLING FOR LOADING AND PERFORMANCE EVALUATION OF MEMBRANE STRUCTURES

John F. Howell

VIPAC & PARTNERS PTY. LTD.

1.0 INTRODUCTION

Physical models and building construction have a long historical association. Many of the early theories of structural action were developed as a result of model studies. In some related fields such as shipbuilding, models were used in preference to drawings until fairly recently. Designers of membrane structures have used very sophisticated models for the design processes of form finding, structural analysis, patterning and others.

Now however the use of physical models is mainly restricted to architectural purposes and the rapid presentation of visual information to clients and users. The use of physical models as an analytical tool has decreased as analysts have developed more powerful numerical or mathematical modelling techniques but may be used for program verification (1). In fact the enormous increase in analytical capability over the past decade has meant that we can now analyse practically anything using existing computer programs. Unfortunately this development in structural analysis has not been matched by an equal improvement in our ability to define loadings nor to assign appropriate material properties, especially in the new field of fabric structures. The analytical methods are extremely powerful but the quantification of boundary conditions remains imprecise.

It is also true that the cost of a computer analysis of a complex structure with many nodes and the necessary inclusion of non linearities of membrane structures may be very high. For a complete dynamic analysis the costs are even higher. It is in these areas of uncertainty or of unacceptable cost that the use of physical models is of real value.

It is important that the degree of sophistication of modelling, both physical or mathematical reflect the importance of the problem.

It is inappropriate to perform a full dynamic analysis with wind tunnel testing for a minor structure which would mostly be sized on serviceability rather than live load stresses. Similarly it is inappropriate to use static loads or static response calculations for large important structures such as the Haj Terminal or the planned 10 hectare pnuematic for Northern Alberta.

This paper is an attempt to present physical modelling in this two tier heirarchy. Simple structures demand simple load definitions and response predictions, normally based on static or quasi static methods. Complex or important structures require more sophistication in the evaluation of loads and due consideration to be given to the effects of the load/structure interaction yielding structural response prediction. Such problems require dynamic analysis if the applied loads are time dependent.

2.0 STATIC OR QUASI STATIC ANALYSIS

Structural designers normally reduce all loads to static or equivalent static loads for ease of computation. This approach is reflected in codes of practice where, for example, static design wind loads are prescribed. In Australia, snow loading is seldom a design consideration and for membrane structures, the prime design load apart from self weight is that due to wind action. For modest membrane structures, the designer requires an equivalent static wind load and its distribution over the surface. Generally, each membrane structure apart from simple pnuematics has a different shape, for a variety of reasons. They are very difficult to codify for a prescribed wind loading and relatively small changes in geometry can result in significant changes in wind loading. The designer then has little recourse but to adopt a very conservative estimate of wind load or to engage in wind tunnel testing in order to satisfy the regulatory authorities. Wind tunnel testing need not be prohibitively expensive providing a level of sophistication is adopted that reflects the importance of the structure.

2.1 WIND TUNNEL TESTING

Over the past two decades, wind tunnel testing of buildings has developed significantly as a design tool. Wind tunnel models are now routinely employed for major buildings. The importance of assessing loads on low rise buildings has been recognised and recently significant advances have been made in the assessment of wind loads on such structures (2,3 and others).

Successful wind tunnel testing requires that both the natural wind and the structure are modelled appropriately. The modelling of the wind must include the atmospheric boundary layer with its associated turbulence spectrum. This requires that the velocity and turbulence profiles be accurately modelled as shown in Figure 1. The techniques involved in this are well established - see for example (4, 5) and most modern wind tunnels can model the natural wind with good accuracy.

A typical environmental wind tunnel is shown in Fig. 2 in the photographs.

For the assessment of static wind loads a rigid geometric model is usually employed - see for example (6). The scaling of this must be consistent with the scaling of the wind and commonly results in model scales of 1:200 to 1:400, but there is some flexibility here. A length scaling of 1:500 results in a time scaling of 1:150 and a velocity scale of 3:10. The frequency resolution corresponds to about 0.7 Hz full scale with current equipment and sampling rates.

The historical development of building wind tunnel testing has made several important steps. Even a decade ago, commercial wind tunnels were using manometers to measure pressure distributions over models. This gives a good indication of mean pressures but cannot reflect the fluctuating component (7). Typical results for the Mennheim lattice shell are shown in Figure 3. Often these same wind tunnels used smooth flow rather than fully developed boundary layer flow with the nett result that mean pressures were over predicted but fluctuating pressures ignored. Some of these results are still included in codes of practice. It is rare for a structural failure to occur if these results are used but local failures of cladding due to high short term pressures or suctions are not uncommon. With the development of the scanivalve and suitable pressure transducers, the true fluctuating pressure could be measured. This allowed recording of peak pressures and the reasons for local cladding failures such as at eaves and ridges were better understood. The use of these new data for structural design, however yields even higher forces seen by the main members such as purlins or cables. The method is unable to take into account the lack of correlation between the peak pressures (8,9). While a realistic evaluation of cladding loads is obtained, main members will be oversized if fully correlated peak wind pressures are used to size the members.

Recent work by Stathopoulos and his colleagues (10, 11) has concentrated on this problem using the principle of pnuematic averaging. Peak pressures are evaluated as described above but the spatial averaging provided by the structure is accounted for by connecting several pressure taps to a common manifold and then measuring the nett pressure. The technique represents a major advance in predicting the member stresses and response of structures from results obtained on a rigid model. Previously these results were only available from aeroelastic or dynamic models (12, 13) and required very expensive models and instrumentation which could not be justified for most membrane structures. The method is being successfully used by Cook (14) in an experimental investigation of the wind loads on air houses and will be routine in the future wind tunnel tests of membrane structures carried out at the University of Bath.

This recent development has brought the routine use of wind tunnel models within the budget of most membrane structures. It is not able to predict instabilities due to wind action, however and care should be taken when applying results of this type of investigation to large wind sensitive structures. Fortunately modest size membrane structures are well behaved under wind action, provided a reasonable state of bi-axial stress is maintained (15), due to the large damping these structures exhibit. For large wind sensitive structures, however, full dynamic modelling is the only method currently available for the evaluation of response.

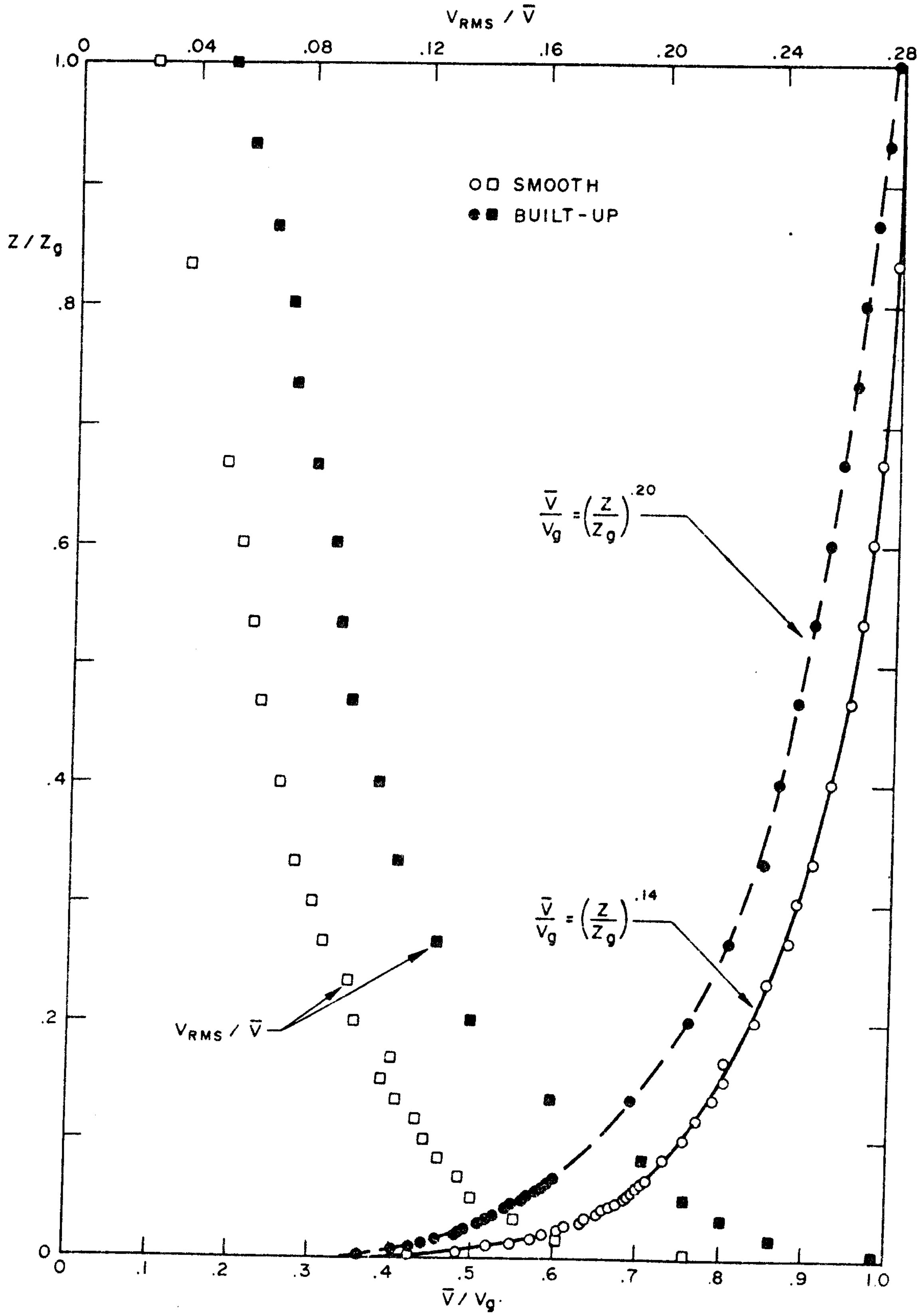


Figure 1 Mean Speed and Turbulence Intensity Profiles for Two Typical Terrains

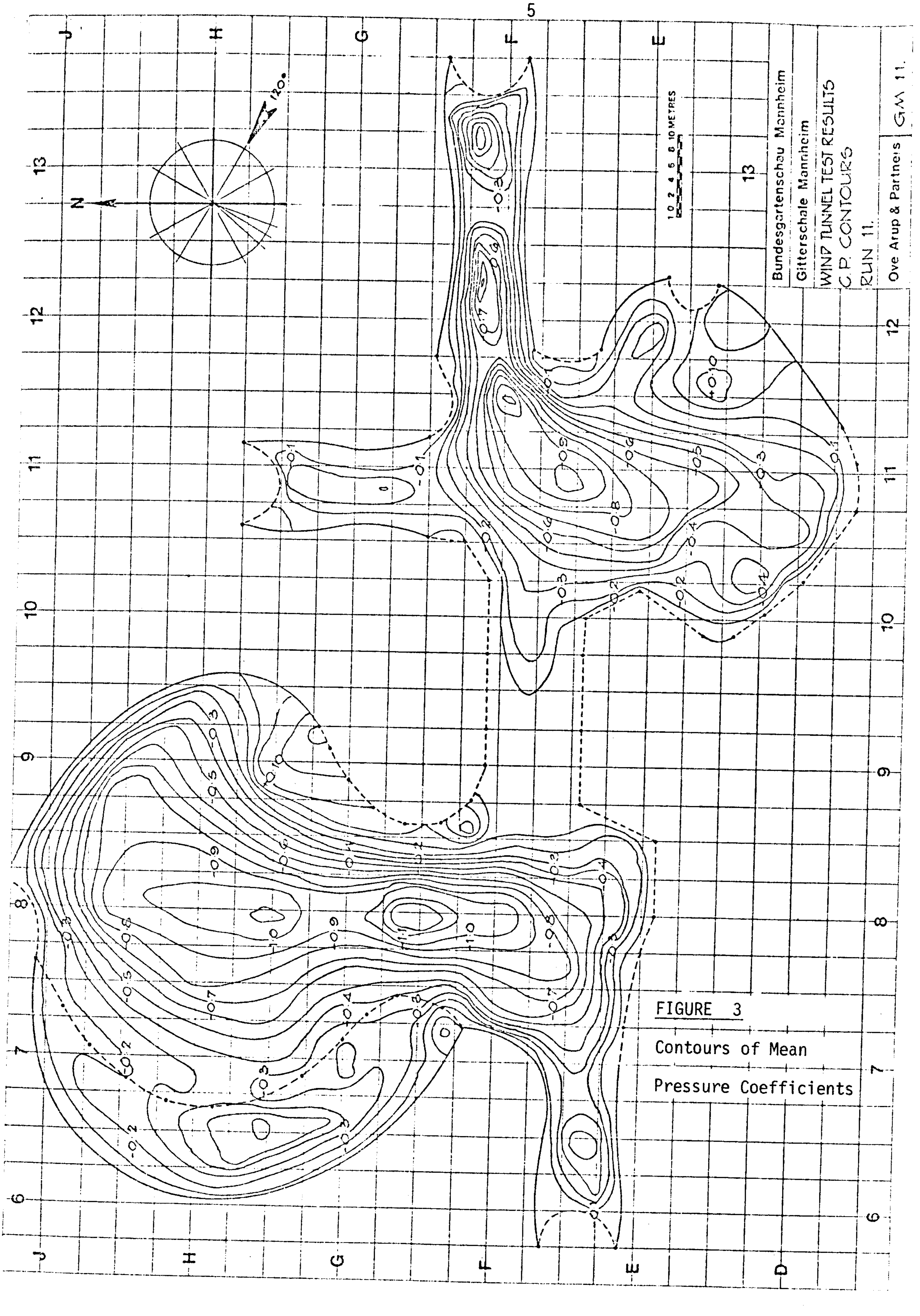


FIGURE 3

Contours of Mean Pressure Coefficients

2.2 STRUCTURAL MODEL TESTING

In spite of the enormous development in analytical capability in the last decade there are still some structures where the evaluation of load capacity is more readily done by computer. These structures are generally large, with very many members which cannot be easily lumped together mathematically and are generally non linear. Such a structure was the Mannheim Gitter-schale for BGS 75. The design procedure is detailed in Happold + Liddell (16) and (7). A plan view of this structure is shown in Figure (4) and in some of the later photographs. Model tests were used extensively in this project, from the initial form finding hanging chain model of Frei Otto to the structural and wind tunnel models of the engineers, Ove Arup. The structural model commenced with a 1:16 perspex model of the Essen gitter-schale which had a simple super circle plan and was to be constructed of the same 50 mm square hemlock timber laths on a 0.5 m grid. The modelling procedure is described below and the following notation is used:

I_{xx} = the second moment of area of one timber member corresponding to out of plane bending (or if the surface is constructed of a double layer grid, the second moment of area of two timber members acting together.)

I_{yy} = the second moment of area of one timber member (or two if double layer grid) corresponding to in plane bending.

A = the cross sectional area of a timber member (or two if double layer grid).

a = the spacing of nodes along timber members.

A' = the cross sectional area of one diagonal tie.

k = the ratio of the spacing of the diagonal ties to the minimum spacing corresponding to ties across every parallelogram.

E = Young's modulus for the timber members.

E' = Young's modulus for the diagonal ties.

S = a typical overall dimension of the structure, for instance a value of the span. Any dimension can be chosen as long as corresponding dimensions are used on the model and full size structure.

In order to ensure that the behaviour of the model is representative of that of the real structure and to interpret the results of the model test, it is necessary to understand the scale effects. Scale factors are derived from dimensionless groups made up from the properties of the structure which affect the structural behaviour.

For example if the critical load/unit area on the shell is controlled only by the out of plane bending stiffness/unit length $\frac{EI_{xx}}{a}$ and the span S then the relevant dimensionless group is $q_{cr}/\frac{E\ I_{xx}}{a\ S^3}$. To scale up the critical load from structure 1 to structure 2, the following expression is used:

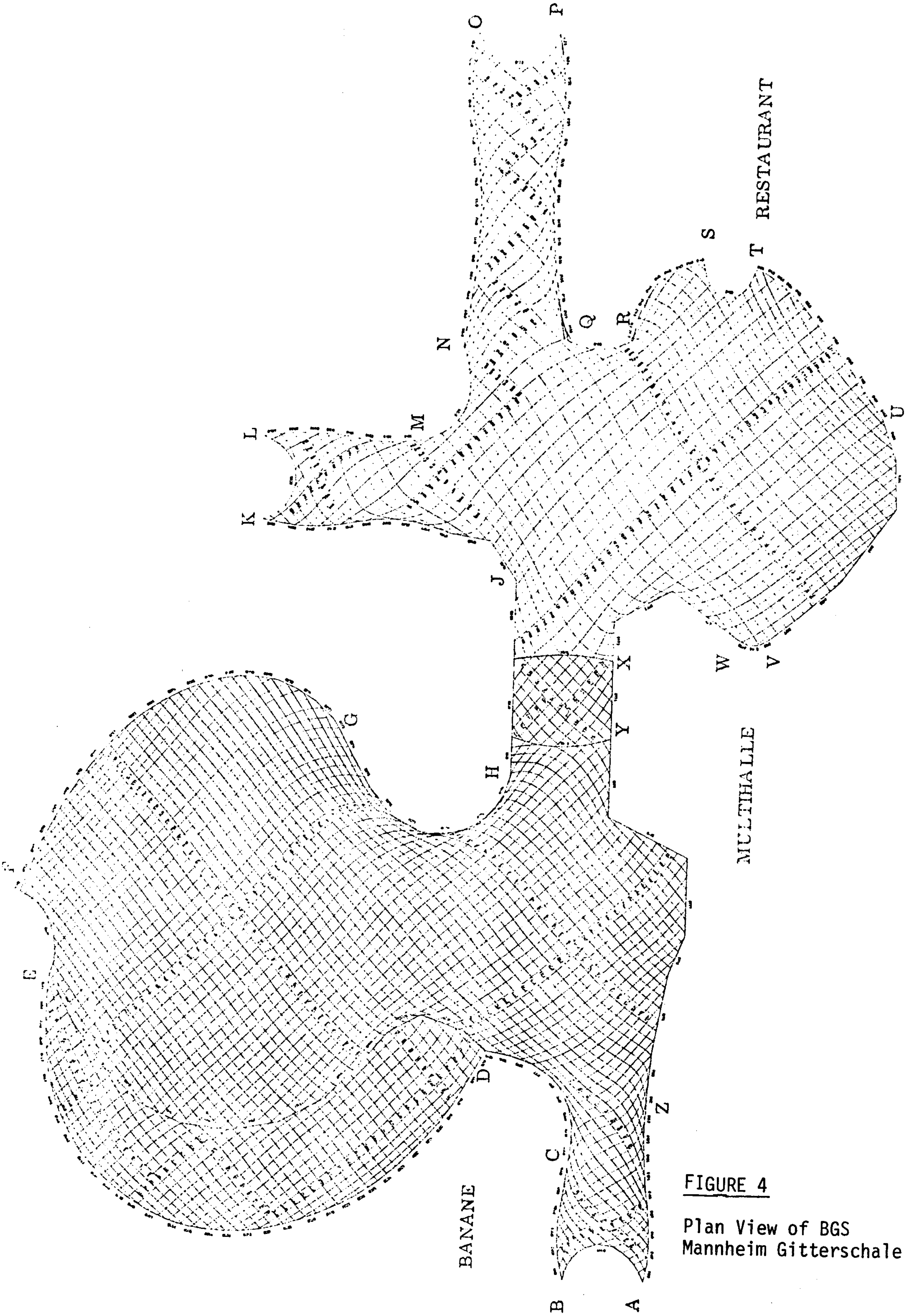


FIGURE 4

Plan View of BGS Mannheim Gitterschale

$$\frac{q_{cr}\ (1)}{q_{cr}\ (11)} = \frac{\left(\frac{E\ I_{xx}}{a\ S^3}\right)(1)}{\left(\frac{E\ I_{xx}}{a\ S^3}\right)(11)}$$

For a lattice shell with some diagonal stiffness, the out of plane bending stiffness is the most important property controlling the buckling load. Therefore, the above scale factor is the most important.

There are several other properties which also affect the behaviour, particularly the member area/stiffnesses and these can be used to form other independent dimensionless groups. If these groups are numerically the same for the model and for the real structure, then these properties will be correctly scaled and the behaviour of the structure will be correctly represented by the model. In this manner dimensional analysis has been used to identify the dimensionless groups.

The properties of the structure which define and control its behaviour are as follows:

1. S = Span — Dimensions $\equiv L$

   If the model is geometrically scaled then its size can be represented by a typical dimension, say the span.

2. $\frac{E\ Ixx}{a}$ = the out of plane bending stiffness of the surface per unit length — FL

3. $\frac{E\ Iyy}{a^3}$ = is proportional to the contribution of the timber members to diagonal stiffness, if the joints between timber members are rigid — FL^{-1}

4. $\frac{EA}{a}$ = is the axial stiffness along the timber members per unit length — FL^{-1}

5. $\frac{E'A'}{ka}$ = is proportional to the contribution of the ties to the diagonal stiffness — FL^{-1}

   i.e. $q_{cr} = f\left(S, \frac{EIxx}{a}, \frac{EIyy}{a^3}, \frac{EA}{a}, \frac{E'A'}{a}\right)$

We need only two units or dimensions to describe all the variables in equation 2. and they are a unit of length L (for example m) and a unit of force F (kp). (Note: 1 kp = 1 kg Force)

Thus, $\frac{E\ Ixx}{a}$ has dimensions or units $\frac{F}{L^2} \times L^4 \times \frac{1}{L} = FL$ and the other structural properties have dimensions as shown above. As there are six terms in equation 2. including q_{cr}, and two dimensions it can be rewritten in non-dimensional form in terms of four (6 terms - 2 dimensions) independent non-dimensional groups:

$$I = \frac{q_{cr}}{\frac{E\,I_{xx}}{a\,S^3}} = \frac{q_{cr}}{\frac{E\,I_{xx}}{a} \times \frac{1}{S^3}}$$

$$II = \frac{S^2\,I_{yy}}{a^2\,I_{xx}} = S^2 \times \frac{E\,I_{yy}}{a^3} \times \frac{1}{\frac{E\,I_{xx}}{a}}$$

$$III = \frac{S^2\,A}{I_{xx}} = S^2 \times \frac{EA}{a} \times \frac{1}{\frac{E\,I_{xx}}{a}}$$

$$IV = \frac{S^2\,E'A'}{k\,EI_{xx}} = S^2 \times \frac{E'A'}{ka} \times \frac{1}{\frac{E\,I_{xx}}{a}}$$

It is possible to form other non-dimensional groups such as $\frac{a^2\,A}{I_{yy}}$, but these further groups are only combinations of I to IV above.
Hence,

$$\frac{q_{cr}}{\frac{EI_{xx}}{a\,S^3}} = f\left(\frac{S^2\,I_{yy}}{a^2\,I_{xx}}, \frac{S^2\,A}{I_{xx}}, \frac{S^2\,E'A'}{k\,E\,I_{xx}} \right) \qquad (4)$$

Equation 4 shows that non-dimensional group 1 is a function of II, III and IV only. Hence if the model is constructed so that the numerical values of the groups II, III and IV are the same as on the full size structure, then the group I will also have the same value for model and full size structure. If group I has the same value for the model and the full size structure, then the collapse load on the structure can be found from the collapse load on the model since $\frac{E\,I_{xx}}{a\,S^3}$ is known for both.

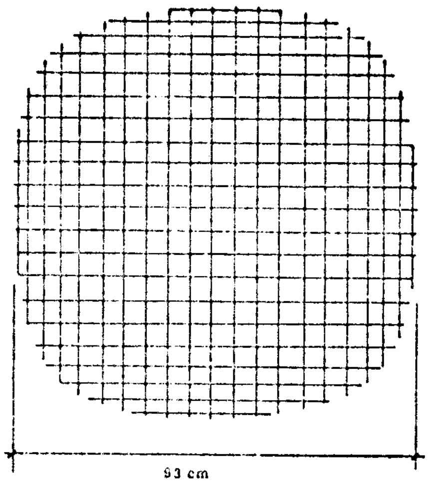
The model has to be constructed such that the non-dimensional groups II, III and IV have the same value as on the full scale structure. Groups II and III are more difficult to model but they have less effect on the value of group I than does group IV. The effect of group II may be overshadowed by that of group IV if the diagonal ties have a larger contribution to diagonal stiffness than the bending stiffness of the main members. Group III represents the effect of the axial stiffness of the main timber members. Provided that this axial stiffness is relatively much higher than the diagonal stiffness then its actual value will not change the collapse load appreciably since the deformation of the structure will be mainly bending of the timber members and changes of length of the diagonal ties.

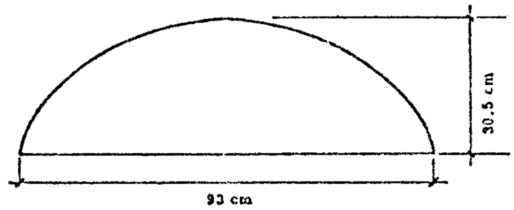
Group II can be modelled by choosing the depth to breadth ratio of the model members. If it is not possible to model group II exactly then safe answers would be obtained if the numerical value is too low on the model.

Similarly, safe answers would be obtained if the numerical value of group III is too low on the model. If both the model and the structure are constructed on a double layer grid, then the model will give safe answers if the scale depth of the model members is greater than that of the true structure. This is because I_{xx} increases faster with depth than does A. If the model is constructed on a single layer while the structure has a double layer, then safe answers will be obtained if the model members are greater than $\sqrt{13}$ times as deep as the scale depth of one layer of the full size structure.

Early in the design process for the Mannheim dome, it was decided to make a 1/16" scale model of the 15 m. span Essen dome because the fabrication dimensions were available from Professor Otto. It was intended to use the model to help understand the behaviour of lattice shells and possibly to carry out load tests. It was also decided to make the laths as thin and flexible as possible so that the structural properties modelled those of the Mannheim multi-hall shell as closely as possible. The most suitable material for the model laths was perspex strip which had a Young's modulus 1/4 of that of timber. It was also easily worked and jointed.

The basic lattice for the model consisted of 3 x 1.7 mm. laths at 50 mm. centres. The dimensions of the model were as follows:





The model was loaded by hanging grouped 4" long nails at the nodes, the average weight of each nail was 12.5 grams. Each load case consisted of a uniformly distributed load plus a point load at one of three points denoted as centre, side and corner. With the UDL constant, the point load was increased and its deflection measured. This enabled the failing load to be determined. The UDL was then increased and the same procedure repeated. The failing point loads were then plotted against the UDL to establish the critical UDL.

Four sets of tests were carried out with different conditions of diagonal restraint. These were:

A. pinned joints

B. glued joints, i.e., no rotation at the joints

C. pinned with loose ties

D. glued with nylon ties at all nodes.

For test case A the 'corner' point gave the lowest failing load. With this case the symmetry of the structure allowed large sway movements to take place which greatly reduced the failing load. This mode of failure was prevented by the addition of some diagonal stiffenss and with ties this point became the strongest.

The centre point gave the most consistent failing loads. In the following graph the maximum centre point load is plotted against UDL to predict the critical UDL.

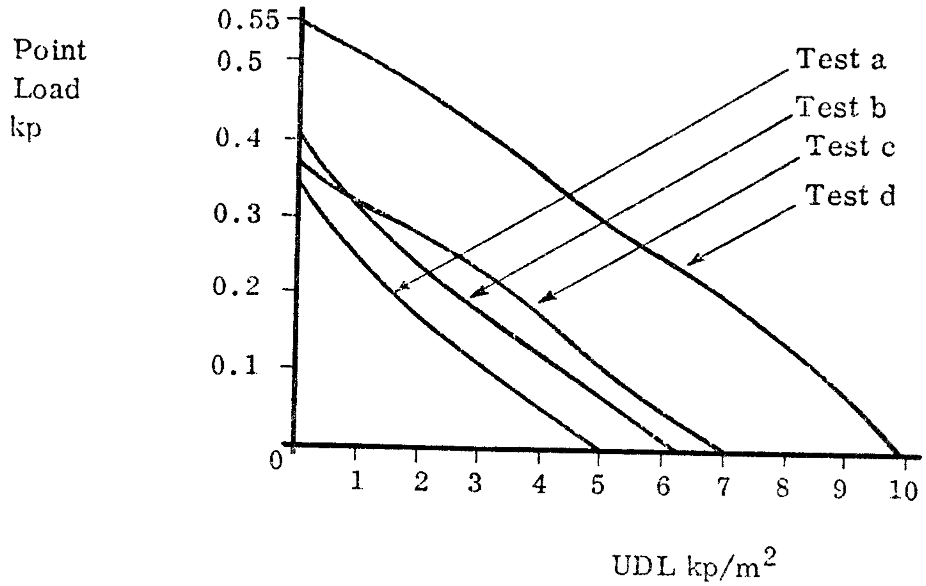


Figure 5: Prediction of Critical UDL
from Max. Point Load vs. UDL Plot

In the following table these results are scaled up to predict failing loads for both the Essen Shell and the Mannheim Multi-hall Shell with single layer grid and with double layer grid.

	Collapse Load including Structure Own Weight in kp/m^2	
	Rigid Joints	Rigid Joints with Ties
Essen Shell (single layer)	150	- *
Mannheim Multi-Hall (single layer)	3.8	- *
Mannheim Multi-Hall (double layer)	100	160
Mannheim Restaurant Shell (single layer)	5.8	- *
Mannheim Restaurant Shell (double layer)	150	240

* Model results cannot be meaningfully scaled.

Although care was taken to choose typical dimensions for scaling, the Mannheim shells are not geometrically similar to the Essen model and so the results may be inaccurate. The results of the tests however do indicate the advantages to be gained by adding diagonal stiffness.

The Mannheim multi-hall model was constructed in a similar way to the Essen model described above to a geometric scale of 1:60. It was made from 1.40 mm deep by 2.60 mm wide perspex members in a single layer with a joint spacing of 5 cm. One perspex member therefore represents 60 x 5/50 = 6 double layer members on the full scale structure.

The joints were made by drilling small holes in the members at 5 cm centres and then passing small pins through the holes. The pins were then bent over to form the joint. The joints were not glued since the tests on the full scale joint showed that a single bolt connection does not provide sufficient stiffness to prevent relative rotation of the members in the plane of the lattice. However, the tests on the Essen model described in our earlier report showed that the effect of glueing the joints is slight. The effect is further reduced if ties are present.

The model was built on a timber base board with perspex rod and sheet to represent the supporting columns, beams, arches, and concrete walls. No attempt was made to scale the stiffness of the supporting structure except for the arch in the Multihall. This is because the deflections of the boundaries will not be large enough to significantly affect the behaviour of the shell.

Some of the tests were performed with diagonal ties consisting of stout linen thread added to the model. The ties were at a spacing corresponding to 3 $\sqrt{2}$ m on the full scale structure and were attached to the nodes by wrapping the thread around the pins and then adding a drop of glue.

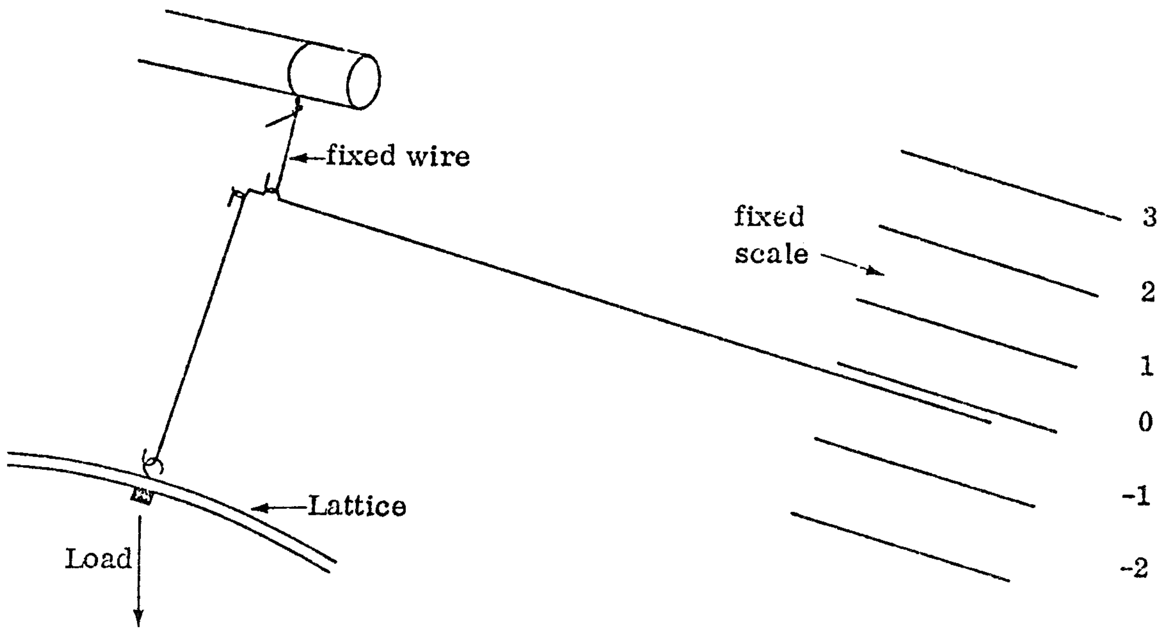
Photographs of this model and the Essen model are included at the end of this paper.

The model was tested using a similar procedure to that employed for the Essen model. A distributed load was first applied to the model and then a point load at various locations in turn. At each location the deflection of the structure was recorded as the point load was increased.

This procedure was adopted since it is possible to predict the collapse load from the load-deflection curves without actually collapsing the model. It was important not to collapse the model since once started, the collapse is difficult to arrest and would result in considerable damage. This is especially so when the model has ties, due to the higher load carrying capacity.

The load was applied using 10 cm nails each 12.5 gms. The deflection of the structure under a point load was measured using a dial gauge for the first experiments. Later, a lever arrangement was fabricated out of fine wire to avoid the friction inherent in a dial gauge.

The lack of friction in the lever enabled readings to be obtained using smaller point loads. This meant that the stiffness of the structure could be measured without affecting it with gross local deformations. The lever arrangement is shown full size in the following diagram.



The model collapse loads of 2.8 kp/m^2 with no ties and 12.5 kp/m^2 with ties have to be scaled to predict the collapse load of the full scale structure.

The method for scaling the model test results is described above.

Using the relevant parameters, the collapse load scales as

$$\frac{q_{cr1}}{q_{cr2}} = 3.96 \times 12.2 \times 10^6 \times 0.1 \times 4.64 \times 10^6 = 22.4$$

The full scale structure collapse load can, therefore, be predicted as follows:

With no ties $2.8 \times 22.4 = 63$ kp/m^2

With ties $12.5 \times 22.4 = 280$ kp/m^2

It is now necessary to consider the effect of not scaling other non-dimensional groups. By far the most important of these groups is that which relates the joint stiffness to the timber member properties. A suitable group can be wirtten as

$\frac{nS^2}{ab^2E}$ where S = the span.

This can be rewritten as $\frac{nb^2\ S^2}{aEI_{xx}}$

The influence of this group on the collapse load is to over estimate the collapse load, i.e. under predict the structural load capacity.

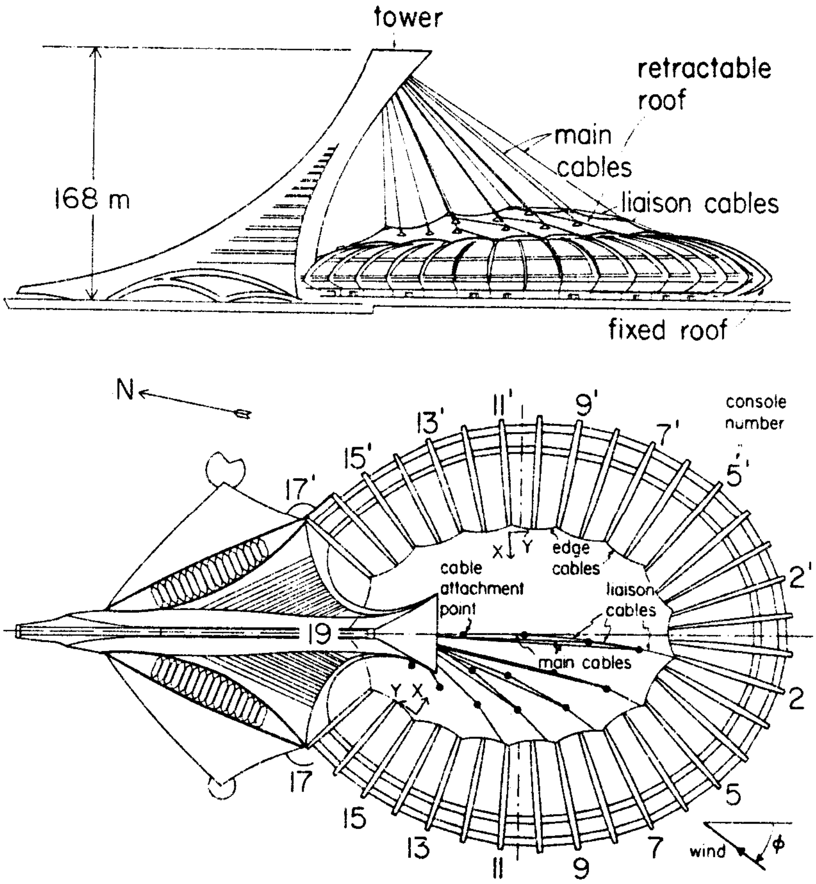
In spite of this drawback the model was exceptionally useful in providing qualitative data showing the type of buckling failure to be expected and the most critical areas of the structure.

For this structure, snowloading was the critical design load case and the static load capacity was of prime importance in establishing the adequacy of the design.

3.0 DYNAMIC ANALYSIS

For large, important or wind sensitive membrane structures, the quasi static approach detailed above is not sufficient. Aerodynamic instabilities, local panel resonances and other dynamic effects cannot as yet be predicted by analytical methods. Just as the major tall buildings are designed using dynamic or aeroelastic models, so too are large membrane structures such as the Haj Terminal, the Dalhousie ice hockey arena (17), the Montreal Olympic Stadium (18) and the Oklahoma Football Arena (12).

For dynamic similarity a minimum of thirteen non dimensional parameters is required to fully describe a membrane roof system. Irwin (18) describes the relative importance of these in great detail for the Montreal Olympic Stadium shown below.



Montreal Olympic Stadium after Irwin & Wardlaw (18)

The main parameters for cable behaviour are $M/\rho S^2$, $EA/\rho U^2 S^2$ and the damping term $D/\rho U^2 S$, where U is wind velocity.

For a sealed or nearly sealed structure, the internal volume contributes a pnuematic stiffness if the membrane roof deflections produce a net change of internal volume. The importance of this was shown by Howell (12) and later by Abu Sita (13). Irwin (18) discusses this point in detail and points out that correct scaling of pnuematic stiffness requires a different scaling of the model internal volume from the geometric scaling unless the ratio of model wind velocity to fullscale velocity is 1:1. It appears unlikely that modes of membrane vibration that result in a net volume change would ever be excited to a large amplitude. This is because they radiate low frequency acoustic waves into the external air resulting in damping of the membrane motion. To simulate the acoustic damping correctly at model scale, similarity of the parameter $(U/c)^{-2}$ is required. This is equivalent to Mach number scaling.

Some parameters however can be relaxed, such as the mass scaling of the membrane. Added mass effects dominate the mass scaling and are orders of magnitude greater than membrane self weight at typical frequencies.

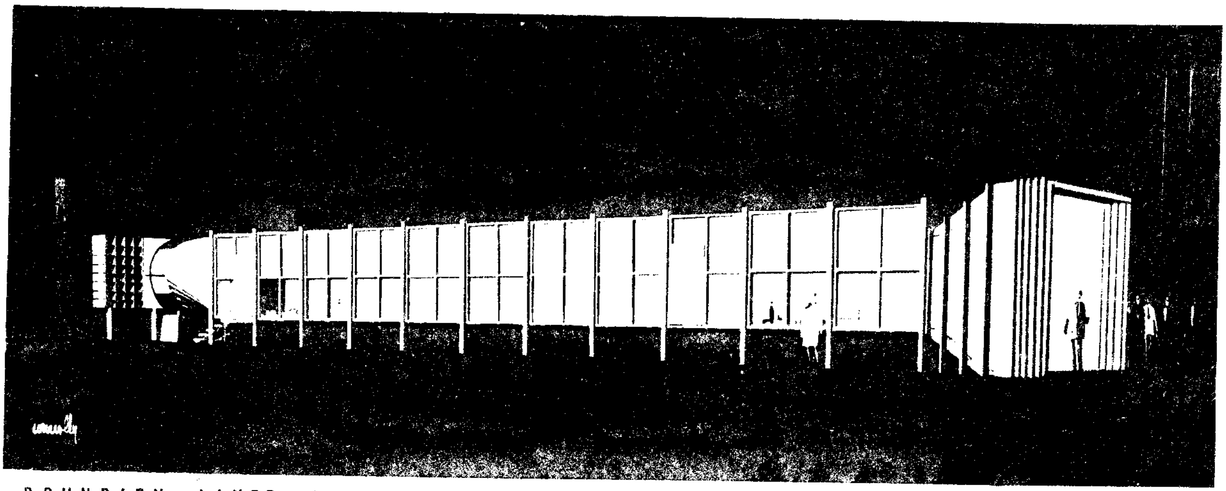
It is worth noting also that on membrane structures the natural frequencies will depend on the mean wind speed due to the dependence of membrane tension on wind speed.

One of the main reasons for conducting aeroelastic wind tunnel tests is to discover any unforseen aerodynamic instabilities. Thus large amplitude vibrations are looked for. Taut membrane models, however, are very sensitive to wind tunnel noise which may result in large amplitudes at some critical wind speeds. The large vibratory forces reported by Irwin & Proulx (19) are now known to be acoustic in origin.

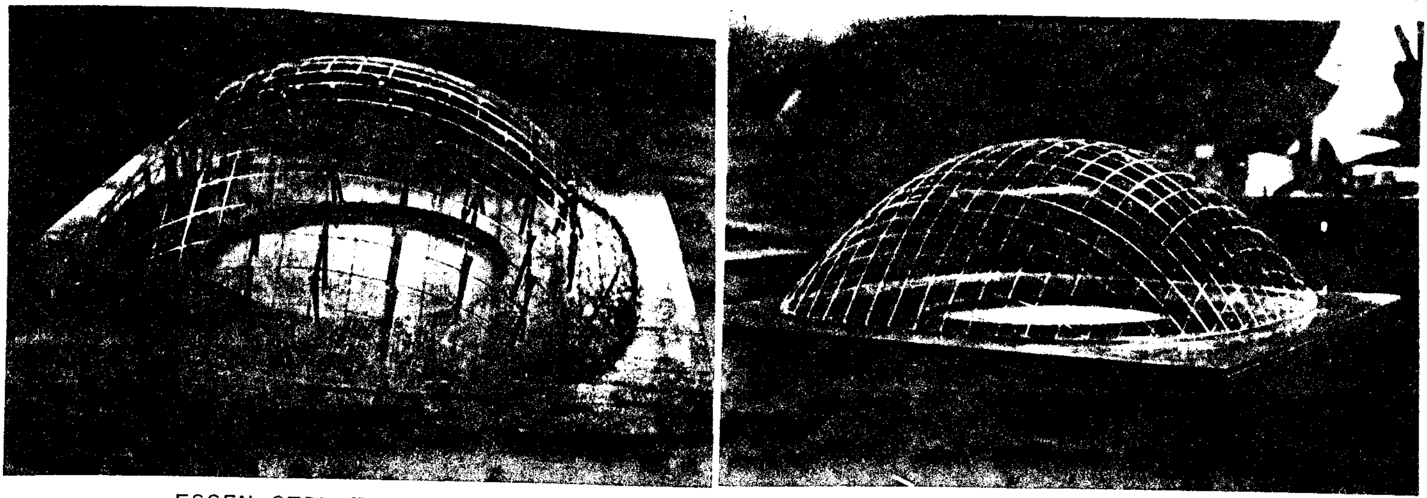
4.0 CLOSING REMARKS

Providing proper precautions are taken, the wind tunnel testing of aeroelastic models remains the only satisfactory method of investigating aerodynamic instabilities or local resonance effects for membrane structures. In general the cost of such an investigation precludes its adoption for all but major structures or where there is some evidence that the structure may be wind sensitive. For other structures, recent developments in pneumatic averaging of fluctuating pressures measured on rigid models have made wind tunnel testing an economical design tool for membrane structures.

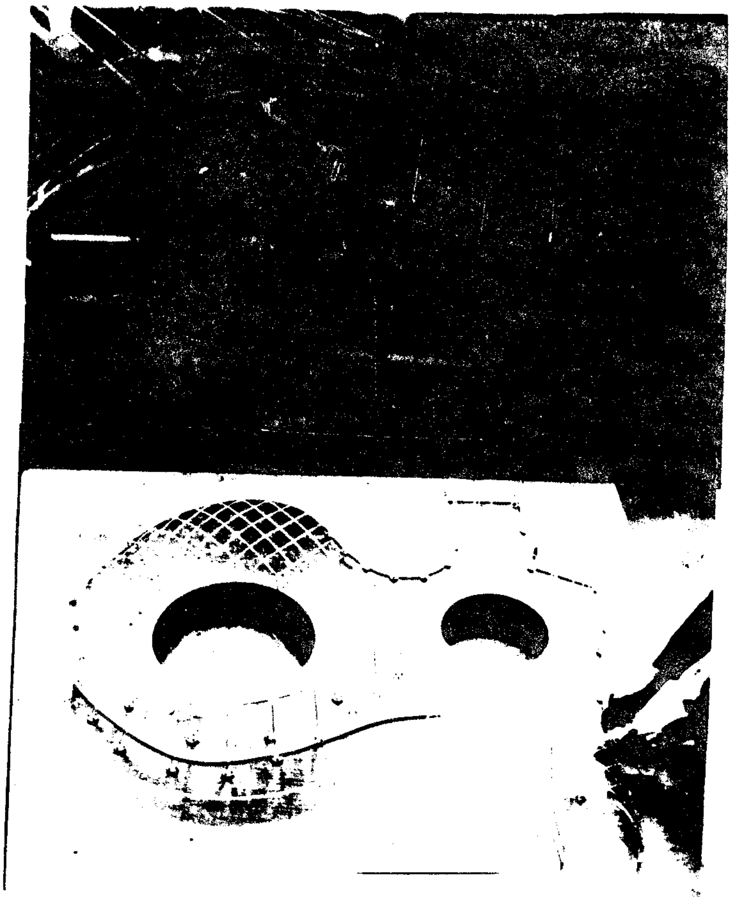
For some special structures, structural models may yield a clearer insight into the behaviour of the system than numerical models, at least in the early stages of design. They also provide a valuable tuning of computer models for later analysis.

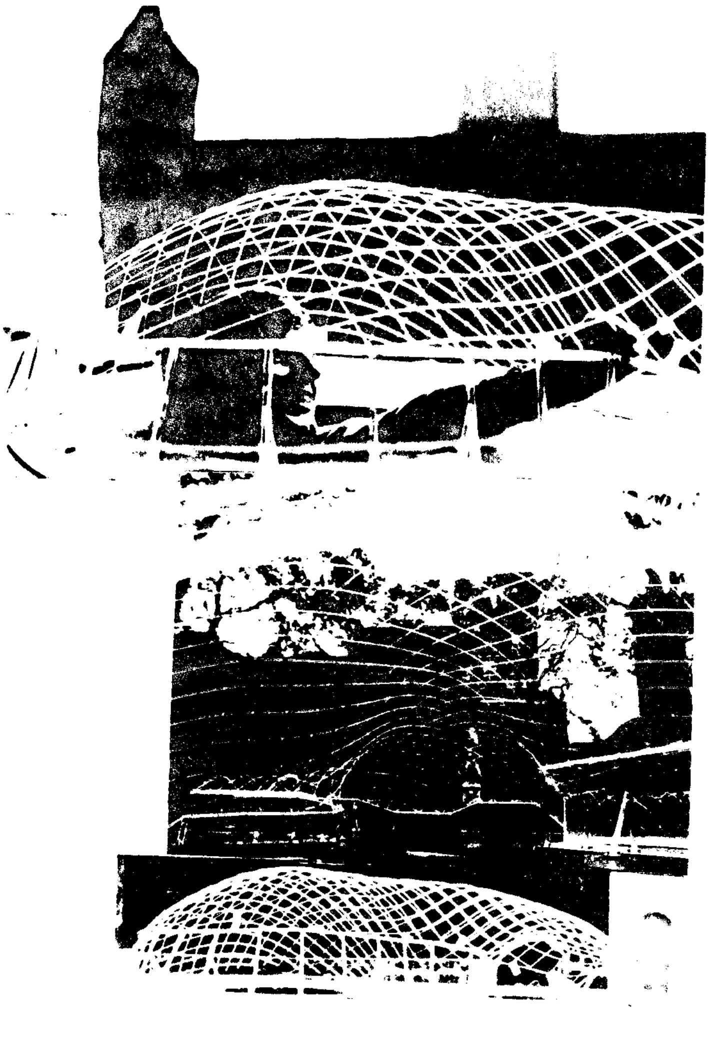


BOUNDARY LAYER WIND TUNNEL



ESSEN STRUCTURAL MODEL





MANNHEIM STRUCTURAL MODEL

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DEVELOPMENT OF A PVC COATED POLYESTER FABRIC FOR AUSTRALASIAN CONDITIONS.

Robert J. Hutton

Nylex New Zealand Limited

1.0 INTRODUCTION

Before beginning, I would like to thank Mr. Sedlak and the University of New South Wales for the opportunity to share with you the development of our PVC coated polyesters. We commend the initiative of the University in arranging this seminar. Over the past decade we at Nylex have watched closely the development of materials and building systems in the Northern Hemisphere and in the last few years have developed two products specifically for the Australasian membrane structure market. I propose to break my talk into three segments. Firstly I will give a brief history of our technology base. Then I will cover the development parameters and procedures used to ensure that we made a product that meets the bulk of the market's needs as well as giving reasonable service life under Australasian conditions. Thirdly I will detail the manufacturing and quality control processes used in the manufacture of Camlon Airflex fabrics.

2.0 A BRIEF HISTORY OF NYLEX TECHNOLOGY BASE

The Nylex history regarding spread coating technology has generally paralleled that of the European coaters. During the early sixties and seventies PVC coated fabrics for industrial markets were produced by Nylex on both sides of the Tasman. However, more recently it has been concentrated in New Zealand where we have a modern spread coating line. In New Zealand we began producing PVC coated nylons for the transport industry in 1968 following the completion of a technical agreement with Galon Marborex, one of the leading Scandinavian coaters at the time. However, it was not until 1970 that we really began to learn more about the harshness of the climatic conditions in the Southern Hemisphere and the effect of prolonged UV light exposure on PVC coated nylon . At that time we undertook a series of trials in conjunction with New Zealand Railways where they compared what we could produce with the PVC coated nylons used by British and other

European Railways. Some of our trial fabrics had PVC formulations containing higher than normal pigment loadings as well as varying percentages of UV light inhibitors. Following the results of these trials, in which the European fabrics failed to give a reasonable service life compared to some of our trial fabrics, New Zealand Railways wrote a specification which is still current and we have supplied their requirements ever since.

Once New Zealand Railways had changed from canvas, the transport industry in general began to ask for the same product and we upgraded our standard Camlon tarpaulin fabrics to the Railways' specification. Apart from some fune tuning and updating of raw materials and fabrics, our current tarpaulin fabrics can all be traced back to those early trial fabrics. Even today, European transportation fabrics have lower pigment levels and little or no UV light inhibitors in the PVC coating. New Zealand Railways are currently averaging six years service life with their covers - a fact which has assisted us to gain significant penetration into general transportation applications on both sides of the Tasman.

So where has all this led us?

We had a range of tarpaulin fabrics engineered for prolonged life under Australasian conditions. We had combined technology based on each side of the Tasman with the Australian base having built up a wealth of knowledge in outdoor formulations as a result of experience in the awning and metal cladding markets. We had a number of technical agreements and associations with overseas producers and suppliers; and we had a market potential in Australasia which had grown from the canvas circus tent era and was beginning to follow the Northern Hemisphere trend of membrane structures made from PVC coated fabrics for a wide variety of applications.

3.0 DEVELOPMENT PARAMETERS AND PROCEDURES

With the history I have briefly covered, we set out to establish what product or products were required to satisfy the membrane structure market's needs during the initial growth period. We had already done some development work on a fabric for an inflatable warehouse in conjunction with Hoechst and Hood Sails in New Zealand during 1975. However, this project did not proceed.

In setting the development parameters we first looked to what information was available from overseas - especially Europe. There was no sense in re-inventing the wheel and with assistance from the major yarn producers, especially Hoechst, we were able to build up a considerable amount of information on base fabrics, coating formulations and final specifications including some government regulations and specifications used overseas. We also looked at what Australasian building codes would need to be met as well as establishing the grade of product which would satisfy the majority of Australasian applications. Many of you here today have assisted in this regard.

We decided to begin with two products now known as Airflex 750 and Airflex 950 which in essence, are very similar to the membrane Types 1 and 2 listed in the West German Building Code.

The first parameters to be met were those of strength and dimensional stability. While the 940 dtex nylon used in the tarpaulin fabrics had the inherent strength it could not match the superior dimensional properties of polyester. So the first decision was to use a base fabric woven from polyester yarn. We chose Trevira type 710 yarn in 1100 dtex which had a proven history in European membrane fabrics and because we already had experience with this yarn in producing a coated product for flexible bulk bags. This yarn is made up of 200 very fine continuous polyester filiaments twisted together at a twist of 60 times per metre length. The two woven base fabrics chosen were as follows:

For Airflex 750 the yarn is plain woven to a construction of 9 threads per centimetre in both warp and weft directions. This gives a base fabric weight of approximately 200 gsm.

For Airflex 950 the yarn is woven in a panama or matt 2/2 weave to a construction of 12 threads per centimetre in both warp and weft directions. This gives a total weight of approximately 275 gsm.

Having settled on the base fabrics our PVC technologists set out to formulate PVC plastisols which met the parameters required. They looked at formulations available from Europe and it was here that our dilemma became apparent. The European formulations were little different to a flame retardant version of our current tarpaulin fabrics and we were looking to develop formulations which would be significantly better than our basic tarpaulin fabrics plus meet the strict Australian Flame Retardancy standards for buildings.

Following numerous laboratory and plant trials, we settled on two plastisol formulations. The first, known as the base coat because it is applied directly to each side of the base fabric, has a number of functions to perform

- it ensures that a good permanent bond is made between the PVC coating and the fabric. This bond isimportant in that it ensures delamination does not occur under flex conditions and that HF welded seams can be relied upon to give a permanent join.
- it forms the first stage in protecting the fabric from deterioration due to UV light and mechanical damage due to abrasion.
- it also forms the first stage in imparting flame retardant properties to the product.

The second, known as the top coat, makes up the bulk of the coating weight. The top coat is coated over the base coat on each side of the fabric. The top coat which is coated in a 60:40 Face:Back weight ratio provides most of the extended life properties for the finished product . Especially formulated for prolonged outdoor exposure, flame retardancy, HF weldability and abrasion resistance, the top coat is probably the most advanced outdoor formulation produced by the Nylex Group.

Both Airflex products have been tested by the Australian Wool Testing Authority Laboratory for flame retardancy against AS1530 Pts. 2 and 3 and we understand that there are few other membrane fabrics which perform as well as these two products. We have also had light transmission tests made for the various colours produced to date and while we could increase the translucency of our white fabrics, this could only be done with due regard being given to the reduction in performance life which would result. Both simulated and actual outdoor weathering tests are continuing to be monitored using our Melbourne laboratories and the Allunga test site in Northern Queensland. The final product specifications have now been settled, however we expect to continually make minor improvements as new improved raw materials, especially pigment systems, become available. We also anticipate the development of stronger, heavier fabrics will be required as the market and the size of structures develops.

We believe that, just as our standard tarpaulin fabrics are a step ahead of the standard Northern Hemisphere transportation fabrics, so are these two new Airflex products better suited for use in the Australasian climatic environment.

4.0 PRODUCTION AND QUALITY CONTROL

Having shortened our three year development project into ten minutes, I would now like to take you briefly through the manufacturing process used to produce our Airflex fabrics and also cover some of the routine quality control procedures used.

First the raw materials.
The woven polyester base fabrics are purchased in Europe and inspected for faults before coating. The plastisol ingredients are batched by weight according to the formulation and colour required. The plastisol is then mixed, ground and quality control tested for viscosity and particle size before being released for coating. The knife spread coating is performed on our Bruckner coating line. Here you can see the first base coat being applied to the fabric before passing into the first fusing oven. The machine has a number of sophisticated controls to ensure the correct amount of plastisol is being applied and that base fabric tension is constant. The back top coat is applied and the second coating head and fused in the second oven. The one side coated fabric is then taken to the start of the machine and the process repeated for what will become the face side of the fabric. At the end of the second pass through the machine the product is trimmed and quality control samples taken for laboratory testing.

These tests include

- tensile
- tear
- abrasion
- flame retardancy
- adhesion
- flex cracking
- cold temperature flexibility
- weight

The material must pass our minimum release standards before being allowed to proceed to the final inspection tables where it is visually inspected for defects and rolled into the appropriate roll size ready for sale.

5.0 SUMMARY

To date we have manufactured Airflex 750 in four colours and significant applications so far have included

- use in a frame supported structure used as a relocatable, cinerama, type theatre known as Cinema 180 which has been travelling to various fairs around New Zealand. The membrane was fabricated by Hoods using alternate panels of red and yellow Airflex 750. This structure used approximately 1000 square metres of fabric.
- Airflex 950 was used for a low profile air supported and cable restrained roof over an ice skating ring in Invercargill in New Zealand. Approximately 3000 square metres of White Airflex were used. This fabric was a little unusual in that we used a black base coat in order to give increased opacity inside the ring to help to lower energy costs.

This roof was fabricated by Potter Industries in the South Island of New Zealand.

In order to maintain a check on the materials' performance at this site there are test samples attached to the building which we intend monitoring during the life of the membrane to check deterioration and help predict a safe service life. We would recommend this procedure for all new structures built in this part of the world.

Ladies and Gentlemen, I trust that I have been able to give you some insight into our technology base, the development parameters we set and have met for our Airflex products and also a brief look at our production and quality control procedures. We believe we have developed products which will perform in the harsh Australasian climate and we look forward to working with you in the development of locally designed and fabricated membrane structures.

ASPECTS OF CLIMATE CONTROL IN MEMBRANE STRUCTURES

John A Ballinger
Director, SOLARCH - Solar Energy Research Unit

Vinzenz Sedlak
Director, Lightweight Structures Research Unit

Stewart C J Smith
Research Assistant, Lightweight Structures
Research Unit

Graduate School of the Built Environment
University of New South Wales

1.0 INTRODUCTION

The use of membrane structures as a form of shelter goes back to the time of man's earliest building, and in many parts of the world those early examples persist, such as the Bedouin Tent or the Indian Teepee. Today there is a growing interest in such structures using a much wider range of materials. In an age where the future of our energy supplies is in doubt and energy costs are rapidly escalating, it would be as well to look at the thermal behaviour of such structures. In many instances membrane structures are erected to modify the external climate of a particular location. Perhaps a warm environment is needed for a swimming pool during the winter, or a dry space is needed for storage of perishable goods. Alternatively an emergency shelter is required for refuge in a harsh climate. In all these situations we aim to provide a modified internally a modified version of the external environment.

Traditionally, massive construction was used to provide a thermal barrier relying on the capacitance or time-lag of heavy masonry to insulate the interior from an inclement exterior climate. In the case of membrane structures it is necessary to consider the role of the envelope in a different manner. Authors such as Gill (1) refer to the membrane as being like a "filter" between the inside and the outside environment. Conceptually this view is valid although in practice, the available solutions tend to be more simplistic. Our technology has not yet caught up with our fantasy, as will be explained later. The membrane "filter" view allows us to specify the idealized performance requirements of a membrane. It should be able to "breath" and so allow a selective exchange between the inside and outside environment. For example Passive Solar Design philosophy requires a membrane that accepts the sun's energy into the enclosed space during winter, whilst rejecting it in summer. Whilst the sun's winter energy is being allowed to enter we at the same time require that conductive losses through that membrane be kept to a minimum.

To summarise these requirements so far; we need a membrane that is transparent to short wave length radiation (<2.5 microns as emitted by the sun) during winter and reflective to it during summer. The membrane however should be opaque to longwave length radiation (>2.5 microns), and it must have a high thermal resistance to minimise conductive exchange year round. In conventional Passive Solar Building structures we use windows to admit the sun's energy, shaded for summer and insulated with curtains at night to reduce conductive loss, whilst the remainder of the external skin in the form of walls and roof is insulated with various materials. To some extent, such an approach applied to membrane structures would reduce them to conventional solutions. Oh, if only we could develop a living membrane that changed its properties as did the leopard his spots!

2.0 THERMAL STORAGE

In most Australian environments however there is generally more than adequate sun during the winter months to provide space heating by passive design techniques. Unfortunately the sun's energy is available for only about one quarter of the day in winter and so it becomes necessary to incorporate a means of heat storage. If one released heat into the enclosure (solar or otherwise) sufficient for 24 hours, in a period of only 6 hours without adequate storage, the overheating of that enclosure would be quite a problem. With rapidly rising energy costs it would be fool-hardy to ignore such an energy source as we have done in recent years, and so the problem of heat storage needs to be solved.

In all but the most highly sophisticated heat storage media the common physical characteristic is high mass, which common sense suggests should be located on a sound base and not incorporated into the membrane. This being so, we need not include thermal storage in our brief for an "ideal" membrane.

3.0 IDEAL MEMBRANES

To maintain a thermally comfortable environment within an enclosure we must balance the energy gains against the energy losses. Where the energy gains are continuously provided using conventional energy such as electricity, gas, oil etc. it is wise then to ensure that the membrane has a high thermal resistance and the ability to store energy may not be required.

As stated before the ideal membrane must be able to be seasonally transparent to solar radiation and have a high thermal resistance. The latter can be achieved either by trapped air between multiple layers of the fabric skin or by the introduction of a layer of bulk insulation as a core to a double skin membrane. Other combinations are of course possible depending on the purpose or aesthetic requirements of the membrane. Bubner (2) summarizes these methods of increasing resistance and lists ten variations including multiple skins, cushions and quilts, applied foam layers, attached insulation mats and sandwich construction. He also includes some of the U-values to be expected from multi-layer arrangements. If the conductivity of the proposed materials is known however, it is quite simple to estimate the U-value of a particular build up from the basic formulae given in undergraduate texts such as IHVE (3) or Ballinger (4). Generally single skin membranes of 0.5 to 1 mm have U-values ranging from 5 to 7 W/m^2. deg. C which is similar to that of 3 mm glass (6 W/m^2. deg. C). Such values are far too high for good energy conservation and satisfactory wintertime thermal comfort. U-values of 0.4 to 0.6 W/m^2 . deg. C should be the goal in structures requiring reasonable thermal comfort.

4.0 THERMAL COMFORT

Besides reducing heat loss or heat gain, high thermal resistance enclosures help to improve thermal comfort by maintaining more appropriate room surface temperatures. One's sense of thermal comfort is influenced more by the temperature of the surrounding surfaces than the dry bulb air temperature. 'Environmental Temperature' is considered a reasonable measure of comfort and is defined as approximately:

$$Tei = \frac{2Tr + Ta}{3}$$

Tr = mean radiant temperature of all room surfaces
Ta = dry bulb temp.
Tei = Environmental Temp.

The higher the thermal resistance of an external envelope element, the closer the inside surface will follow the inside air temperature.

These values, and good insulation generally, depend on reliable construction, installation and maintenance in addition to correct design. Where air layers in multi-skin membranes are too large (greater than 100mm) then convection currents can be set up and so the heat losses (or gains in summer) increase.

5.0 THE PARASOLE

Membrane structures as shade from the sun or shelter from rain provide many opportunities for creative design. The climate inside (or under) such a structure can only be at best a modification of that outside as only selected elements are rejected. By careful arrangement of screens prevailing wind can be either captured or deflected as desired. Such applications are well documented in historic writings and of course by the defence services. Any attempts to over control the conditions in such open structures usually results in the consumption of excessive amounts of energy. In applications where pneumatic membrane structures are used for swimming pool enclosures, the high resistance skin will help reduce condensation. Above average humidity levels are desirable to reduce energy loss from the pool due to evaporation.

The control of excess solar energy in summer is just as important as its collection in winter for most parts of Australia. This must be considered when selecting the outer surface materials of the membrane (unless it is only intended to erect it for winter). Except for horticultural use most enclosed membrane structures should have a reflective surface and specific allowances for sun penetration or collection.

6.0 THE LIVING FILTER

To return to the concept of a membrane as a "living filter" between inside and outside. There have been many schemes to achieve this aim in which often highly sophisticated techniques are proposed. Some of these are passive in operation but most require complex controllers for pumps and valves etc. Schemes range from proposals for double or multiple skin membranes through which soap foam is injected to self-regulating absorber-reflector cells with solar energy recovery.

A definitive paper on solar active roofs by Laing (5), a meteorologist, proposed that a roof be made selectively reflective or transparent to solar radiation at will. He proposed a scheme for pneumatic structures using a double skin divided into tubular pockets each containing a moveable plastic flap, reflective both sides over half its area and clear over the other half and manipulated by air pressures in the tube. When relaxed, the flaps will allow radiation to pass through the skins; when in position the reflective sides block off the cell and reflect radiation back; solar to the exterior and longwave radiation back to the interior.

Dietz (6) took up the same idea of an active roof but adapted it to the collection of solar energy. Medlin (7) and especially Geiger (8) have also pursued this line of thinking. The back of the cells or the outer faces of the extended flaps are made black, absorb sunlight and get hot. The heat is removed before it passes into the main enclosure by air circulated through the cells. If the air heated in this way is hot enough it may be put to good use. The most likely procedure would be to store the heat collected in a rock pile below floor level unless there was an immediate use for it such as drying grain. In such an application large volumes of heated air must be passed through the grain to dry it. In many applications where the need is to heat space for human comfort then the earlier solution of Laing would be both more sensible and more economical. Many of these ideas do not collect sufficient energy to justify the expense involved in their manufacture.

In the colder climates of the northern hemisphere which experience clear sunny days it may be that solar active roof systems will have a wide application. However, in the temperate climates of Australasia, passive solar techniques will undoubtedly have a much wider and cost-effective application.

7.0 CONCLUSION

The indigenous lightweight construction of primitive man is passive and has been able to contend successfully with hostile environments in a limited and specialized way. Modern man expects a greater degree of control over his indoor climate for the most part. This desire for greater control presents new problems, especially when conservation of energy is considered important.

There is a need for considerable research into the passive control of environments within membrane structures. Most work to date would seem to be centred around the cold northern climates which would not seem to be particularly revevant to the climates of Australasia.

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"Control of Comfort Conditions within Lightweight Structures", (S C J Smith, July 1981).

EXPERIENCES IN MANAGING CONSTRUCTION PROJECTS INVOLVING LIGHTWEIGHT MEMBRANE STRUCTURES.

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1.0 Introduction.

This paper is essentially about contracts, and because the marriage contract is the most hazardous type known maybe we can start there.

I was once told by a friend of mine, a psychologist specialising in marriage guidance counselling, that the biggest single threat to the marriage contract arises from the fact that the parties are generally unaware of each others expectations in respect of the relationship. The problem here is that the expectations are often unrealistic in the first instance. Nevertheless because they are not brought to the surface, discussed and put into perspective, the linger on. Ultimately a resentment develops as both parties come to the conclusion that they are being cheated of their entitlements. In many ways contracts for fabric projects tend to suffer the same threat and for the same reasons. Let me give you a couple of hypothetical examples:

<u>Case No. 1</u>.

The matter of minor wrinkling is not raised until the moment the client first inspects the erected structure and notices several areas of uneven stressing. He then advises the contractor that it was his expectation that the structure would be completely free of wrinkles. He considers the wrinkles to be defective workmanship and wants them removed entirely. He says he will be stopping all progress claims until this is done.

The contractor responds by stating that some minor wrinkling is inevitable with this type of building and in this case the uneven stresses do not jeopardise structural integrity.

The outcome is subsequently unclear because the contract does not specify a degree of acceptable wrinkling. However the contractor is in the financial hot seat because he is awaiting the major progress claim following delivery to site of the structure. If he is forced to back down and return the entire membrane to the factory for modification then the resultant cost may be enormous.

Case No. 2.

The client is most upset by several small patches glued to the structure. Because the membrane is translucent the patches stand out visibly from the inside. The client regards the patches as unsightly imperfections and demands the situation be rectified. He withholds progress payments.

The contractor responds by saying the patches had to be used over punctures which occurred during erection and that this is a normal risk of the medium.

Again the outcome is unclear because the contract does not deal with the possibility of patching. As before, if the contractor is forced to return the entire membrane to the factory and replace whole panels the cost may be substantial.

We see therefore that fabric architecture is indeed a complex medium and that inexperience can prove both confusing and costly. Bearing this in mind we would do well to briefly examine a number of possible parties to a fabric project in Australia with a view to appreciating their limitations at this time. We may then touch on a limited number of ways in which a contract may be tightened up to delineate responsibilities, particularly with regard to limiting the liability of the contractor to an equitable arrangement. If the orientation of this paper is towards safeguarding the interests of the contractor then this is only because the present naivety in Australia at all levels relating to membrane structures places the contractor in the greatest jeopardy.

2.0 Possible Limitations of Parties to a Fabric Project.

2.1 Contractors acting as agents for overseas fabricators.

This group is very much on the increase. When Clarence Council first called tenders for a pneumatic structure over their Olympic Pool in May 1979 only one agent responded. When they called tenders a second time a year later five agents emerged.

As a general rule these agents have no practical experience in the field of fabric architecture either from a design or fabrication aspect. There are undoubtedly one or two exceptions to the rule but in the case of the Clarence project it is unlikely that any of the five agents involved had ever erected a fabric structure of any size or sophistication.

Inexperienced agents are always oblivious to the intrinsic limitations and special requirements of the fabric medium. They tend to view fabric structures as prefabricated products which can be sold for a fast turn-over and forgotten. Armed with their glossy brochures of overseas structures this group has done more to fuel false expectations in terms of performance and economics than any other. Their sales pitch approach to potential clients often short circuits meaningful dialogue between the client and more experienced parties.

2.2 Fabrication contractors operating within Australia.

This group normally resides on the very fringe of the building industry. Usually they are manufacturers of soft plastic and canvas products such as truck tarpaulins, small tents, caravan annexes etc. In-house design potential is invariably weak as the market for large structures does not warrant them employing full time professionals or developing sophisticated computer systems. For standard structures they often rely on cutting patterns generated by their overseas supplier of architectural fabric. For non-standard structures they usually work in conjunction with consultant architects or engineers who generate the cutting patterns using scale model techniques.

The very nature of their operations usually means that most fabricators in Australia have a weak grasp on architectural and contractual protocol relating to the construction industry.

2.3 Clients.

As a rule clients tend to opt for fabric architecture for economic reasons, but their general feeling is to be wary owing to lack of experience with the medium. This wariness can degenerate into paranoia as they become more and more confused by all the conflicting advice they receive from so called 'experts' within the industry. Consequently while they are looking for the cheapest possible solution to their problem they are also inclined to demand more security than they would expect for a conventional project. In their last tender Clarence Council asked for a 10% retention over a two year defects liability period.

Most of the clients for large fabric structures at this time tend to be councils and other semi-government bodies wherein a large amount of political infighting among members is intrinsic. Voting to proceed with fabric projects, or any project for that matter, is rarely unanimous and opponents of the project can be quick to gain political mileage if negotiations falter either before or after the signing of the contract. The problem with fabric architecture in this respect is that it is still largely novel in Australia and controversy leading to quick headlines is easy to generate. When this happens and the project becomes 'public' it creates further tension over contractual negotiations.

Having little or no experience with the fabric medium the client often lacks a yardstick by which to judge the final structure. Viewing the building at practical completion from a relativity vacuum the response of the client can be unpredictable and can vary immensely. Strange as it may seem my experience has been that the higher the quality of the design and finish the more likely is the client to find minor fault. My own opinion on this phenomenon is that if the client perceives that the final building is of a high architectural finish then he is more likely to judge it by the standards of conventional architecture. If on the other hand the structure is of a uniformly low quality this tends to reinforce any preconceived notion that fabric architecture is a cheap and nasty alternative to the real thing. In the latter case the client is usually less likely to be critical of minor faults and shoddy workmanship.

2.4 Architects and Engineers.

Many professional firms are now doing at least some homework on fabric architecture spurred on by the success of the medium on large scale projects in the United States and elsewhere. The largest roof in the world, the 110 acre terminal at New Jeddah International Airport, is evidence enough that fabric is the future and cannot be denied. I could talk here about the appeal of the pure form to the enquiring mind and other metaphysical hyperbole, but in the final analysis the simple truth is that progressive consultants see fabric knowledge as possibly another bullet in their gun at a time when the building industry is in severe recession.

Unfortunately there are still large numbers of consultants who have not been able to embrace this new technology and this group tends to fear that fabric may in fact be a bullet in their back. This group feels highly threatened by a building medium of which they have no knowledge and in which they cannot therefore fully participate.

The interests of clients cannot be adequately protected by this latter group who are often drawn into projects to prepare specifications and draw up tender documents following an independent decision by a client to opt for fabric architecture.

2.5 Building Authorities.

We have had excellent rapport at times with various building authorities relating to fabric projects, but more often than not the experience has been painful to say the least.

I suspect every designer in Australia is suffering under the present building approval system, not simply because it tends to create a design straighjacket but more so because it is totally fragmented. A seemingly endless array of statutory authorities, departments and sub-departments co-exist, most with overlapping responsibilities and wide discretionary controls.

This creates a tremendous problem in relation to fabric architecture which is almost impossible to evaluate in terms of the guidelines established for conventional architecture. At present there are no uniform standards for membrane structures in Australia. Design submissions are therefore usually evaluated from first principles by officials with only the remotest knowledge of the subject. To expedite matters and obtain a favorable decision designers must often submit large quantities of supporting data, the collation of which is time consuming. A protracted building approval period can therefore eventuate and this can only place strain on the contractual relationship, particularly if the client is losing revenue or is on a rise and fall contract. Geodome's application in 1978 for a building permit for a basketball stadium at Melbourne University required detailed submissions to nine seperate departments and took 18 months to push through.

It is also not unusual for building authorities to demand significant design modifications following the granting of a provisional approval. This occurs as officials wax and wane over safety features not within their normal scope of reference. This can again create contractual strain, particularly if the modifications are expensive to instigate. If any of the modifications relate to the actual membrane following the start of fabrication then this can be enormously expensive, if not impossible, to accomodate.

In 1980 following the issue of a provisional approval for a portable pneumatic theatre in NSW the Department of Services changed their minds several times during the fabrication period on half a dozen significant design features, despite assurances that this would not occur. As an example the original design called for a petrol powered back-up fan. This was later deemed unacceptable and L.P. gas was agreed upon. Later again the department demanded another change to diesel. And finally two weeks before final erection they demanded that the diesel have an automatic self start system. Unfortunately the diesel in the fabricated back-up unit could not be converted and so the unit had to be completely refabricated.

Standard forms of contract place a large emphasis on contractors complying with all statutory regulations. This is a sweeping responsibility for contractors given the lack of widely accepted standards and one which the astute contractor will need to consider carefully when financially committing himself to a project before all building permits have been fully approved.

At this time one would assume that positive steps need to be taken to establish a steering committee capable of drafting design and safety standards for membrane structures which might be acceptable to both the industry and authorities in Australia. Hopefully this seminar might lead in that direction.

3.0 Examination of a Hypothetical Case Involving the Failure of a Pneumatic Building.

3.1 Qualifying comments.

I would like to outline a possible scenario relating to the failure of a pneumatic structure and then a good deal of insight may be gained by dealing with some of the possible implications. I have purposely chosen an air supported building because with this type of structure the mechanical and structural systems are entirely interdependent and small defects or design faults, as well as the faulty erection of seemingly minor details, can precipitate widespread damage and create grey areas of liability.

The purpose of the exercise is not to provide an exhaustive and definitive analysis of the events but simply to reveal the potentially volatile nature of the pneumatic medium from a contractual viewpoint.

3.2 The events.

It is six months into a 12 month defects liability period. The structure is a large air supported building over an Olympic Pool owned by a council. It has recently been re-erected by council workers for use during the winter season.

In the early hours of the morning while the complex is closed the structure suddenly depressurises in the middle of a heavy rainstorm. It whips around like a massive sail as it loses prestress ripping out an anchor shackle which is thrown over a fence hitting a passer-by in the head.

As the structure sinks lower it comes into contact with the lighting system which is severely damaged. The membrane itself is badly torn as it thrashes violently against the safety support system. Thousands of litres of storm water rush inside the structure and run down stairs into adjacent facilities causing massive damage to carpets and other fittings. And finally the structure's two main fans, which are not of the limit-load type, burn out after running on against zero back pressure.

The Council later claims that a $25 quick release duct bracket on the flexible air supply duct failed leading to deflation. The Council maintains that the failure was due to either poor design of the bracket or to an intrinsic defect in its manufacture. In either case it asks the contractor for the project to repair the bracket and all damage resulting from its failure which at this stage runs into $250,000. The Council also gives notice that it will want compensation for loss of revenue during the entire winter season calculated to be another $80,000. Furthermore the injured party gives notice that he has permanent brain damage and will be taking an action for $200,000 against the council while joining the contractor as a third party to the action.

And the $530,000 question is: Where does the contractor stand?

We assume that the contractor has a standard form of building contract, say a Master Builders General Contract or an Australian Standard Contract such as AS 2124. He gets out his contract, reads it, and discovers that generally speaking anything that can be construed as a defect, imperfection or other fault due to faulty workmanship, materials or design can warrant remedial work by the contractor. Our contractor then takes another glance at the newspaper photo of the decimated structure lying like a giant lasagna at the site and concludes that it is indeed now imperfect in many ways.

He then decides to check his Contractors' Indemnity and Public Risk Policy which is current with the Guardian Royal Exchange Group and which is regarded to be reasonably standard for the Insurance Industry. He reads all the very smallprint which previously had escaped his attention and comes to the conclusion that this might indeed be a matter of the good news and the bad news.

A meeting with his underwriter follows and this reinforces his opinion that the issue is most sensitive. He finds his underwriter is extremely cautious and senses that this is for three reasons:

a) There appears to be no precedence whatever for a claim of this nature.

b) The underwriter is concerned that the circumstances leading to the failure of the building are not clearly defined, or necessarily agreed upon by the parties.

c) The underwriter is concerned that the contractor allowed the principal to re-erect the structure during the maintenance period.

The outcome of the meeting is therefore quite vague as to possible indemnity but several considerations do émerge.

a) On the question of the damage to property within the original contract it appears the contractor has full indemnity for everything, apart from the bracket damage itself, providing it can be proven that the bracket was defective and that the defect was in existence prior to practical completion of the project. If it is proven however that the bracket failed because it was insufficiently designed to withstand the rigors of the application our contractor has no indemnity for either damage to the bracket or resultant damage to the remainder of the contract works. To be protected in this latter event the contractor would need to carry some form of professional indemnity insurance, which he does not have.

b) On the question of the loss of revenue claim it appears the contractor has no indemnity at all.

c) In respect of the personal injury claim the contractor would normally have full indemnity regardless of whether the duct bracket was defective <u>or</u> poorly designed, but in this instance he may have jeopardised his cover by allowing the principal to re-erect the structure.

d) In respect of the claim for damage to property outside the contract works the contractor finds the situation much the same as for the injury claim ie. he should have full indemnity throughout the maintenance period but the fact that he allowed the principal to re-erect the structure jeopardises his cover.

In a piece of lateral thinking the contractor then considers the possibility that some other factor than the bracket caused the deflation. It seems reasonable that an air duct could be ripped off following a deflation from other causes and it is generally accepted that there were no witnesses to the event. The contractor therefore rings the Electricity Commission and is pleased to learn that there was a five minute power black-out in the area on the night in question although it is not possible to ascertain if this occurred before or after the structure deflated.

Armed with this knowledge the contractor prepares to argue that temporary power failure and the absence of a back-up fan or generator caused the deflation. But when he checks with his underwriter again he is shocked to find that his failure to instal a back-up power source would almost certainly constitute a design ommission given the inevitability of mains failure at some time. This would leave him without indemnity against claims relating to damage to the contract works and to loss of revenue.

Inevitably the contractor concludes he must allege that the council workers have improperly connected the duct bracket during re-erection. Proving that this actually occurred may be the only way the contractor can completely alleviate himself of all liability. But he wonders how he can substantiate this point bearing in mind he was not present during the re-erection and the bracket was damaged extensively during the deflation. He knows that the principal will flatly deny any accusation of improper connection.

We leave the scene as the solicitors start to move in and the matter heads in the direction of the Supreme Court.

4.0 General Comments.

4.1 Deflation Liability.

My own feelings are that losses and damages resulting from the depressurisation of a pneumatic structure are an intrinsic risk of this particular building form. Even the most painstaking design by professionals and the most sophisticated equipment is no guarantee against a deflation. For a start there is no such thing as a fail-safe mechanical system. The Three Mile Island nuclear reactor failure should be proof of this. The world's largest pneumatic, the Pontiac Silverdome, has deflated and been damaged at least once. And that roof cost over $4 million.

It is therefore not reasonable to expect a contractor, or his insurer, to be responsible for claims resulting from a deflation following practical completion beyond rectifying any faults or design flaws which may have led to the deflation. Standard forms of contract do not give adequate protection in this regard and contractors need to adopt special clauses to ammend this situation. If a principal is not prepared to accept the risks of deflation and possibly insure against them then he should consider the extra investment in obtaining a self supporting membrane structure.

It is relevant that membrane structures are usually employed as roofs and roof failures currently constitute the largest area of building litigation in the United States and probably in Australia as well.

4.2 Re-erection.

Fabric structures lend themselves to dismantling and re-erection only when they are specially designed for this purpose. The demands upon a temporary membrane structure are always far greater than upon a permanent one. My own observations are that constant dismantling and re-erection on a seasonal basis can virtually halve the life of the building.

At any rate dismantling and re-erection during the defects liability period by the principal creates uncertain areas of liability in the event of a subsequent failure. The contractor should therefore include dismantling and re-erection in the contract if this is to occur during the maintenance period. If this is not possible then the defects liability period should terminate whenever the principal commences dismantling.

4.3 Maintenance and Servicing.

A procedure of maintenance, particularly on pneumatics, needs to be established by the contractor, with the contractual condition that all warranty lapses in the event that the principal does not strictly adhere to his obligations. It is advisable that the principal should enter into a service contract for the duration of the maintenance period with the mechanical subcontractor responsible for the fabrication of the mechanical system. Inspections should be at not greater than 3 monthly intervals.

4.4 Insurance.

No contractor should embark on any fabric project without Contractors' Indemnity Insurance for the full value of the contract sum, plus Public Liability cover for at least $500,000. The standard Contractors' Indemnity policy provides for coverage only at the site and this must therefore be extended to provide coverage during fabrication at a factory (if the structure is being fabricated in Australia) and during transit to the site.

5.0 Summary.

If there is an overview to be gained it is that inexperience is the common denominator for confusion in fabric projects. It would not be too harsh for me to say that the last two tenders called for major fabric projects in Australia have degenerated into Theatre of the Absurd for that very reason.

I refer to the tenders called by Clarence Council and North Sydney Council for pneumatic structures over their respective Olympic Pools. I think it would also be fair to suggest that in both cases the design brief and specifications were prepared by consulting firms with little or no experience in the field of membrane architecture.

The Clarence structure was first put out to tender in May 1979 and the lowest tender was approximately 80% over the council's initial estimate. As it turned out this estimate had been based on information supplied by the most obscure sources imaginable. The project was subsequently retendered in a greatly reduced format a year later and still came in 30% over the original estimate. A contract was awarded but at the writing of this paper the structure is still not open for public use. This is two years and four months after the project first came up for tender.

North Sydney first put their project out to tender in January 1980 with a requirement that the building reach practical completion by July the same year. Geodome was sent a copy of the specifications but declined to submit a tender because we felt quite positive that no realistic comparison could be drawn between reasonable architectural proposals and junk submissions owing to the looseness of the specifications. The tender went ahead but as with Clarence no contract was awarded. When the project came up for tender a second time the Sydney Morning Herald wrote: "New tenders to build an inflatable cover for North Sydney Olympic Pool will be called by North Sydney Council following allegations of irregularities in the handling of the original tenders."

The final accepted tender was 30% over initial estimates and the structure came into operation one and a half years following the first tender. The structure itself was imported and several mandatory features of the tender specifications, including an inner thermal liner, have not materialised. The standard of the membrane and fittings is of exceptionally poor quality relative to internationally accepted standards.

Fabric architecture is a very esoteric medium and the fact that it can be highly cost effective belies its true complexity in terms of design, analysis, fabrication and erection. It is not unusual for consulting engineers specialising in this field overseas to charge twice the normal fees expected for a conventional building. Properly executed the fabric structure is exceptionally design intensive and requires the attention of people with special skills.

Therefore it seems obvious that clients wishing to nominate a consultant firm to safeguard their interests should choose one which has been actively involved in the construction of at least one major fabric project.

It also makes sense that engineers or architects acting for clients should restrict tenders and quotations to those contractors who have successfully erected at least three major fabric structures <u>in this country</u>. This requirement will then parallel a condition now found in most design briefs for large fabric structures overseas.

NUMERICAL DESIGN OF MEMBRANES

✦ ✦ ✦ ✦ ✦ ✦ ✦ ✦ ✦ ✦ ✦ ✦ ✦ ✦

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INTRODUCTION

This contribution consists of the - hitherto unpublished - material of the second half of a paper to appear in 1982[x], whose first half consists essentially in the material of Reference 20, cited herein. The reader may wish to read Reference 20 for a better under-standing of this paper. The paper deals with the numerical design of lightweight structures using the program PAM-LISA[xx].

It describes a successful membrane design and cutting pattern evaluation procedure and it discusses a technical tissue material model, permitting a clear modelling of actual tissue material behaviour, such as the cinematic coupling between the warp and weft threads and a nonlinear stress-strain behaviour of the fibers.

Then the paper discusses two technical applications performed with the program PAM-LISA, demonstrating the feasibility of the approach and methodology of design in non-trivial cases.

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[x] collection of articles "Pneumatic Building Structures" Stroyizdat Publishing House, Moscow 1982.

[xx] proprietary version of the program MASL for the design of linearly elastic cable and membrane structures mentioned in the introduction ; see also reference 20

A MEMBRANE DESIGN METHODOLOGY

(Figures C1-C9)*

(First published in References 13,20)

Cutting patterns of membranes are collections of planar stress-free pieces of real membrane material, Figs. 8 and 9. They are designed such that they yield a best approximation to the desired membrane shape and state of stress, once fitted together and the membrane erected. For practical reasons it is often desirable to obtain cutting patterns consisting of long straight strips of material, Fig. 9. The following sequence of numerical steps is believed to lead towards optimal membrane cutting patterns, Figs. 1-7, constituting a complete methodology of design of pneumatic structures.

STEP 1 : Shape Finding (Fig. 1)

First, obtain the pure form of the membrane, using isotropic or anisotropic soap film elements with or without pressure loading. In a square frame for example, such a pure form can be obtained by inflating an initially flat layout of soap film elements.

STEP 2 : Substitution under Stress (Fig. 2)

Second, substitute under stress an elastic finite element for each soap film element, in such a way that the elastic element will have the soap film stresses while occupying the same position in space. This implies that the elastic substitute elements must be of smaller dimensions than the soap film element, to allow for the required buildup of stress due to stretching of the material. The analysis program calculates those reduced stress-free dimensions in a special analysis step.

*Figs A and B belonging to the first half the 1982 paper mentioned in the introduction ; see also Reference 20.

STEP 3 : Pattern Finding (Fig. 3)

Third, identify strip patterns on the membrane surface, for example as a collection of strips an integer number of finite elements wide, for development into a plane. If the strips are oriented along geodesic lines within the pure form surface, they are said to form a geodesic pattern, and their development into the plane will be the straightest possible one, Fig. 9. The soap film element nodal point grid within the pure form surface can easily be made to approach geodesic lines by superimposing over the grid a minimal cable net of uniform tension prestress cables (the tensile forces within the auxiliary net may be very small, since in real soap films fluid particles are seen to move freely without material resistance inside the surface, which is also true in the numerical model).

STEP 4 : Cut out Pattern (Fig. 4)

Fourth, obtain the relaxed pattern by cutting the substituted strips of elastic material under tension out of the membrane and by letting them relax. This pattern will be free of stresses, forming doubly curved segments of surface waiting to be developed into a plane.

STEP 5 : Pattern Flattening (Fig. 5)

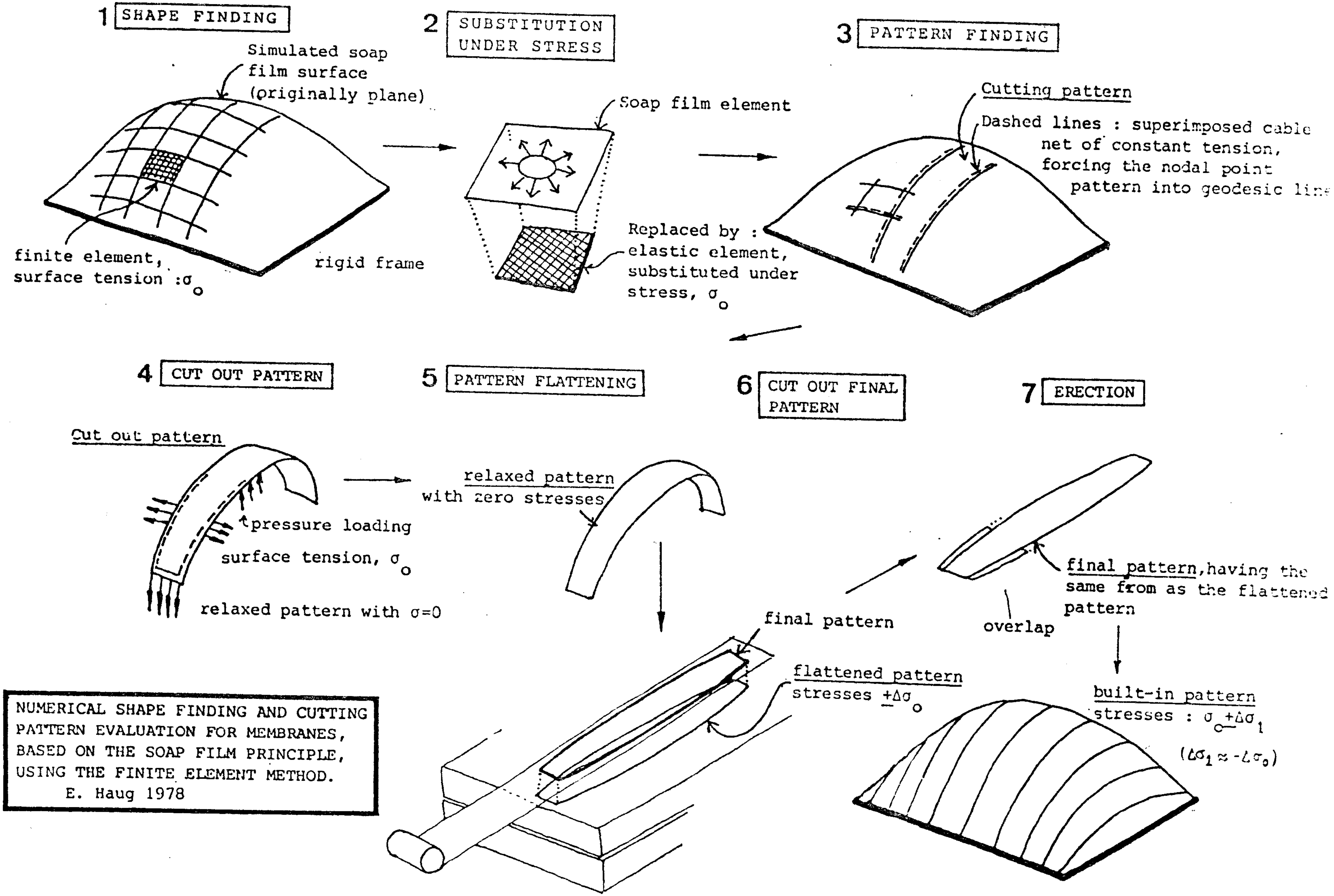
Fifth, obtain the flattened pattern by forcibly flattening the relaxed pattern with the least amount of energy into a well lubricated plane, avoiding wrinkles and friction in that plane. The pattern flattened in this way assumes a position of least restraint within the plane, with the inevitable, but minimum possible, state of selfequilibrating stress deviations from the ideal state of zero stress in the material.

STEP 6 : Cut out Final Pattern (Fig. 6)

Sixth, obtain the final pattern by cutting out identical strips of totally stress-free membrane material exactly following the shape of the strips of the flattened pattern.

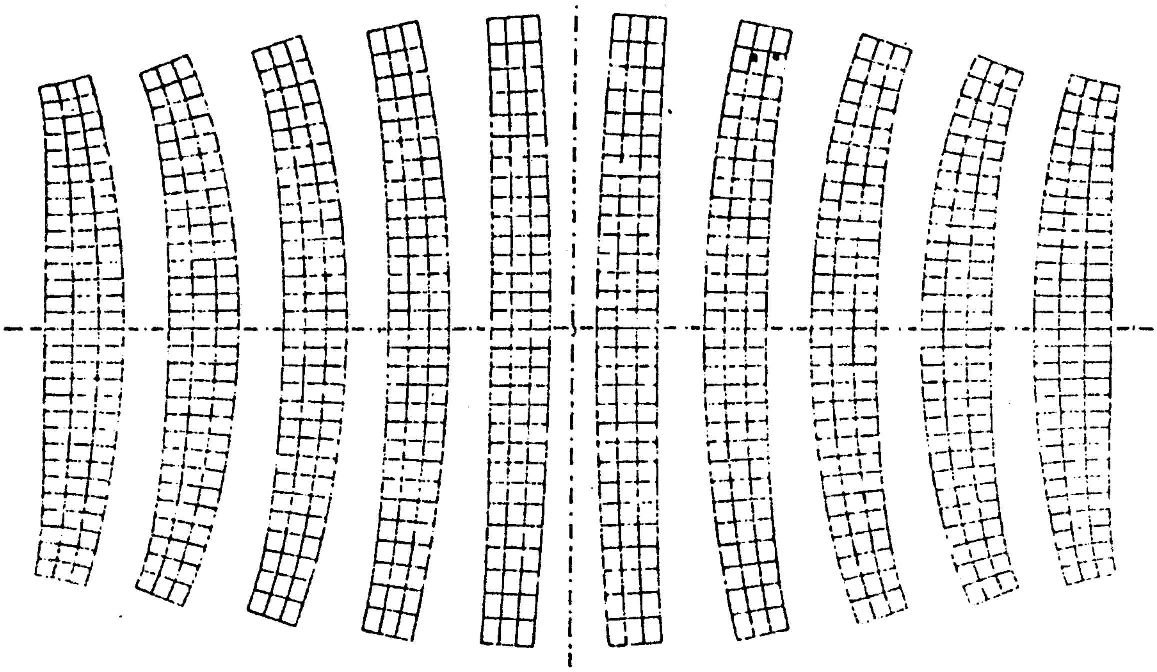
STEP 7 : Erection (Fig. 7)

Finally, obtain the erected pattern by assembling the final pattern and by reapplication of the shape determining factors. This last pattern will have the stress state of the pure form but with deviations ressembling closely the stresses in the flattened pattern, with reversed sign. The stress deviations are due to the deformations necessary to deform the flat final pattern into a doubly curved erected pattern. Due to the resistance of the final pattern to being curved, the shape of the membrane with the erected pattern built in will differ slightly from the pure form. Those form deviations and the inevitable stress perturbations are believed to be a minimum, in an average sense, when the described shape finding procedure is applied.



NUMERICAL SHAPE FINDING AND CUTTING PATTERN EVALUATION FOR MEMBRANES, BASED ON THE SOAP FILM PRINCIPLE, USING THE FINITE ELEMENT METHOD.
E. Haug 1978

FIGURES C1 - C7



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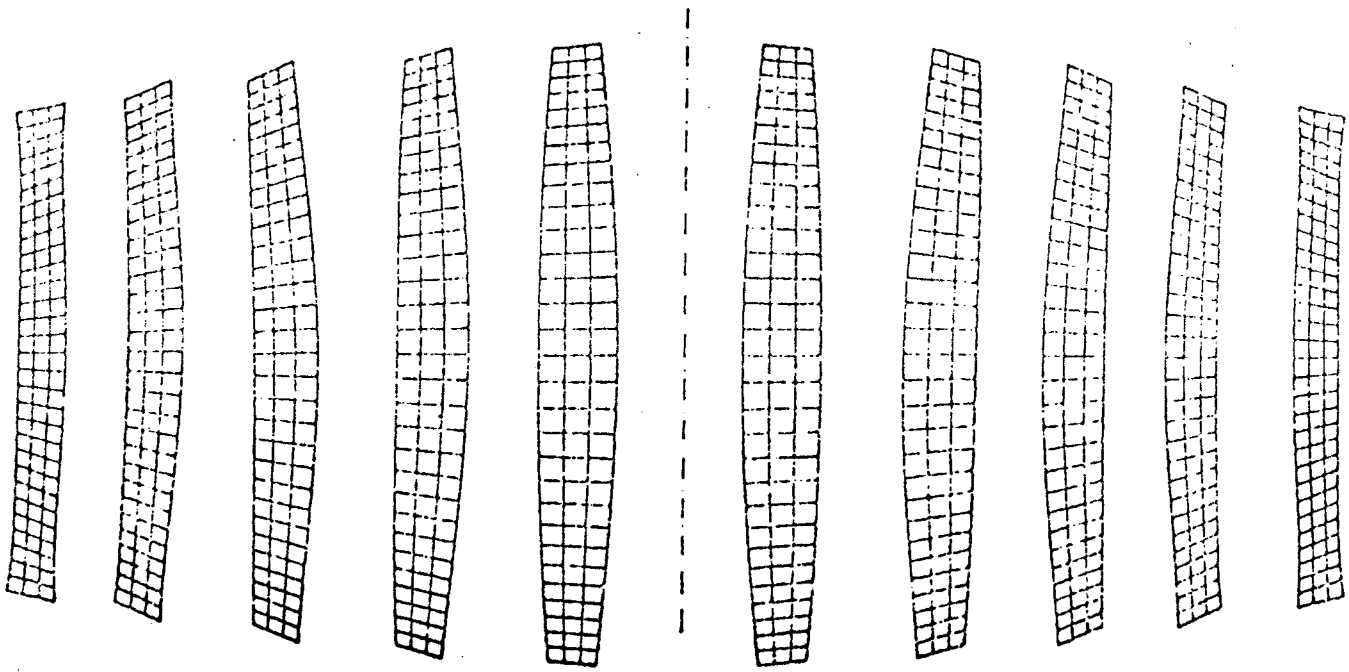
CURVED PATTERN



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GEODESIC PATTERN

FIGURES C8 - C9

A TECHNICAL TISSUE MODEL (Figures D1-D12)

(References 21-27)

One little explored engineering problem in a rigorous analysis of technical membrane structures is the correct numerical representation of the coated fabric material properties, Figs. 1,2. This is the more important the stiffer and stronger a fabric becomes (e.g. Kevlar-Mylar composites, Teflon-coated fiber glass fabrics, etc..) and the more lightweight the structures are at simultaneous high stress levels.

For this reason an easily understandable engineering type coated fabric tissue material model is described in some detail, which may serve as a basis for more elaborate models to come and which excels by its conceptual simplicity and directness in the successful description of the highly complex subject matter.

A microscopic view of a section of a typical two-thread coated fabric weave Fig. 3, reveals the ondulation of the warp and weft threads and their tendency to become straight if a sample of tissue is pulled in one direction. The initial resistance to the straightening is mainly due to the small, but over short distances nevertheless important, flexural rigidity of the pulled threads and of the threads in the other direction, which are becoming curlier in the process. The flexural inertia is significantly due to the presence of the coating material in which both sets of threads are embedded.

The stress-strain curves, Fig. 4, of a uniaxial tension test of a tissue are therefore rather nonlinear, with a lower tensile resistance in the initial phase during which the pulled fibers straighten out and with a higher stiffness and resistance later on once the fibers have been stretched out fully. It is the cinematic interdependence of the weave threads that renders a tissue fabric response initially nonlinear even for an assumed linear elastic or inextensible behaviour of the material of the fibers.

The second principal source of nonlinearity lies in the nonlinear stress-strain behaviour of the individual fibers of which the tissue threads are made, Fig.5. Polyester fibers, for example, are first stiff, then they soften suddenly and at high strain levels they stiffen again.

Nonlinear Beam Model

Both sources of nonlinearity can be easily incorporated into an engineering model of a coated fabric tissue, in which the uni-and biaxial material responses are derived from a nonlinear engineering beam model of one typical repetitive crossing point of the warp and weft threads singled out of the tissue.

This tissue model, incorporated into the finite membrane element of the program PAM-LISA, Fig.6, replaces at each integration point of a finite element the warp and the weft threads by nonlinear engineering beam elements, following the initial ondulation of the warp and weft threads, Figs. 7,8,9. At the cross point of the threads a short cross beam element with its axis perpendicular to the midplane of the fabric maintains the distance between the model beams and assures the cinematic coupling between the two families of threads, Fig.10 (the in-plane shear resistance of a coated fabric is mainly due to the low shear resistance of the coating material and it is modelled independently by an added orthotropic plane stress shear-only material property).

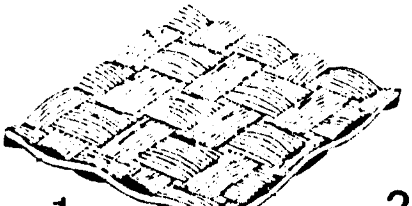
In the computer program the model simulates a membrane continuum by a substituting a small structure made of nonlinear beams, Fig.9, applied point by point throughout the continuum, and the response of a membrane element to e.g. imposed deformations will be obtained in a sequence of subiterations for equilibrium of this beam model at each point of interest.

The individual nonlinear beams of the model may have linear or nonlinear material properties. In the simplest case, the flexural rigidity is chosen linearly elastic as well as the axial extensibility. The model beams have also been provided with a nonlinear extensibility, characterized by a curved axial stress-strain diagram with possibly linear unloading, thus modelling, Fig.5, the nonlinear elastic or inelastic behaviour of the individual fibers of the tissue. Moreover, the cross beam element, keeping the distance between the warp and the weft beams, may be assigned an axial springiness to simulate the transverse elastic setting of the tissue threads, caused by the mutual compression of the threads due to the redirection of the tensile forces when the tissue is under biaxial loading. If given elasto-plastic properties, the cross-beam may partly account for the phenomenon of a permanent set encountered in most technical tissues, especially during the early cycles of loading history.

The model is believed to be able to carry further refinements, such as visco-elasticity or creep, etc.. and it has served as a valuable asset in practical studies of high demands.

Model Performances

Figs.11, 12, show the stress-strain curves obtained from technical tissues in the laboratory as compared to the stress-strain curves obtained by the proposed beam model indicating high accuracy of model description. The beam model parameters (geometry, axial and flexural stiffnesses) must be chosen judiciously in order to best fit the actual curves, a process which can be made to converge rapidly after a few tries. The beam model geometry is deduced directly from the weave's geometrical properties.



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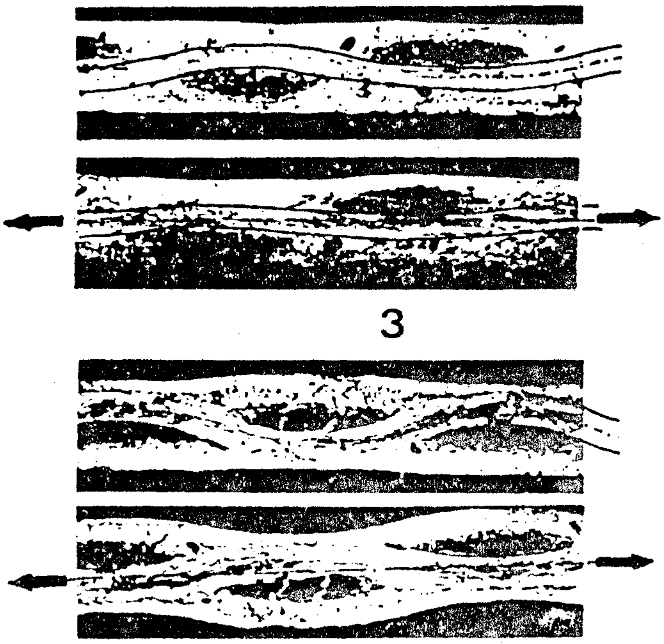

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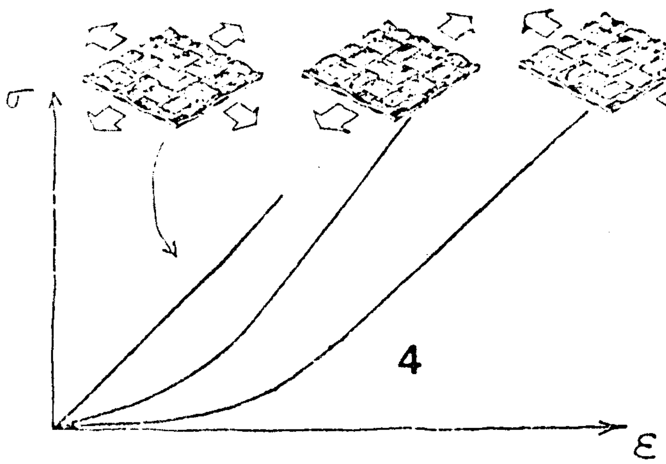

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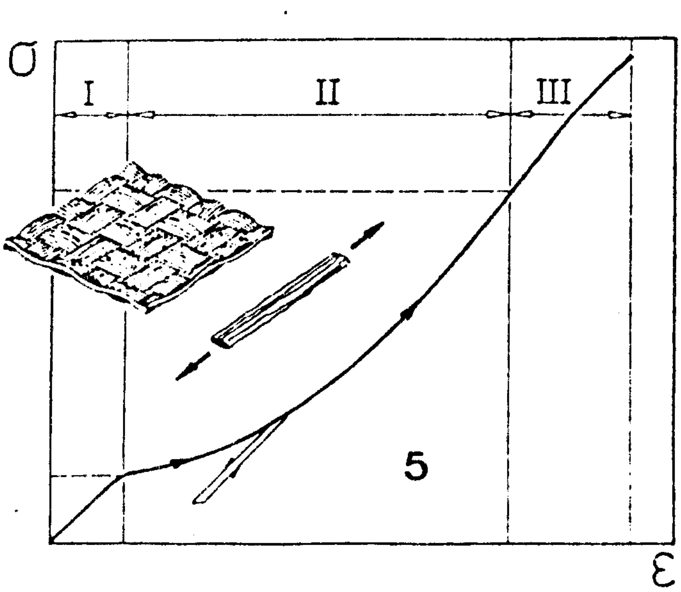

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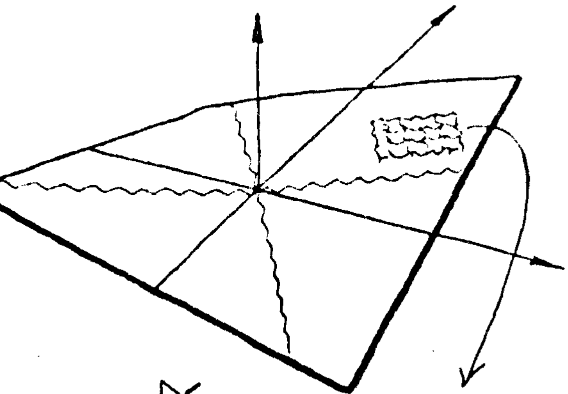

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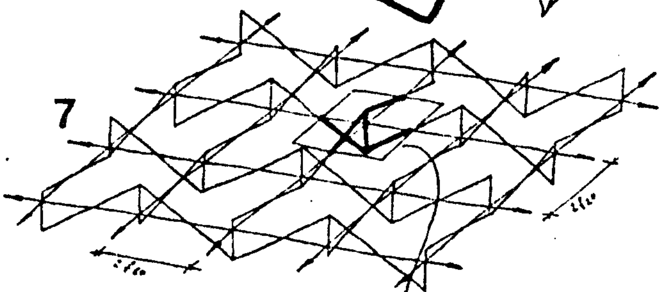

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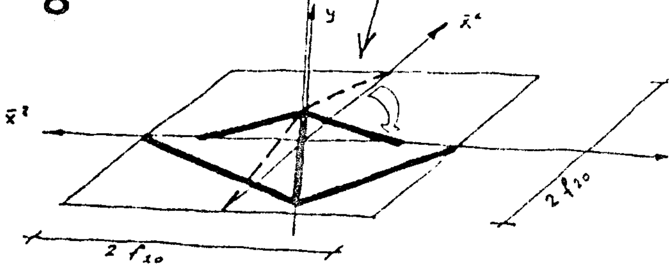

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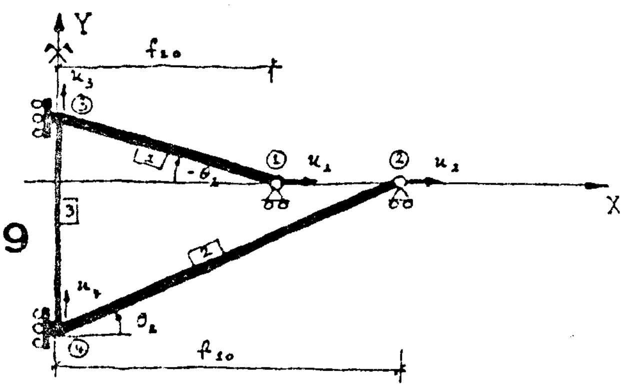

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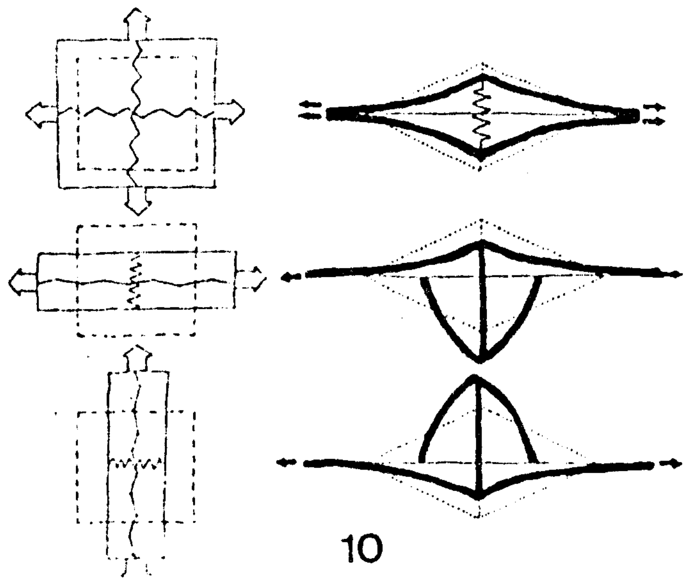

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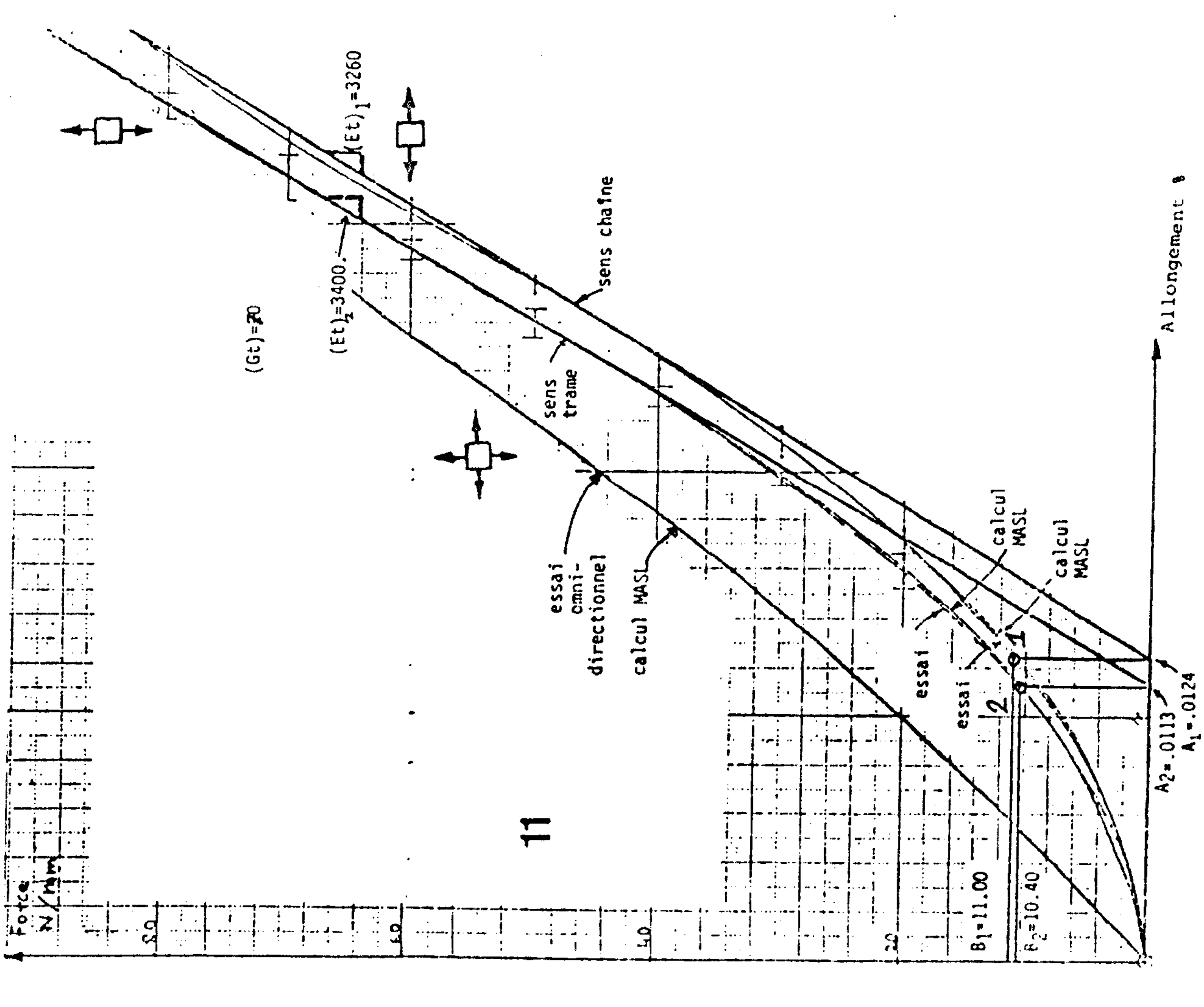
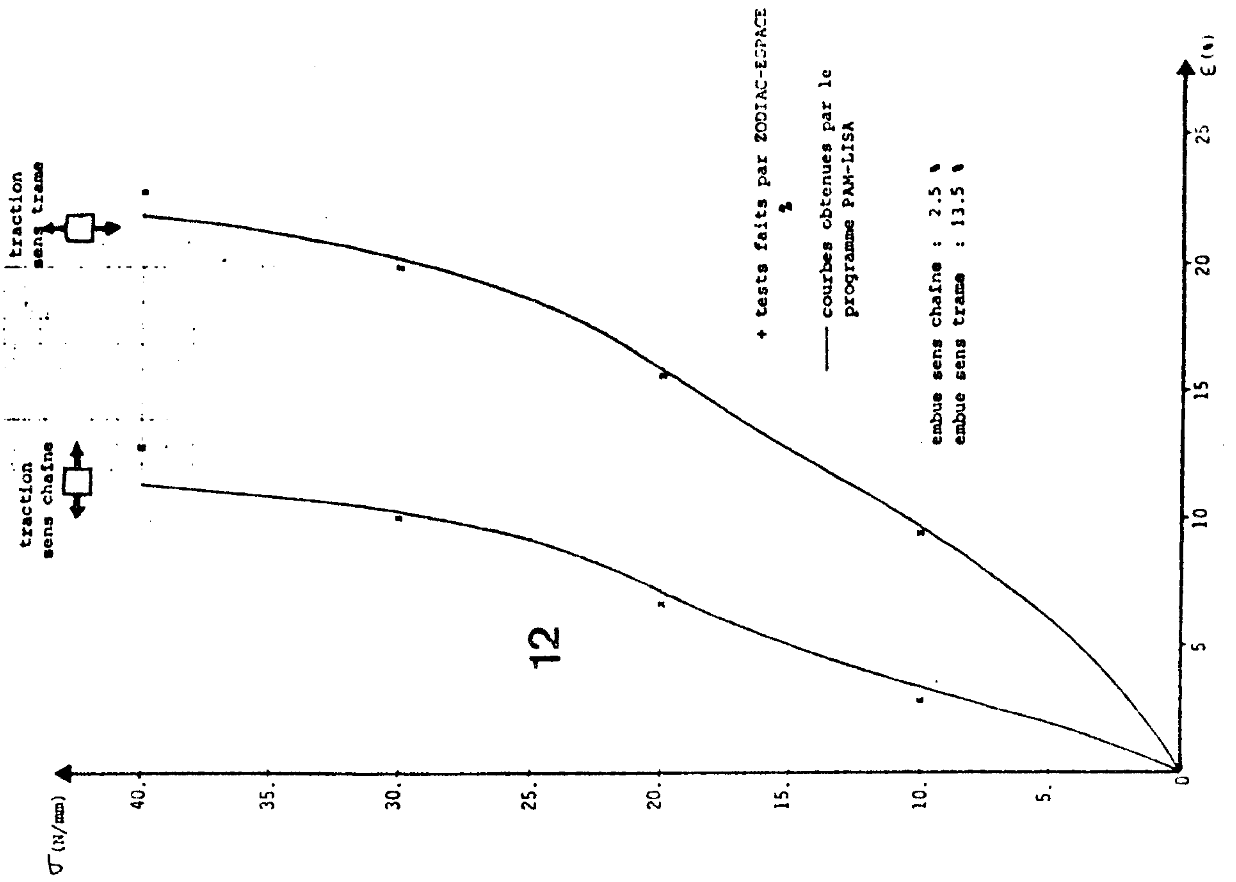
FIGURES D1 - D1





FIGURES D11 - D12

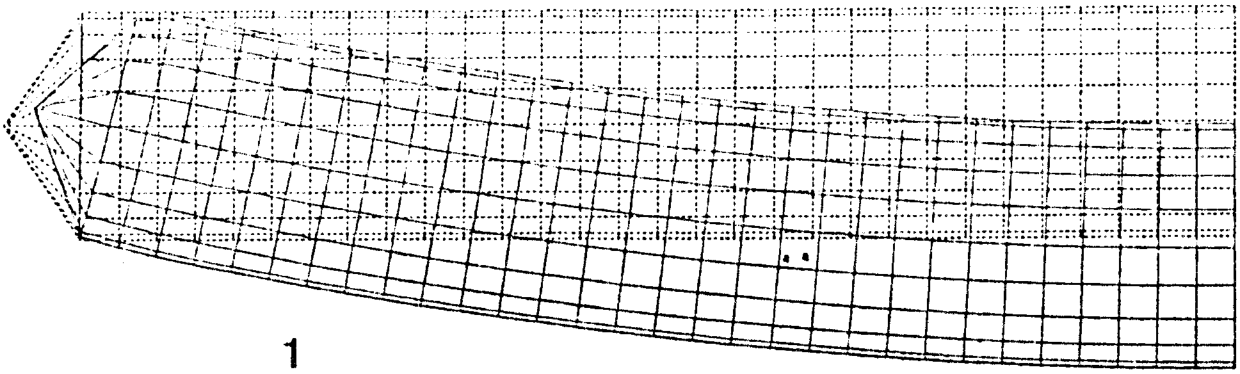
INFLATABLE BEAMS (Figs. E1-E4)
(Reference 28)

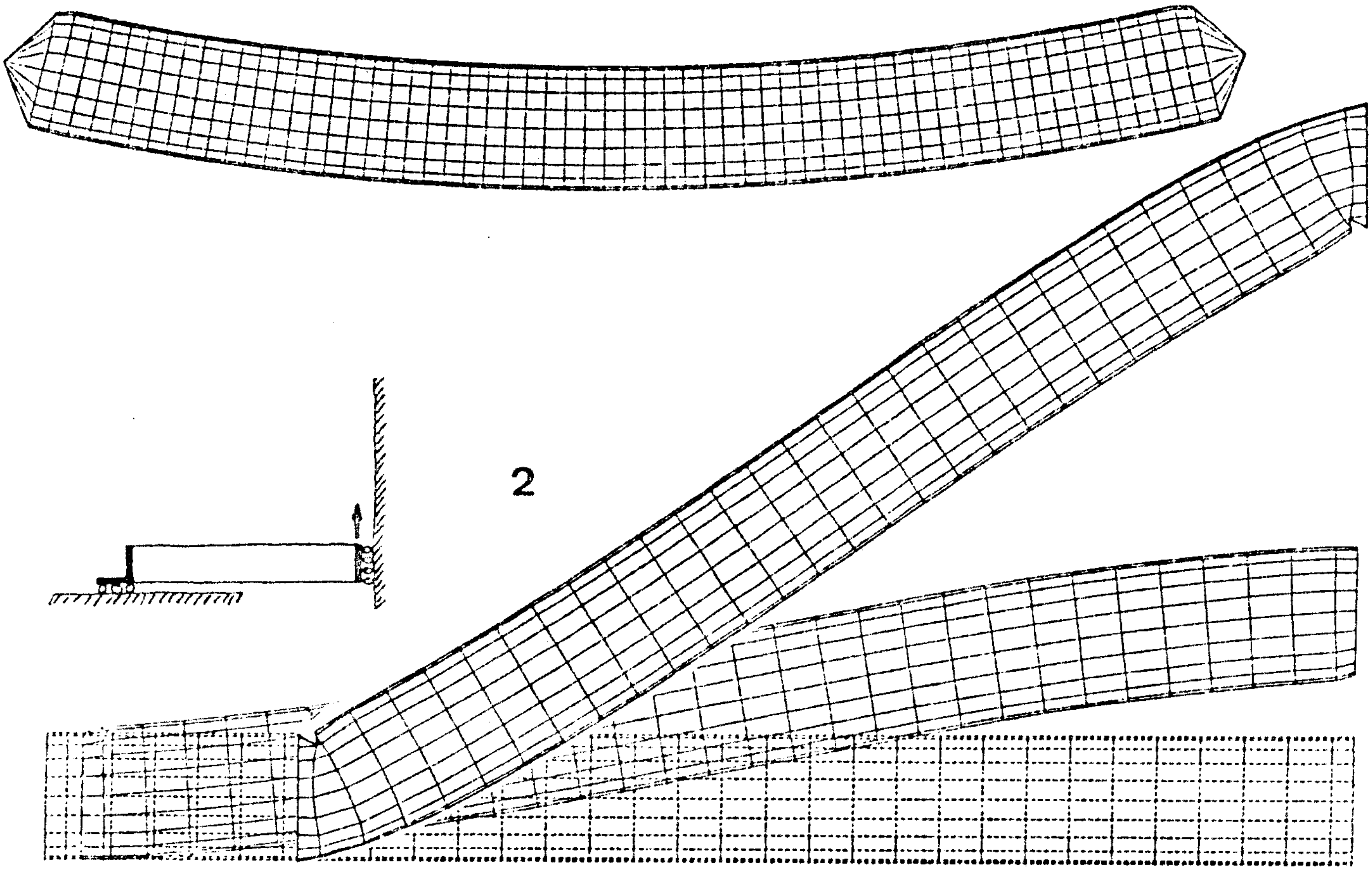
A simple pneumatic tube with a diameter to length ratio of 1 : 10 has been analyzed for simple load cases with PAM-LISA and it has been compared successfully to some tests carried out in the laboratory. The four basic load cases studied were an inflating pressure together with axial compression, flexure, shear and torsion. Due to the large displacements and deformations of the tube the results differed in the last three load cases when the axial deformation of the pneumatic tube is either prevented or permitted to take place.

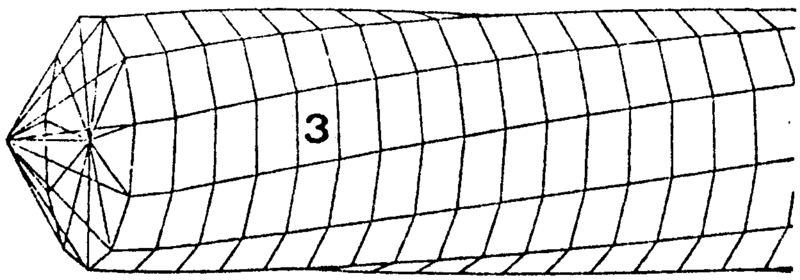
Figs. 1-3 show the resulting deformed finite element shapes due to simple bending, transverse shear and torsion, respectively, in true scale.

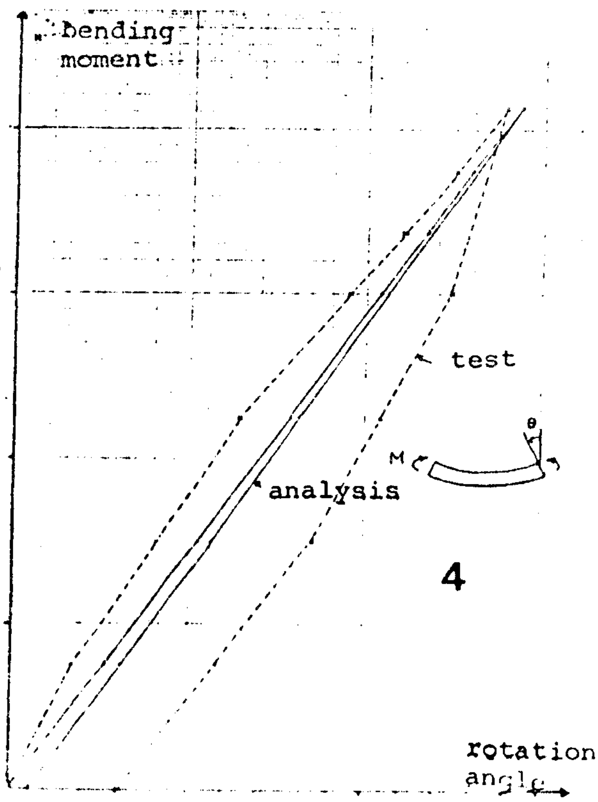
Fig. 4 shows the good agreement between analysis and experiment for example in the case of pure bending. The greater hysteresis of the lab tests is due to some friction in the mechanical joints, assumed perfectly frictionless in the analysis.

The computer models comprised about 300 membrane elements. The pneumatic tubes were made of a commercialized neoprene coated polyamid weave. The possibility of wrinkling of the skin material near the ends of the tubes is automatically accounted for in the analysis program, as seen in Fig. 2, where the wrinkles become visible in the deformed finite element mesh. The geometry of wrinkles may remain invisible in mesh plots, because they may occur inside a finite element, being not permitted to transmit compression in any direction.









FIGURES E1 - E4

VENUS BALLOON (Figures F1-F10)
(Reference 22)

In a pilot study carried out for the French Space Agency, CNES, a balloon of about 9 m diameter having a volume of ca. 400 cubic meters, made of a very thin lightweight and highly complex composite skin consisting of a high strength weave, with several coatings, reflective and protective layers, intended to be launched into the atmosphere of the planet Venus, has been studied with the aid of the computer program PAM-LISA.

In this Russian-French joint project the balloon was to be built in France and it was to be transported by a Russian space vehicle into an orbit around Venus. The balloon was to be released from the transporting vehicle, surpressu-rized to about 50 millibar and the studied balloon was to carry an instrument mass of about 250 kg. The entire mass of the balloon + payload was roughly 370 kg, the mass of the membrane envelope about 75 kg. The relative atmospheric pressure gradient at the cruising level of the balloon within the Venus atmosphere was roughly 8.0×10^{-9} Newton/cubic millimeters, resulting in the buoyancy needed to balance the total weight inflicted on the mass of the balloon under the influence of Venus' field of gravity at cruising level.

The balloons membrane enveloppe, Fig. 1, was to be fabricated from 32 identical meridional sheets of material, glued side by side via 32 fabric ribbons, 5 centimeters wide, which are running from the north pole of the balloon to the south pole. The ribbons were made of the same basic skin material but in such a way, that the ribbon added virtually no strength in the meridional direction.

The high strength tissue of the composite skin (KEVLAR, MYLAR, ..) was woven such that the uniaxial tension test curves in the warp and weft directions, see Fig. D11, differed as little as possible, assuring almost equal stiffness and strength in both tissue directions (this is not true in many commercia-lized fabrics, exhibiting a greater stiffness in the warp direction whose threads are straighter initially than the threads in the weft direction, fig. D12).

At both poles of the balloon rigid metallic polar caps with diameters of about 0.7 and 1.0 meters served to capture the oncoming meridional membrane sheets.

The task was to find a shape of uniform stress, to replace the shape by a skin of given properties with the minimum possible deviations in shape and stress, and to study the obtained balloon for various load cases.

To this end the membrane design methodology, outlined previously, has been applied with the obvious omission of STEP 3 (Pattern Finding), since the meridional sheets of the balloons cutting pattern are geodesic strips.

Due to the symmetry conditions of each of the 32 repetitive sections, only one half of such a section was actually modelled. The finite element model of the studied half comprised a total of 732 membrane elements, namely 176 elements along a meridian and 4-5 elements across the studies half of the section, Fig.2. Near the polar caps of the balloon a few rigid elements have been added in order to simulate the metallic plates bordering the membrane of the balloon.

In STEP 1 of the applied design methodology (Shape Finding) the soap film shape of the balloon under the combined action of the internal inflation pressure, the linearly varying external atmospheric pressure, the suspended pay load, the dead loads at the poles and with a soap film stress, such that the final volume of the balloon corresponded precisely to the volume required for stationary floating at the projected cruising altitute, has been found, Figs. 3,4. The resulting uniform membrane skin tension was about 10.8 Newton/ millimeters.

The program then performed STEP 2 of the design methodology (Substitution under Stress) and it replaced automatically each of the 732 soap film elements by an element of the real, nonlinearly elastic, coated fabric material, such that each real fabric element had the precise uniform target elastic stress state of 10.8 Newton/millimeters while occupying the exact positions of the respective soap film elements.

The shape and stress state of this elastic substitute membrane under pressures and loads are identical to the shape and stress of the soap film membrane.

This is not true, in general, if STEPS 1 and 2 of the design methodology are not followed, as it is shown in Figs. 5,6, representing the cross section through a balloon fabricated from a cutting pattern simply designed after the geometry of a perfect sphere. The shape after inflation enlarges, and the suspended payload introduces stress perturbations, Fig. 9 .

In STEP 4 of the design methodology (Cut out Pattern) the elastic pattern skrinks by the elastic stretches and it becomes a totally stress-free piece of doubly curved surface of fabric material in space.

This surface of fabric skin is made flat in an extra computer run as described in STEP 5 of the design methodology (Flattening), hereby introducing inevitable but minimum parasitic internal stresses whose maxima remained below $\pm$ 30 % of the final stress state of roughly 10.8 Newton/millimeters. The highest parasitic stresses occur near the balloons equator in the meridional direction due to the elastic deformation of the doubly curved fabric surface into a flat piece of fabric. They are the minimum possible ones, because the flattened pattern is not supported laterally. Their magnitude is a function of the size of the pattern and of the stiffness of the fabric material.

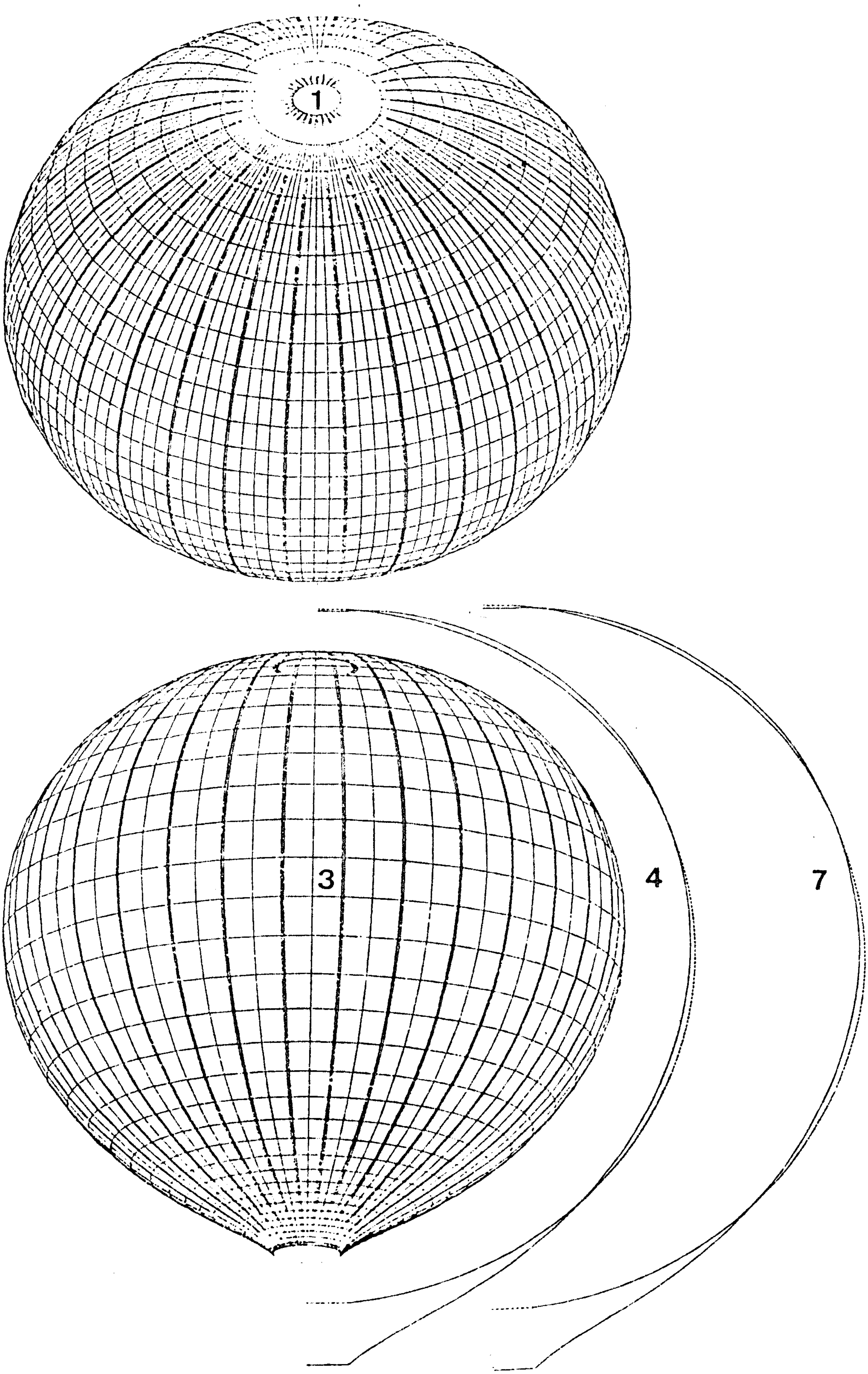
The form of the flat, plane sheet is now used as a cutting pattern in order to cut out an identical sheet from totally stress-free material according to STEP 6 of the design methodology (Cut out of Final Pattern).

According to STEP 7 of the design methodology (Erection), in a final computer run the final sheet is brought into its spatial position, and it is reloaded by the original internal pneumatic pressure plus the other loads responsible for the initial soap film shape. This step corresponds to the physical assembly of the final cutting pattern and the putting the balloon into service conditions.

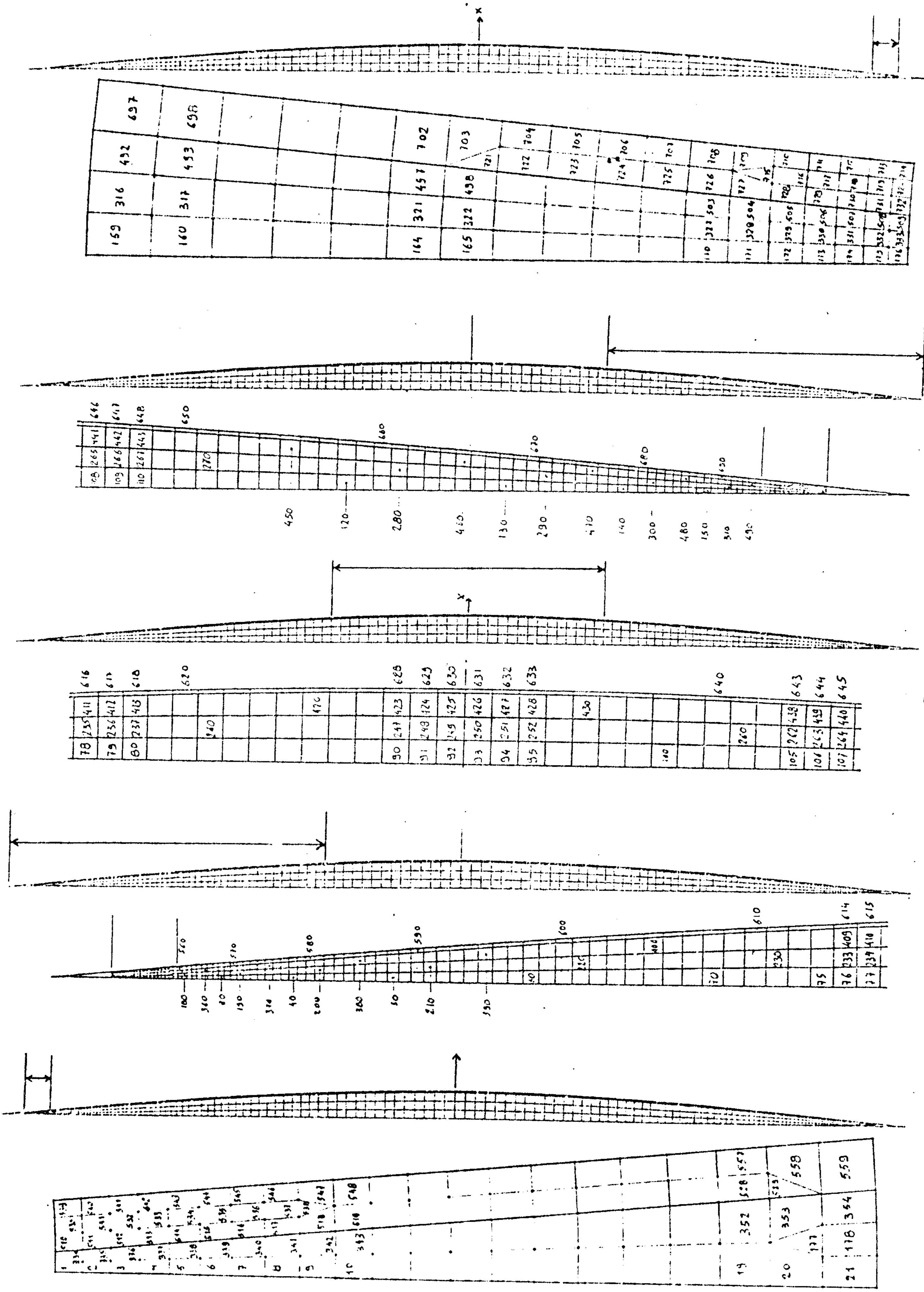
During the process of reloading, the flat final sheet is deformed elastically into a doubly curved three dimensional fabric surface. The corresponding elastic surface deformation will generate inevitable, but minimum, parasitic stresses of maximally $\mp$ 30 % of the average uniform target soap film stress state of about 10.8 Newton/Millimeters. The parasitic stresses of reversed sign are again maximum near the equator of the balloon. The final shape of balloon generated this way differs very little from the original soap film shape, as shown in the cross section through the final balloon, Fig. 7.

The quality that may be achieved through the use of the proposed design methodology is demonstrated by comparing the final stress states near the south poles of the balloon designed after the methodology, Fig. 8, and of a balloon made from sections cut out after the geometry of a perfect sphere, Fig. 9. The stress contour plots show meridional tensions of 21.5 to occur in the spherical balloon, while the stresses in the well designed balloon membrane remain very close to the target value of 10.8 Newton/millimeters.

Finally, the balloons stress state due to hypothetical repetitive inaccuracies in the width of the cutting pattern has been studied. To this end a sinusoidal gap of 0.3 millimeters in amplitude and about 200 millimeters long has been introduced at the least favorable position in the calculated cutting pattern near the north pole of the balloon. The resulting maximum elastic stresses of 27.0 Newton/millimeters in the circumferential direction, Fig. 10, exceed considerably the target stresses of 10.8 Newton/millimeters, indicating that a high precision in the evaluation and the fabrication of the cutting pattern is a prerequisite for the use of modern stiff, high-strength fabric material.



FIGURES F1, F3, F4, F7



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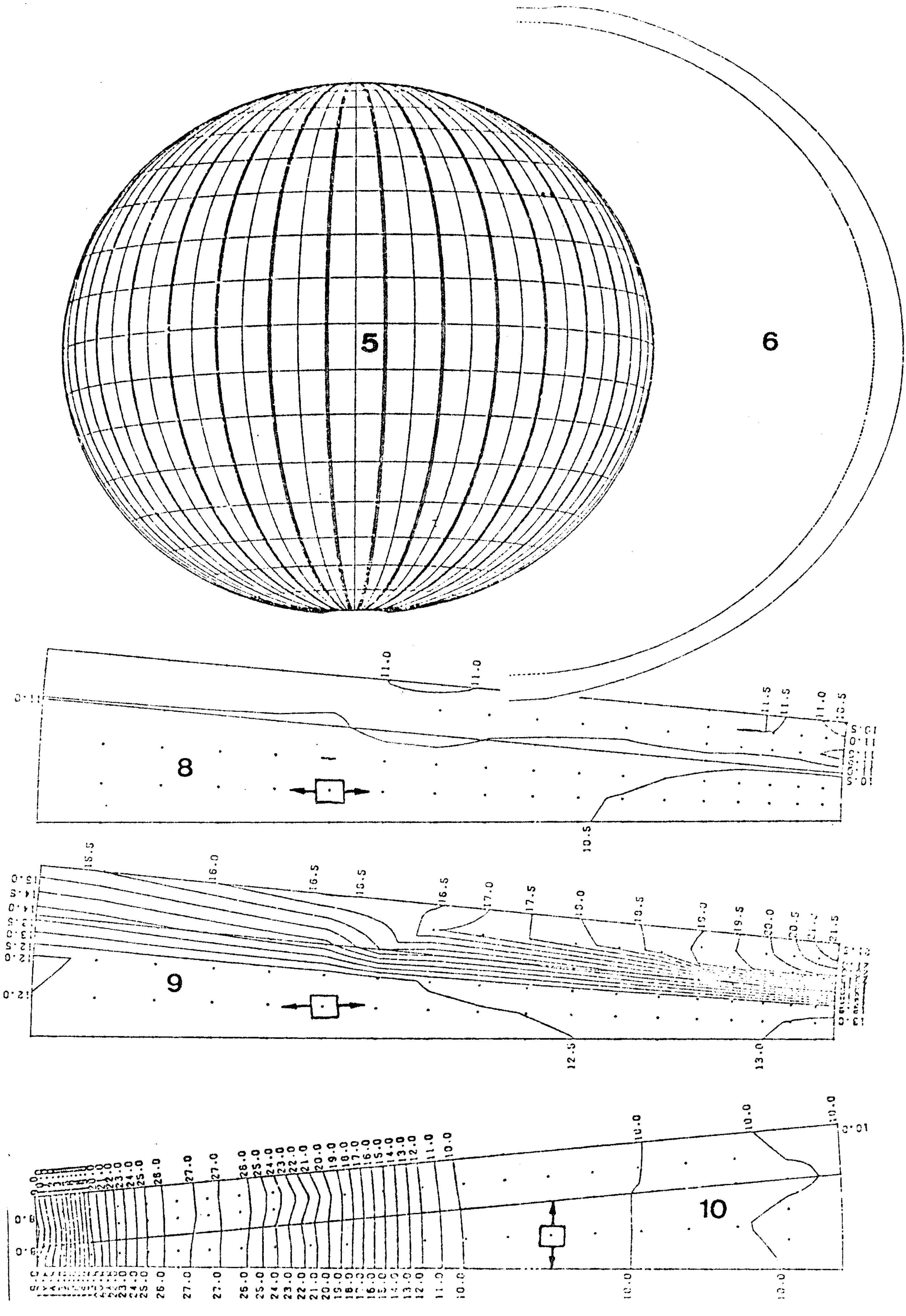
FIGURES F2



FIGURES F5, F6, F8 - F10

CONCLUSION

The paper gave examples on the design and analysis of pneumatic structures using a modern numerical tool.

The program in question, PAM-LISA, permits the complete design of lightweight structures, ranging from simulated soap film forms over precise cutting patterns to the analysis of the resulting structure under loads.

Special emphasis has been given to a general design methodology of membrane structures, permitting the best possible design and introducing a universially applicable, rational, method for the tricky subject of cutting pattern evaluation.

The feasilibity and success of the tool and the methodology have been demonstrated in two demanding examples in industry and space projects.

The proposed tool and methodology are believed to be the missing link in the rational, efficient and widespread use of high technology materials in the engineering and architectural design of permanent pneumatic and tent structures.

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DESIGN AND ANALYSIS
OF PNEUMATIC STRUCTURES
BY THE FINITE ELEMENT METHOD

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C O N T E N T S

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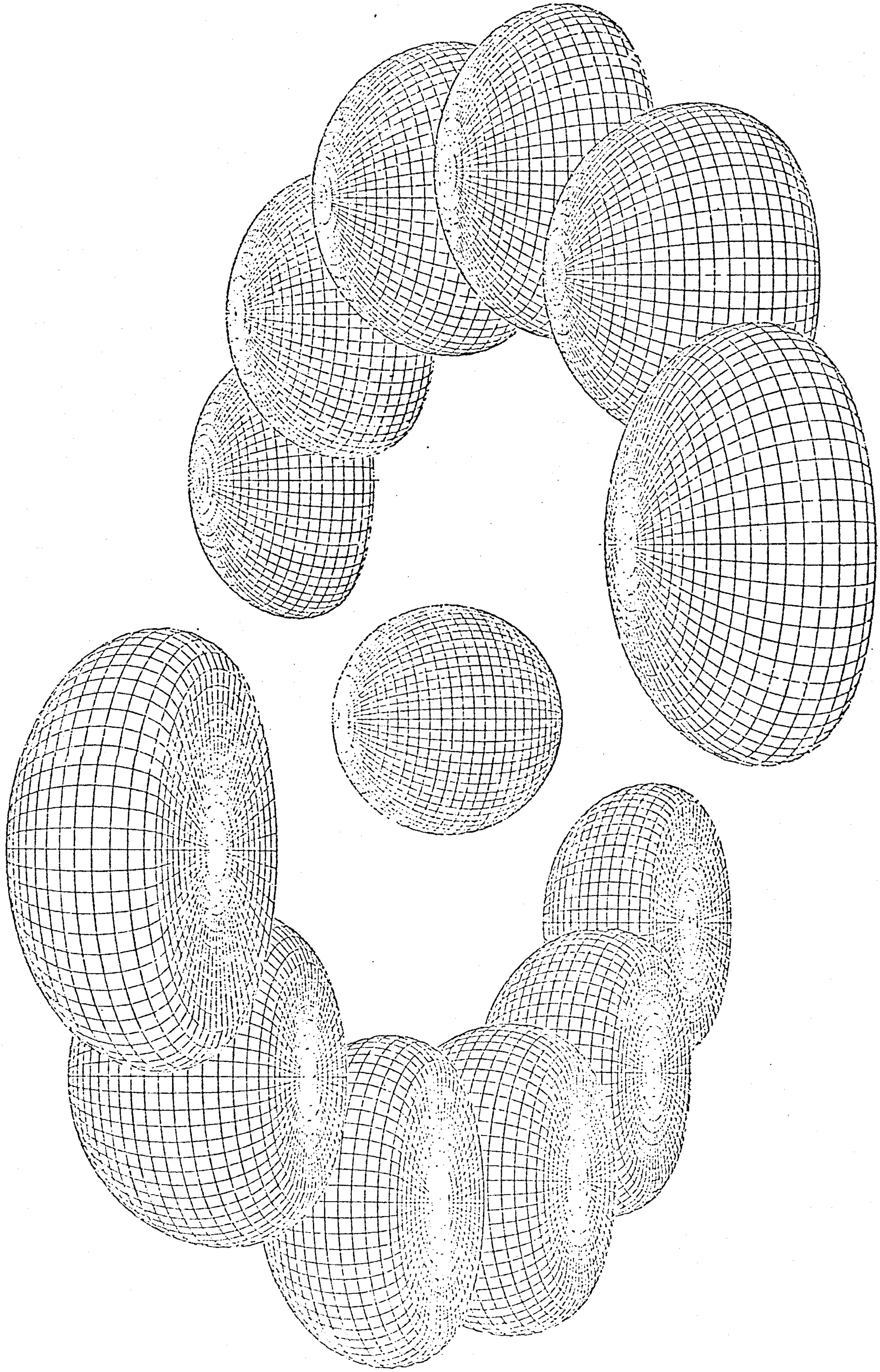
The various examples shown without comment throughout the introductory Part I have been run by J. Oelbermann at the University of Essen at the Institute of Prof. Bubner, using the program MASL, an earlier version of the ESI industrial computer program, PAM-LISA, described in more detail hereunder. The arrangements of the computer plots have been made with great pleasure by the author, who thinks lightweight structures are beautiful and who wishes to invite people to use numerical tools for their generation and design.

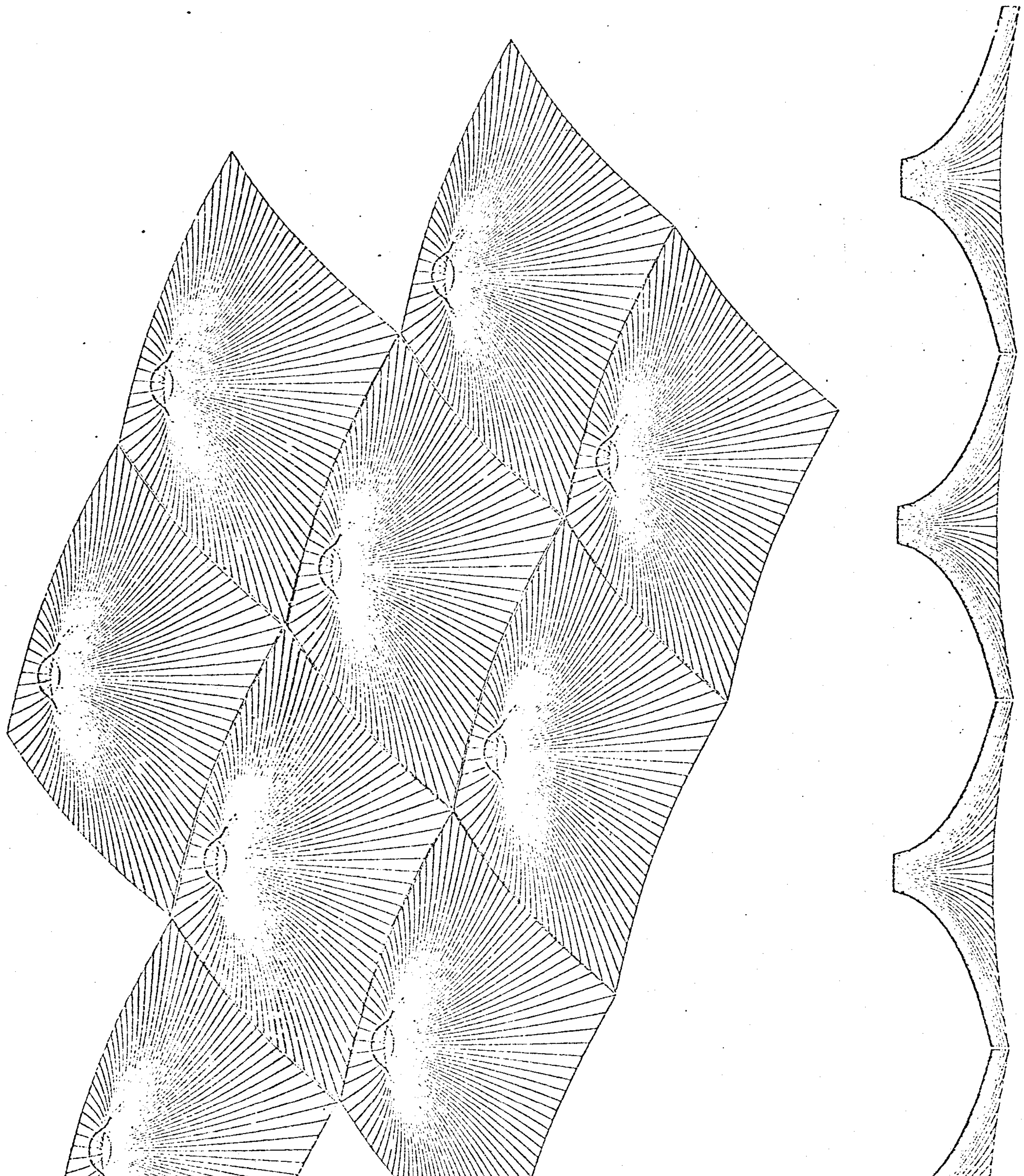
Most computer plots shown in Part II stem from work done at ESI and from work done by J. Oelbermann at Essen.

The membrane design methodology in Part III was invented at ESI by the author and the tissue model originated from ideas put forth by Meffert at the Technische Hochschule Aachen. Some of the figures in Part III go back to work by Losch and Reinhardt at the University of Stuttgart.

The example of the VENUS-balloon in Part IV was done at ESI in a study granted by the Centre National d'Etudes Spatiales, C.N.E.S., during which ESI also benefitted from collaboration with the firms ZODIAC-ESPACE and AERAZUR concerning design and material properties.

The general stimulus concerning lightweight structures the author receives through his corresponding membership in the Special Research Grant SFB-64 at the University of Stuttgart, and the continued support of the staff and the firm ESI in his work are herewith gratefully acknowledged.





PART I : INTRODUCTION

NUMERICAL ENGINEERING

(Références 14-17)

This paper views the system design, the structural realisation and the engineering analysis of lightweight and pneumatic structures from the unifying vantage point of the numerical analyst and designer.

While in the not too distant past the system design of pneumatics may have been performed by architects, the system evaluation by model specialists, the dimensioning of the structural members by structural engineers and some limited structural analysis by a highly sophisticated shell specialist, all these tasks may now be dealt with by any one of the above mentioned with the aid of a modern numerical analysis program and a digital computer of the size of a modern mini-computer.

One such computer program, PAM-LISA, has given rise to the present publication and it is hoped that the effect of design unification and user de-specialization, as well as the virtually unlimited range of applicability of modern numerical tools and apparatus will come out clearly.

The use of modern digital computer programs has become so stereotyped that anybody understanding the basic physical and engineering aspects of a structure to be designed numerically will be able to do so after some basic training. Indeed, the activity of a program user is as intuitive as the one of a physical experimenter or of a manual model builder and has little to do with the approach of a mathematical analyst.

The program user may channel his efforts almost entirely directly to the point of interest rather than having to deal with intricate mathematical formulas, tedious mechanical equations and lengthy manual calculations.

The paper does not discuss the way a computer program is written and how physical evolutions are translated into numerical algorithms. Computer language and algorithms are the preoccupations of program developpers, not of program users, for whom this paper is intended.

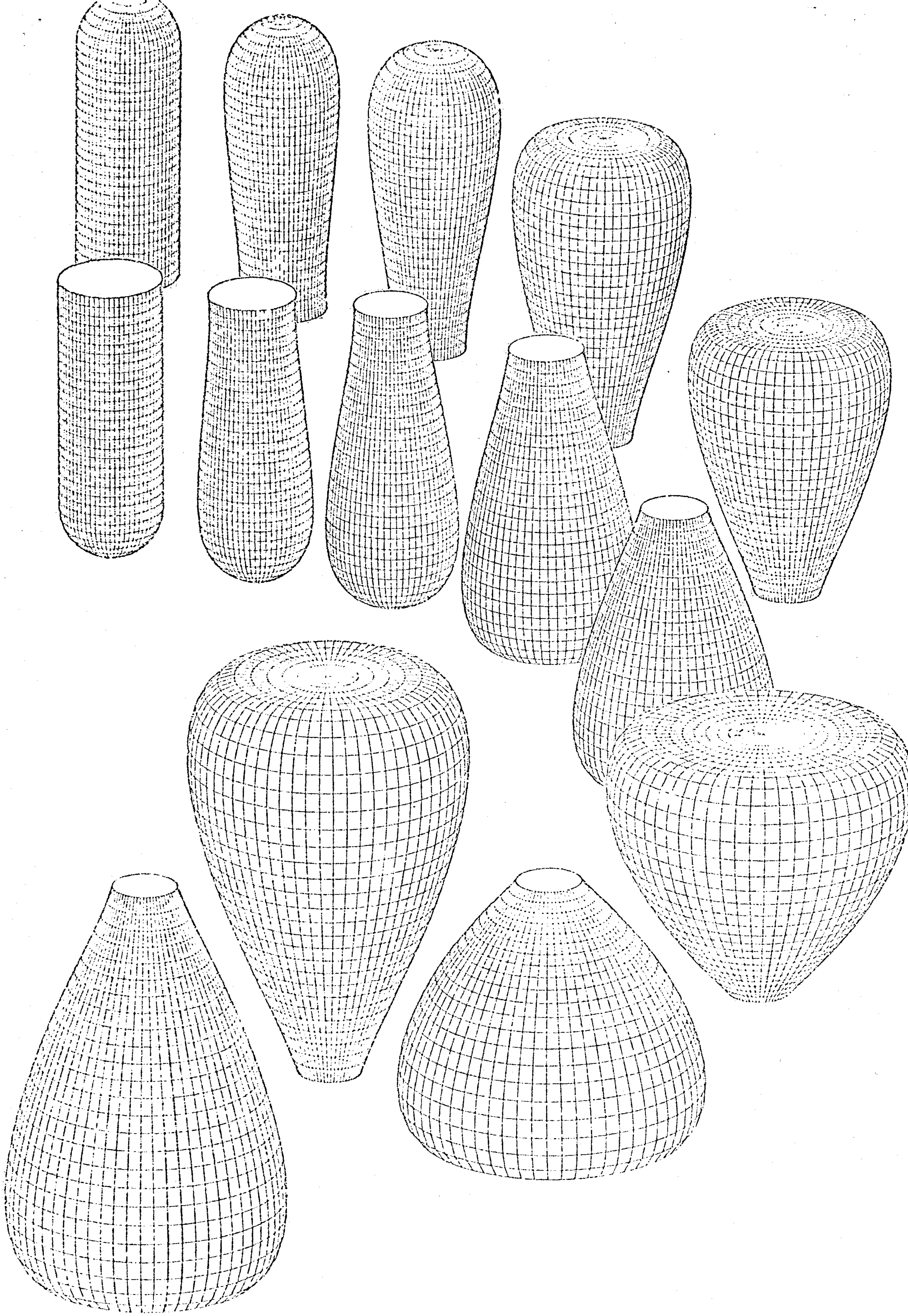
PNEUMATIC STRUCTURES

(References 24, 1-3, 9-13)

Pneumatic structures are frequently made of membrane fabrics having negligeable flexural stiffness. The load carrying capacity of pneumatic membranes may be enhanced by added cables or overlaid cable nets. The main ingredients in a computer analysis of pneumatics are therefore membrane and cable elements.

Pneumatic structures keep their shapes through the applied inner normal pressure, which acts on the leak-proof membrane carrying the resulting structural forces or transmitting those forces to the next higher load carrying system in the structural hierarchy .

Architectural pneumatics are typically lowly pressurized structures with a constant inner normal pressure, corresponding to a column of water of a few centimeters. Tubular pneumatic skelettons and automobile tyres are examples of highly pressurized pneumatics with inner pressures measured in atmospheres. Hydrostatically loaded membranes and envelopes may be considered pneumatics with a variable normal pressure applied to their surface. There exists an entire world of biological pneumatics with cannot be subject of this paper, limiting itself to the discussion of technical pneus.

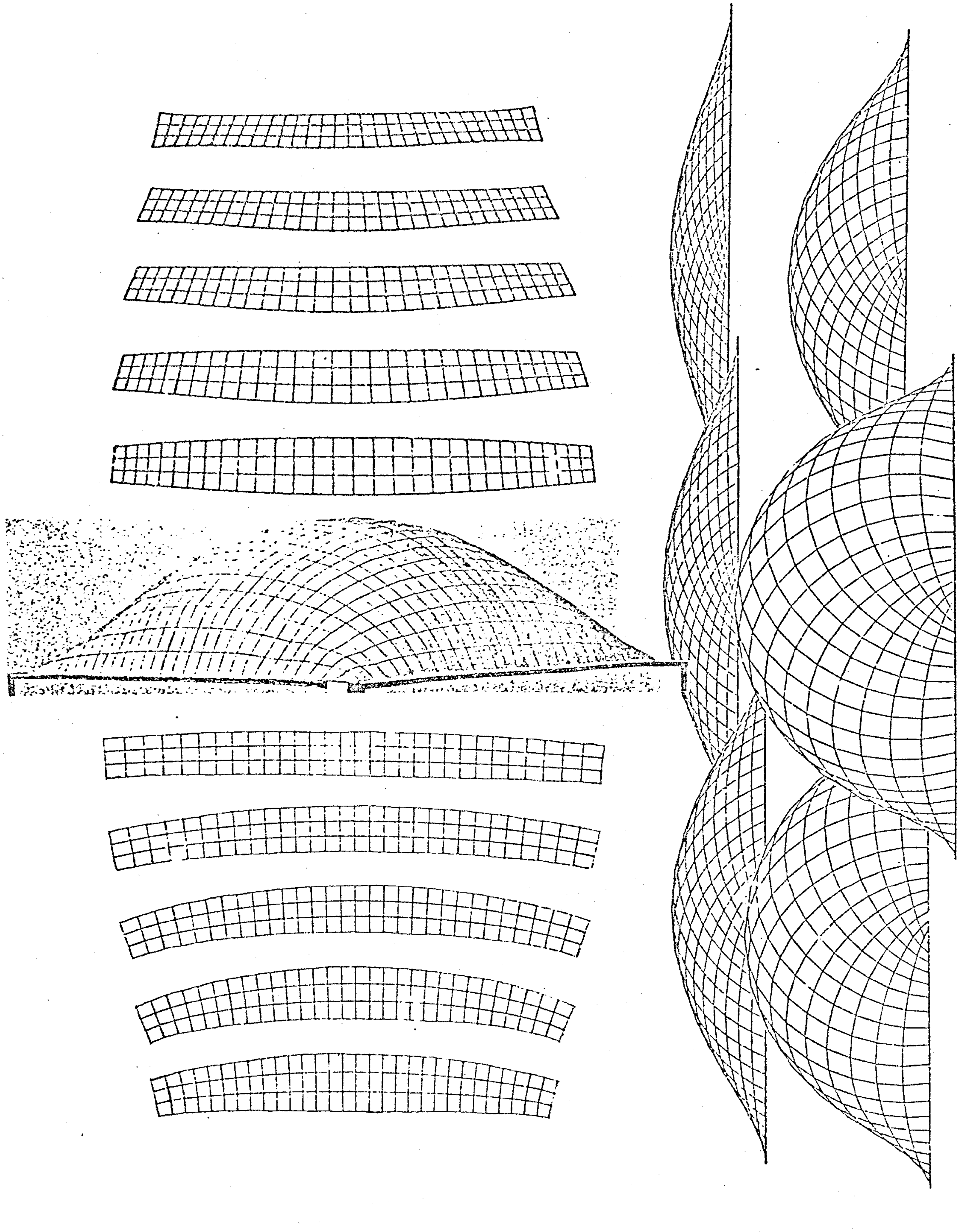


DESIGN METHODOLOGIES

(References 13, 20, 21, 22)

A membrane design methodology for the shape finding, membrane cutting pattern evaluation and for the analysis under loads has been invented for the computer program PAM-LISA. This methodology, however, tends to be universally applicable and it is independent of the numerical approach it has been invented for originally. The same methodology could be applied, for example, in an entirely experimental approach, although some of the required steps may be more easily performed numerically.

Is there any better evidence of freedom and device-independence than the apparent interchangeability of numerical and physical design methodologies ? Facts like those demonstrate the true power of modern numerical methods and such feedbacks constitute ample reward and encouragement for the often tedious work of the program developper.



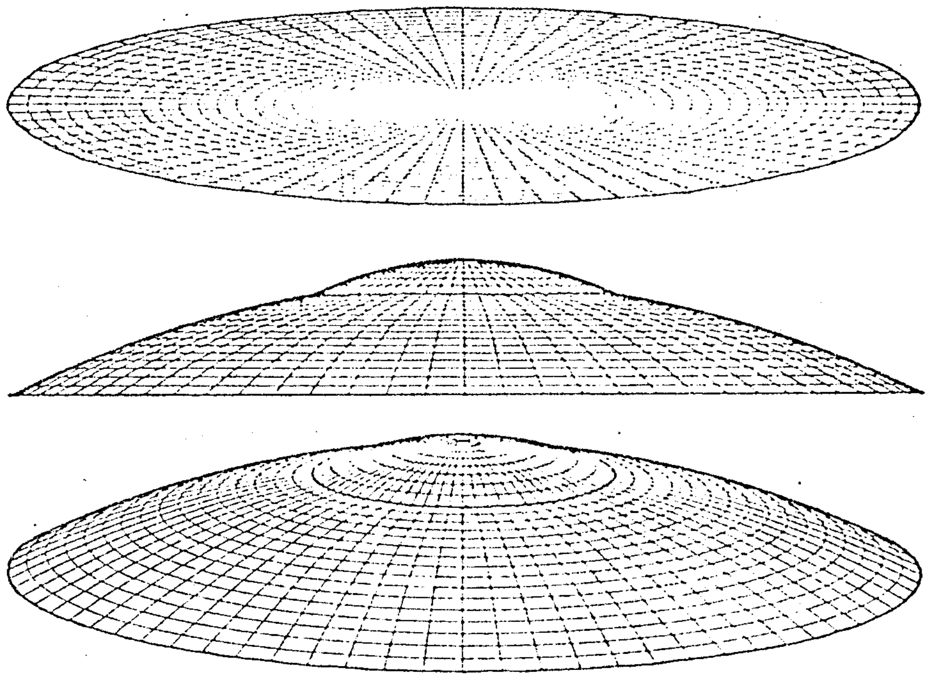
FINITE ELEMENT METHOD

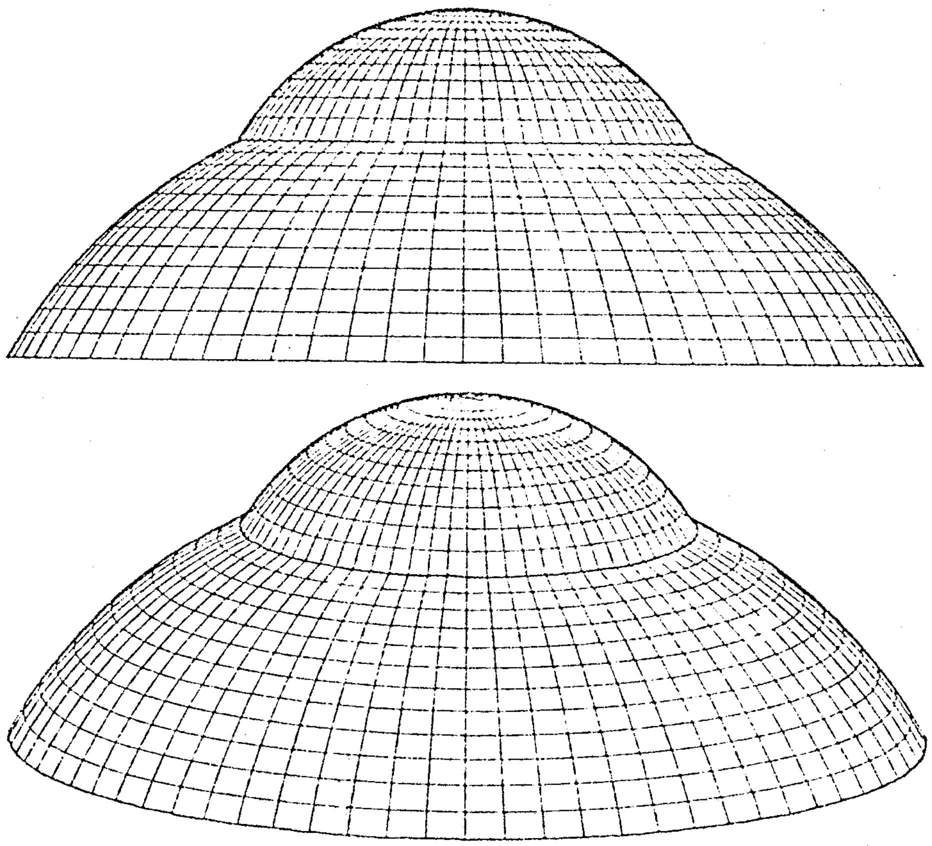
In the finite element method a structure is subdivided in a compatible fashion into many prototype structures whose general individual responses to applied deformations and loads can be programmed for automatic calculation in a computer. The prototype structure (finite element) may be a straight segment of a cable (cable element), a quadrilateral piece of membrane (membrane element), an initially uncurved section of a beam (beam element), a cube-like section of a solid (brick element), etc..., depending on the type of structure to be analyzed.

After the analyst has represented a real structure by an assembly of such elements (mesh), the computer calculates the stiffness properties and the load contributions of each element and it assembles those properties into a set of equations of structural equilibrium at the structural nodal points (points of intersection of the elements). The solution of the set of equilibrium equations is performed by the computer, resulting in displacements of the nodes, which are used by the program in order to calculate the resulting deformations and stresses within the body of each finite element.

If the equilibrium of a structure under load depends on the deformed shape of the structure - as it is typical for all but a few trivial examples in the domain of lightweight structures - the solution must proceed in steps, or iteratively, where each deformed shape serves to define a new geometry, serving as a new basis for the subsequent step or iteration.

The finite element method has become so heavily automated, that a detailed knowledge of its functional aspects is not required for its successful application. This enables the designer to create lightweight structures using the method in an intuitive and truly experimental way, demanding little other knowledge than a physical understanding of the engineering aspects governing the form and the behaviour of the structure under loads.





COMPUTER PROGRAM

(Reference 21)

The examples shown in this paper have been calculated by the implicit static and dynamic finite element computer program PAM-LISA (Programs in Advanced Mechanics - Lightweight Structures Analysis) or by earlier versions of this program (e.g. MASL). The program has been developed by the author starting 1969 at the University of California, Berkeley, under the supervision of Prof. G.H. Powell during the research phase of his doctoral studies, later in Paris, in Essen with J. Oelbermann at the Institute Prof. Bubner, and again in Paris at the private firm E.S.I.

OUTLINE

Part II of the paper gives a general overview concerning the numerical design of lightweight structures with the program PAM-LISA.

Due to the structural similarity and their usefulness in connection with membranes, the paper first discusses some aspects of the numerical shape finding and analysis of cable structures.

Then the paper gives an overview on the computer design of membranes, including soap films, modified soap films, pneumatic and hydrostatically loaded membranes.

Part III describes a successful membrane design and cutting pattern evaluation procedure and it discusses a technical tissue material model, permitting a clear modelling of actual tissue material behaviour, such as the cinematic coupling between the warp and weft threads and a nonlinear stress-strain behaviour of the fibers.

Part IV, finally, discusses two technical applications performed with the program PAM-LISA, demonstrating the feasibility of the approach and methodology of design in non-trivial cases.

PART II : GENERAL OVERVIEW

DESIGN

Architectural design evokes keywords such as system, form, function, beauty, environmental impact, technology, human needs and nature. Engineering design deals with structural systems, materials, dimensions, members, environmental action and integrity. Engineering analysis considers loads, deformations, stresses, strain, vibration, failure and safety.

People say there is little or no interaction between architectural and engineering design. More surprising is the fact that there is also little interaction between engineering design and engineering analysis. That is, engineering analysis results rarely change the basic engineering design, and engineering design considerations often go unnoticed in architecture.

This cannot be true with lightweight structures. There is at least a coupling between system and form, structure and dimensions, and loads and deformations. In this sense, the design of lightweight structures must be interdisciplinary.

This paper deals with the engineering analysis and the system structural design of lightweight structures. Engineering analysis in lightweight structures means both precise shape finding and analysis under loads. The shape finding task is new to engineers. It is the more difficult one. The tasks can be solved by physical experiments, or by numerical experiments, i.e. computationally, as demonstrated hereunder.

CABLE STRUCTURES

(Figures A1-A24)

References (1, 4-8) concern this topic. In using the finite element method, cable structures, Fig. 1, are considered to be made of cable elements, Fig. 2. The simplest linearly elastic straight cable element has two nodal points and it is characterised by its unstressed length, L_O, Young's modulus, E, and surface area, A. To make a structure, the elements are interconnected at nodal points, which can be cable crossings or intermediate points as in a curved segment of a freely suspended cable, Fig.3.

Each cable element is allowed to transmit a tensile force from node to node, and when it can also transmit a compressive force, it is called a "truss element", Fig. 4.

For linearly elastic materials, the tensile (or compressive) force increases proportionally to the change in length, Fig. 5. There are also nonlinear elastic, plastic and time dependent creep or viscoelastic deformations possible Figs. 6, 7 and 8.

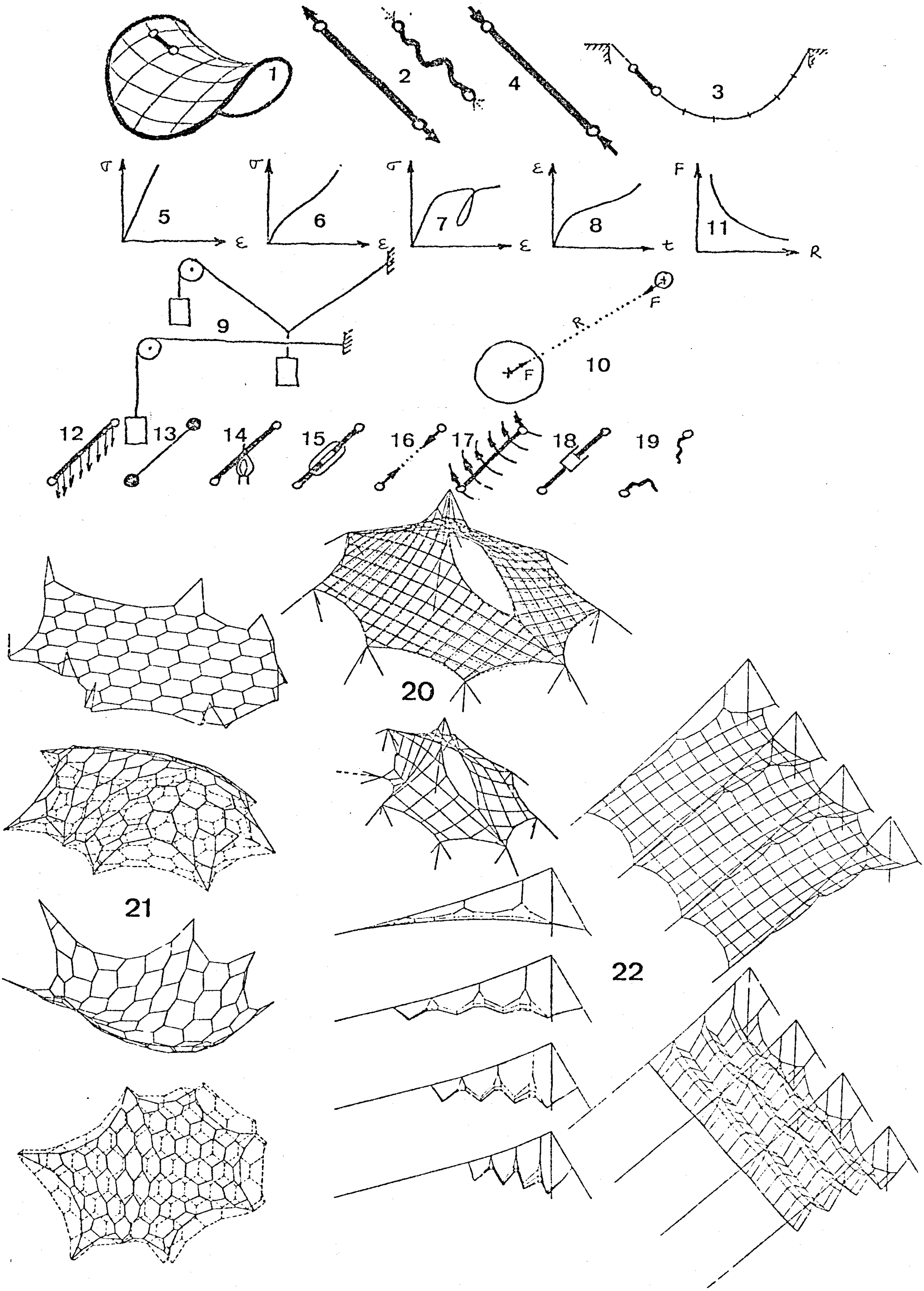
Prestress cable elements, Fig. 9, are indispensable during the process of shape finding of cable net structures. Physically, such elements behave like ropes being prestressed by a constant weight, exerting a constant pull via a frictionless pulley. Numerically, a prestress element between two nodes is characterised by the absence of any material resistance in stretch or compression and by assignment of a constant positive or negative force of a specified magnitude.

Gravity elements, Fig. 10, numerically, are cable elements whose force is inversely proportional to the square of their length and proportional to the product of the joined masses, Fig. 11. They extend the range of application of cable programs to the analysis of the motion of heavenly bodies. Other generalisations of cable elements seem possible.

Cable elements can have deadweight, mass, temperature changes, turnbuckle type length changes, prestress forces, drag forces (for motion through viscous media, water, air), internal damping, rupture characteristics and other loading characteristics, Figs. 12-19 respectively.

If incorporated into a program, the enumerated options allow the analysis of a very wide range of problems with the same analytical tool.

The examples shown, using the authors programs, comprise a simplified numerical model of Frei Otto's Vaihingen Institute, Fig. 20, a hanging net with hexagonal meshes, Fig. 21, a retractable net in various positions, Fig. 22 (all done in Berkeley, 1969). A modified version of the program has been used for the analysis of very long floating anchor cables, Fig. 23, vibrating under wave actions (Paris, 1975) and to the analysis of tethered satelites, Fig. 24 (Paris, 1977).



FIGURES A1 - A22

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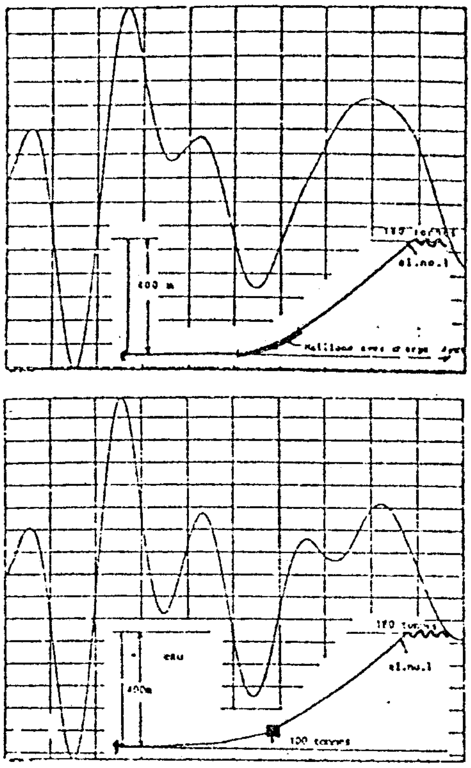

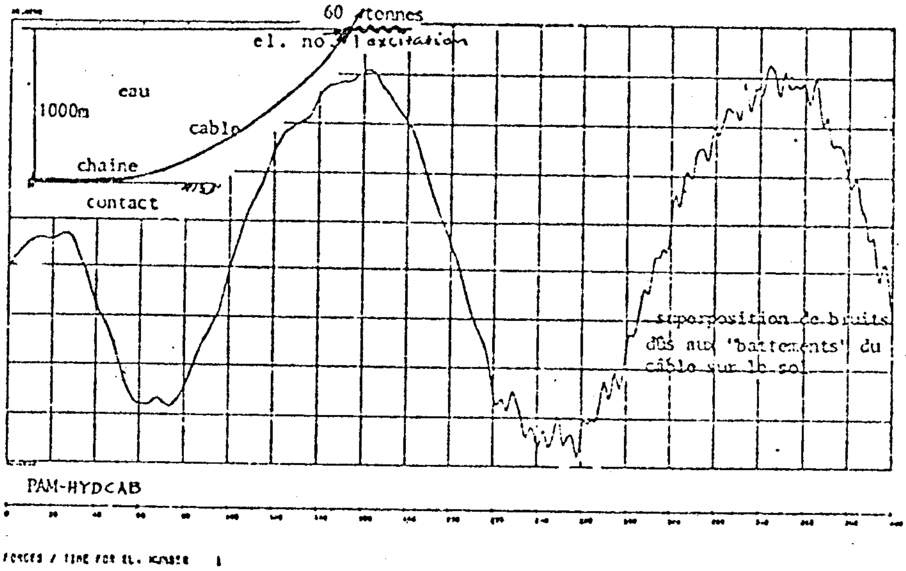

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Analyse Dynamique des Ancrages Immergés

Par la Methode des Eléments Finis

E. HAUG
A. DE ROUVRAY
M. CARIGNAN
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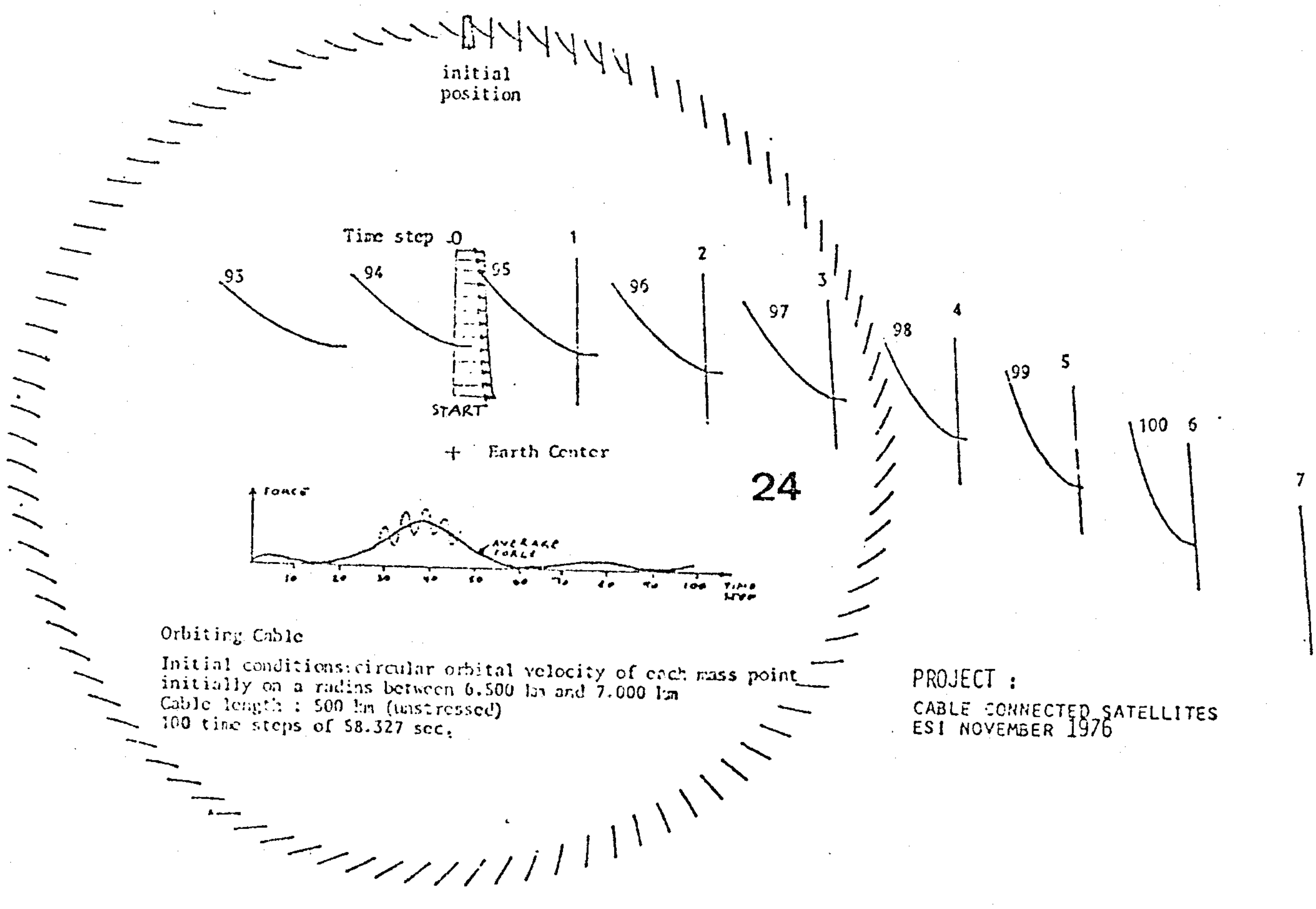

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MEMBRANE STRUCTURES

(Figures B1-B29)

These structures are discussed in detail in Refs. 1,2,9-13,18,19. In a finite element analysis, a continuous membrane structure is subdivided into a number of triangular, quadrilateral or higher order polygons, each being a finite membrane element.

Quadrilateral membrane elements, Fig. 1, are defined geometrically between four corner nodal points and with a thickness. Their midsurfaces are hyperbolic paraboloids. Their material is defined through an isotropic matrix plus up to four embedded layers of elastic fibres in different directions, Fig. 2. Each element can have deadload, Fig. 3, projected live loads, Fig. 4,mass, Fig. 5, normal pressure, Fig. 6, hydrostatic pressure and temperature changes, Fig. 7.

Membrane structures behave much like cable structures, but they have added shear resistance due to the in-surface shear resistance of foils, films and tissues. Membrane structures may be subdivided into prestressed, inflated and hydrostatically loaded films. In recent years, their shapes have been studied in many numerical examples, including isotropic, Fig. 8-16 and anisotropic, Figs. 17-19, soap films, containers, Figs. 20-22, floating membranes, Fig. 23 cable net supported membrane, Fig. 13, automobiles tyres, Fig. 26, barrages, Fig. 24, dams, Fig. 25 and air supported halls, Fig. 27 (Berkeley 1970-71, Stuttgart, 1972, Paris, 1973-79 and with J. Oelbermann, Essen 1976-79). The range of application of the combined membrane/cable program MASL is thus seen to be very great.

The shape finding process of membranes is complicated due to the presence of shear resistance. Since the loading of membrane structures seems to introduce no added difficulties with regard to cable structures, the remainder of the section focusses on the process of shape finding.

Shape Finding

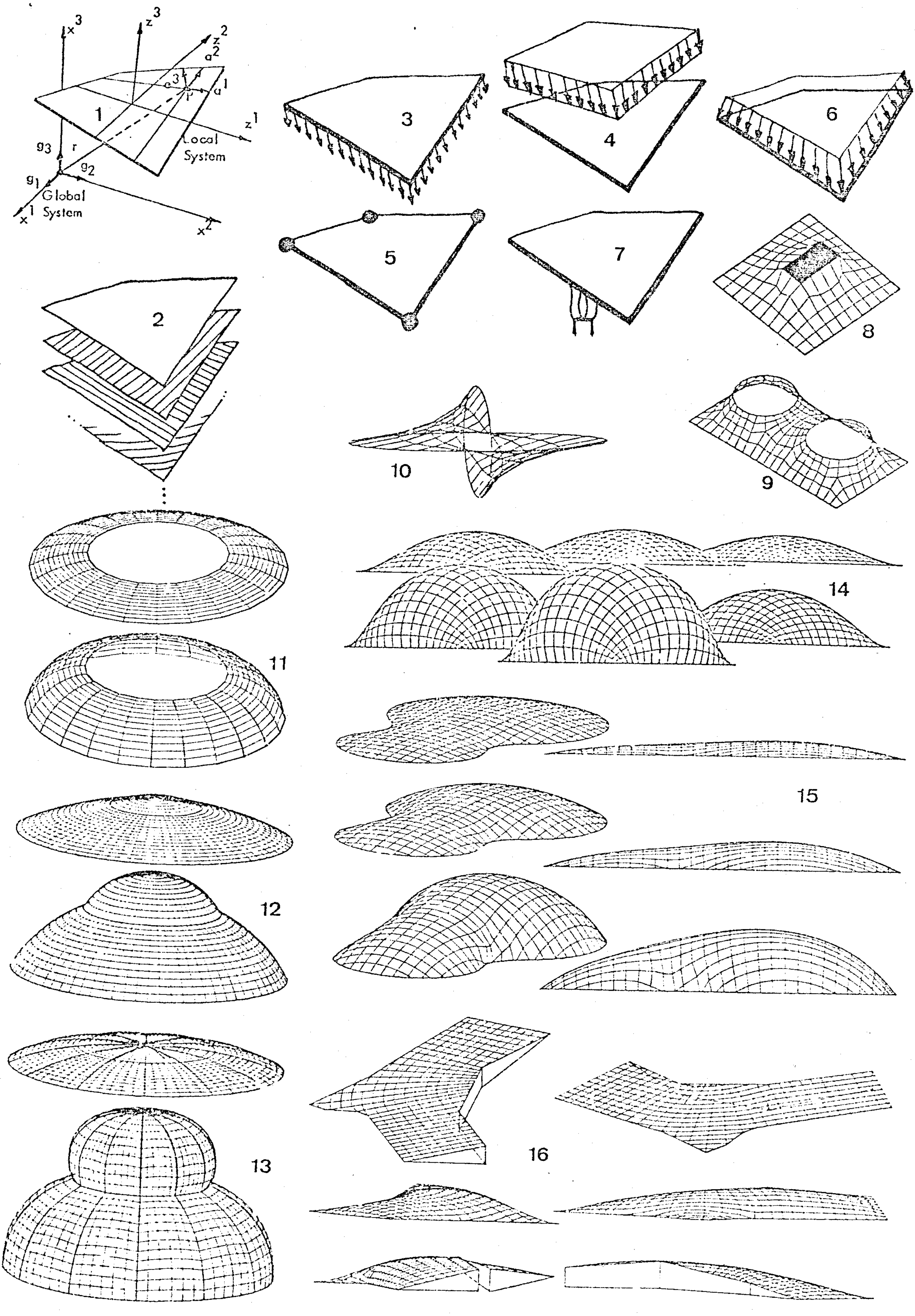
Soap films are physical - "though ephemeral"- structures with the exquisite properties of constant equal uniform tension in all directions at any place in the surface. They form at the same time minimal surfaces. For those reasons soap films have often been chosen as a basis for practical membranes.

Soap film elements assume for membranes the same role prestress cable elements assume for cable structures. They are membrane elements with a stretch independent constant state of isotropic tensile stress. Membranes made of soap film elements can be regarded as matterless pure forms, representing equilibrium states of specified stress and applied loading, if any.

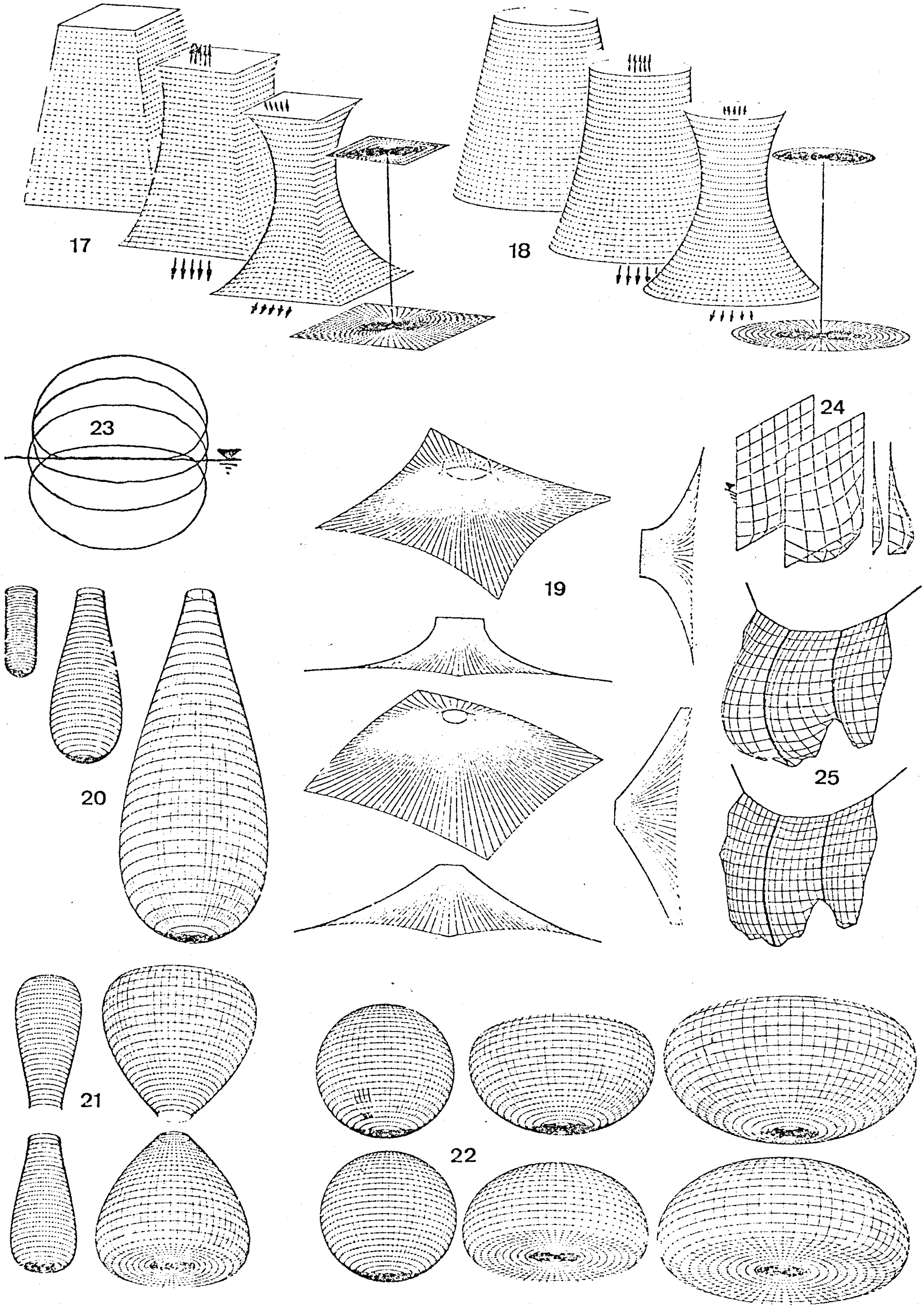
Most real membrane structures are made of orthotropic material with different strength and stiffness in the two principal fibre directions. Therefore a soap film with unequal stress distribution might be a more appropriate basis for the pure shapes of such membranes.

Anisotropic soap films, although not found in nature, can be generated numerically, for example by superimposing a cable net of prestress cables, Figs. 17-19, onto the membrane made of soap film elements. This way shapes of membranes with prescribed anisotropic stress states can be found numerically.

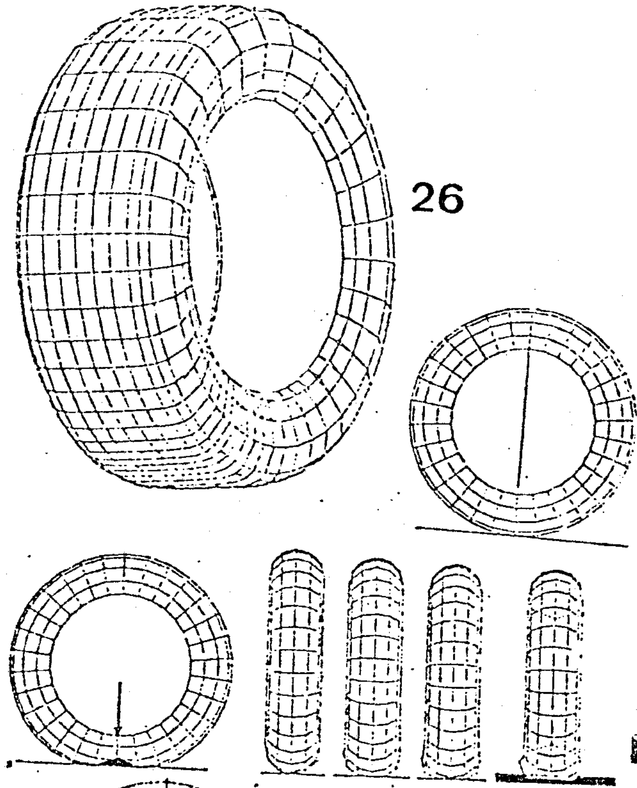
A methodology to evaluate membrane cutting patterns, Figs. 28, 29, from soap film shapes is discussed in the following section.



FIGURES B1 - B16



FIGURES B17 - B25



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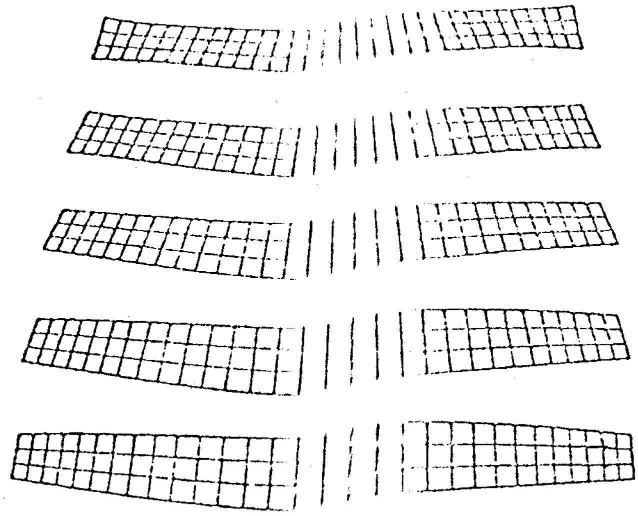

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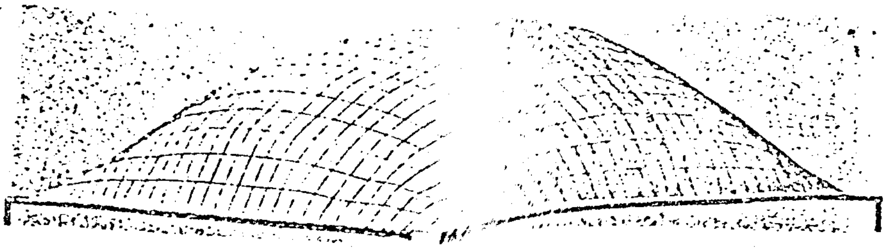

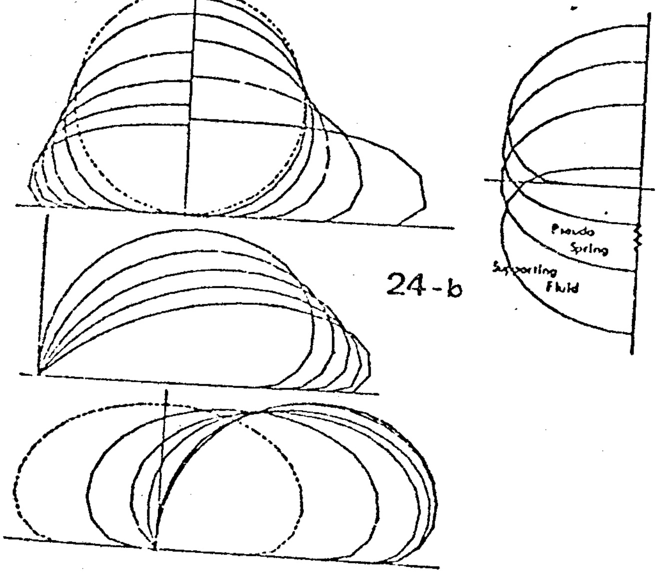

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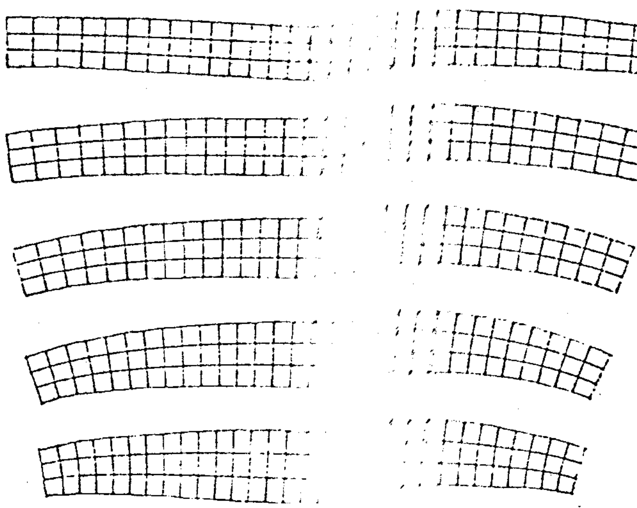

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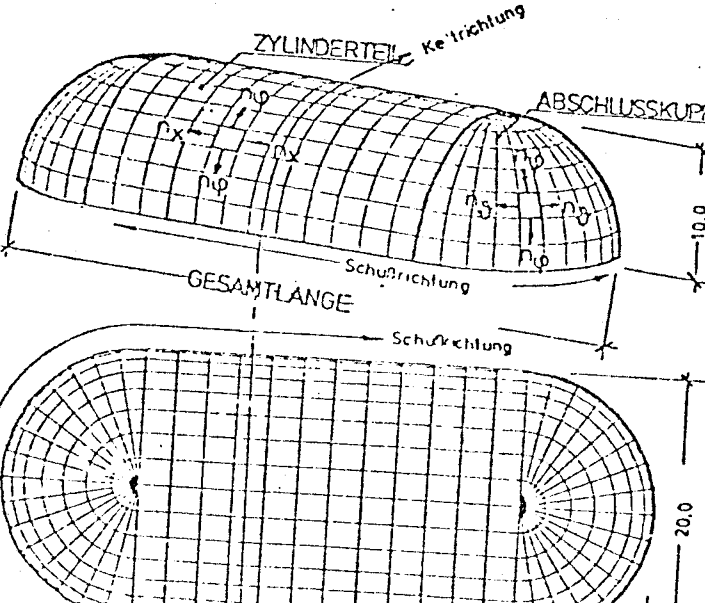

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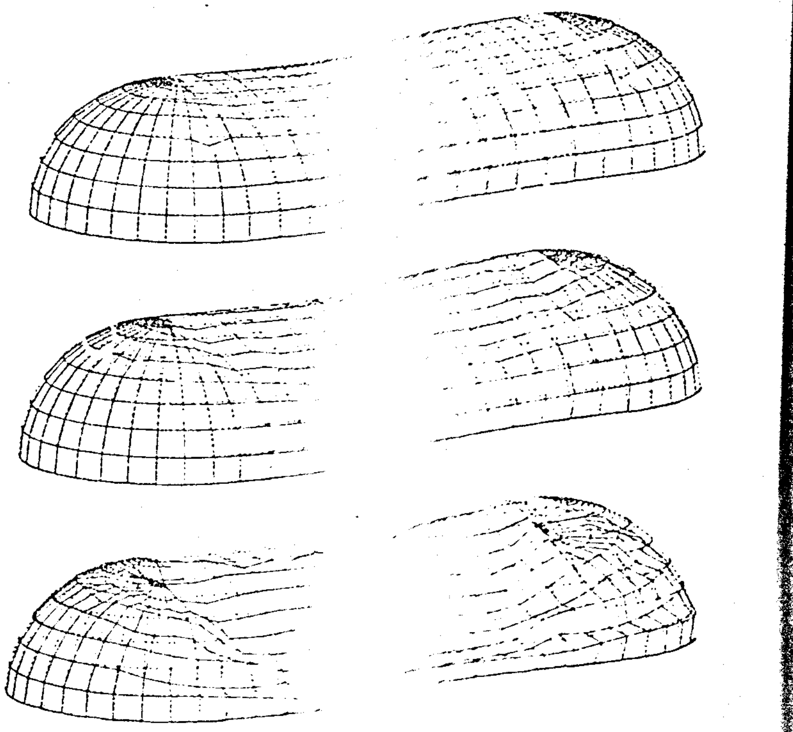


FIGURES B26 - B29

PART III : SPECIFIC TOPICS

A MEMBRANE DESIGN METHODOLOGY

(Figures C1-C9)

(First published in References 13,20)

Cutting patterns of membranes are collections of planar stress-free pieces of real membrane material, Figs. 8 and 9. They are designed such that they yield a best approximation to the desired membrane shape and state of stress, once fitted together and the membrane erected. For practical reasons it is often desirable to obtain cutting patterns consisting of long straight strips of material, Fig. 9. The following sequence of numerical steps is believed to lead towards optimal membrane cutting patterns, Figs. 1-7, constituting a complete methodology of design of pneumatic structures.

STEP 1 : Shape Finding (Fig. 1)

First, obtain the pure form of the membrane, using isotropic or anisotropic soap film elements with or without pressure loading. In a square frame for example, such a pure form can be obtained by inflating an initially flat layout of soap film elements.

STEP 2 : Substitution under Stress (Fig. 2)

Second, substitute under stress an elastic finite element for each soap film element, in such a way that the elastic element will have the soap film stresses while occupying the same position in space. This implies that the elastic substitute elements must be of smaller dimensions than the soap film element, to allow for the required buildup of stress due to stretching of the material. The analysis program calculates those reduced stress-free dimensions in a special analysis step.

STEP 3 : Pattern Finding (Fig. 3)

Third, identify strip patterns on the membrane surface, for example as a collection of strips an integer number of finite elements wide, for development into a plane. If the strips are oriented along geodesic lines within the pure form surface, they are said to form a geodesic pattern, and their development into the plane will be the straightest possible one, Fig. 9. The soap film element nodal point grid within the pure form surface can easily be made to approach geodesic lines by superimposing over the grid a minimal cable net of uniform tension prestress cables (the tensile forces within the auxiliary net may be very small, since in real soap films fluid particles are seen to move freely without material resistance inside the surface, which is also true in the numerical model).

STEP 4 : Cut out Pattern (Fig. 4)

Fourth, obtain the relaxed pattern by cutting the substituted strips of elastic material under tension out of the membrane and by letting them relax. This pattern will be free of stresses, forming doubly curved segments of surface waiting to be developed into a plane.

STEP 5 : Pattern Flattening (Fig. 5)

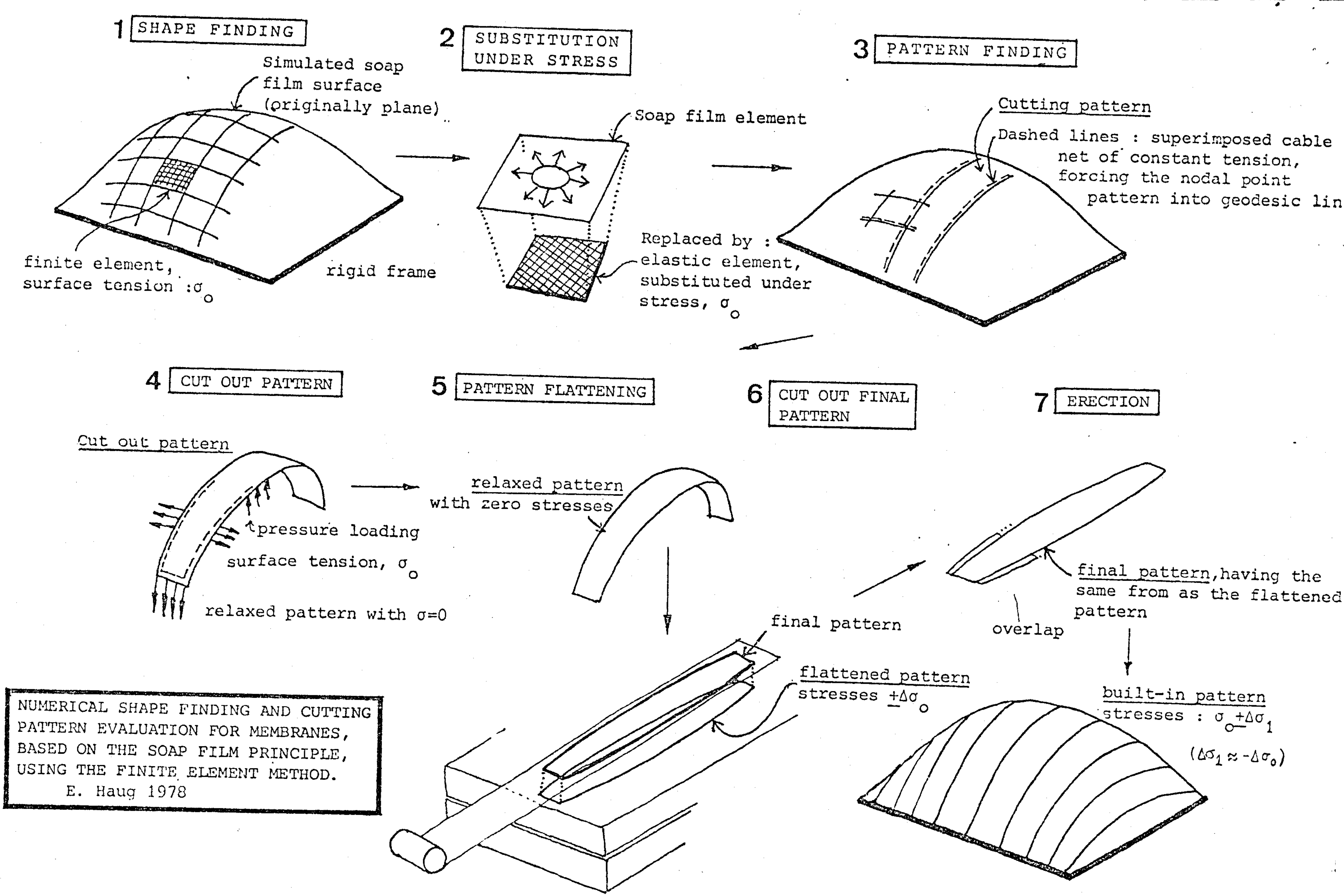
Fifth, obtain the flattened pattern by forcibly flattening the relaxed pattern with the least amount of energy into a well lubricated plane, avoiding wrinkles and friction in that plane. The pattern flattened in this way assumes a position of least restraint within the plane, with the inevitable, but minimum possible, state of selfequilibrating stress deviations from the ideal state of zero stress in the material.

STEP 6 : Cut out Final Pattern (Fig. 6)

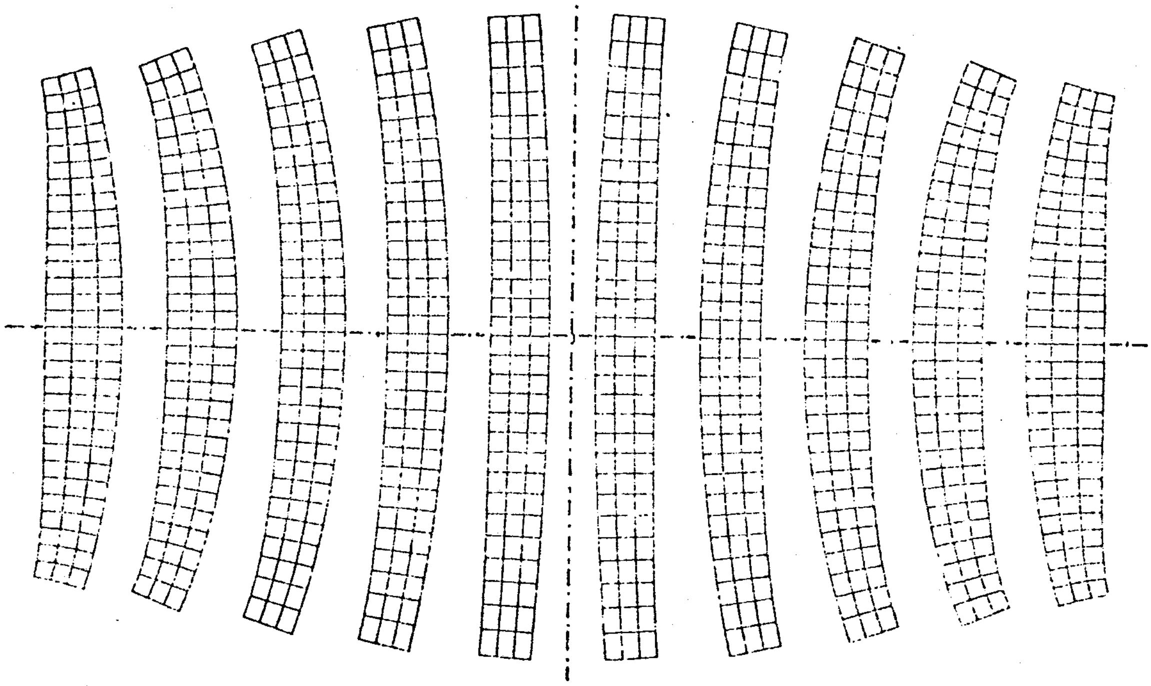
Sixth, obtain the final pattern by cutting out identical strips of totally stress-free membrane material exactly following the shape of the strips of the flattened pattern.

STEP 7 : Erection (F[illegible]

Finally, obtain the [illegible] erected pattern by assembling the final pattern and by reapplication of the [illegible] shape determining factors. This last pattern will have the stress state of [illegible] the pure form but with deviations ressembling closely the stresses in the flatt[illegible]ened pattern, with reversed sign. The stress deviations are due to the deformations necessary to deform the flat final pattern into a doubly curved erected pattern. Due to the resistance of the final pattern to being curved, the shape of the membrane with the erected pattern built in will differ slightly from the pure form. Those form deviations and the inevitable stress perturbations are believed to be a minimum, in an average sense, when the described shape finding procedure is applied.



FIGURES C1 - C7



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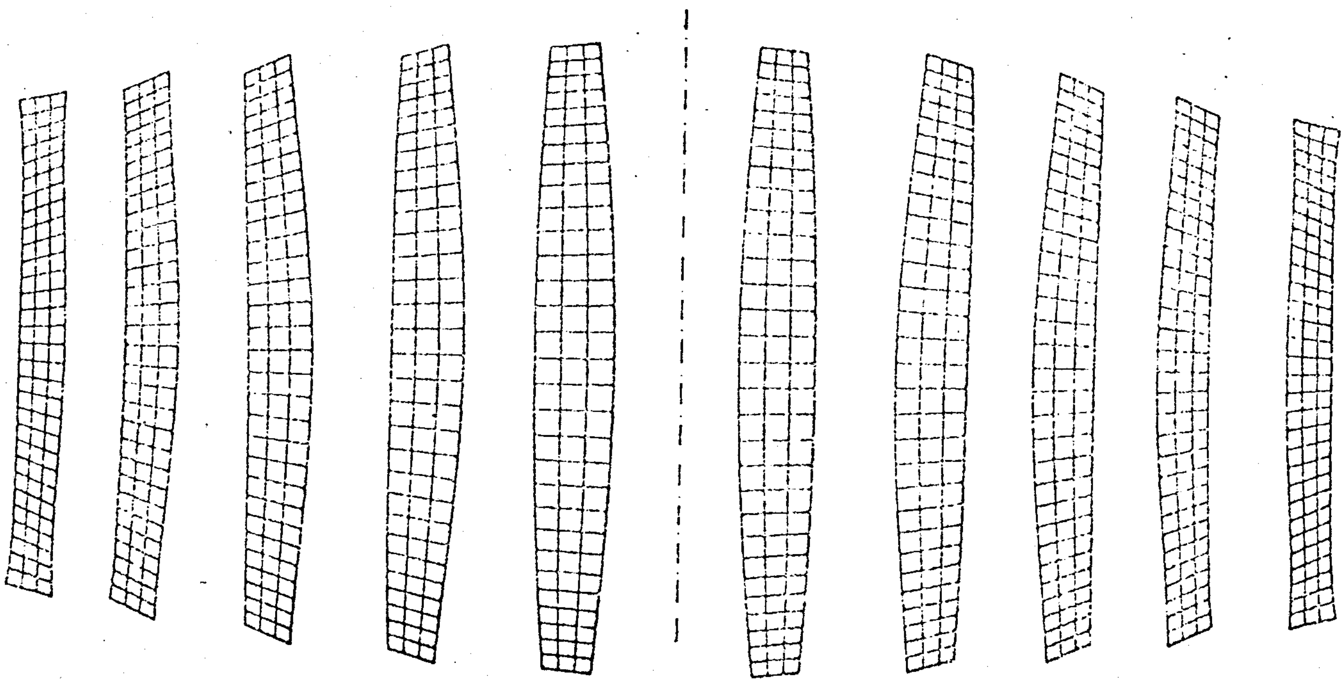
CURVED PATTERN



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GEODESIC PATTERN

FIGURES C8 - C9

A TECHNICAL TISSUE MODEL (Figures D1-D12)
(References 21-27)

One little explored engineering problem in a rigorous analysis of technical membrane structures is the correct numerical representation of the coated fabric material properties, Figs. 1,2. This is the more important the stiffer and stronger a fabric becomes (e.g. Kevlar-Mylar composites, Teflon-coated fiber glass fabrics, etc..) and the more lightweight the structures are at simultaneous high stress levels.

For this reason an easily understandable engineering type coated fabric tissue material model is described in some detail, which may serve as a basis for more elaborate models to come and which excels by its conceptual simplicity and directness in the successful description of the highly complex subject matter.

A microscopic view of a section of a typical two-thread coated fabric weave Fig. 3, reveals the ondulation of the warp and weft threads and their tendency to become straight if a sample of tissue is pulled in one direction. The initial resistance to the straightening is mainly due to the small, but over short distances nevertheless important, flexural rigidity of the pulled threads and of the threads in the other direction, which are becoming curlier in the process. The flexural inertia is significantly due to the presence of the coating material in which both sets of threads are embedded.

The stress-strain curves, Fig. 4, of a uniaxial tension test of a tissue are therefore rather nonlinear, with a lower tensile resistance in the initial phase during which the pulled fibers straighten out and with a higher stiffness and resistance later on once the fibers have been stretched out fully. It is the cinematic interdependence of the weave threads that renders a tissue fabric response initially nonlinear even for an assumed linear elastic or inextensible behaviour of the material of the fibers.

The second principal source of nonlinearity lies in the nonlinear stress-strain behaviour of the individual fibers of which the tissue threads are made, Fig.5. Polyester fibers, for example, are first stiff, then they soften suddenly and at high strain levels they stiffen again.

Nonlinear Beam Model

Both sources of nonlinearity can be easily incorporated into an engineering model of a coated fabric tissue, in which the uni-and biaxial material responses are derived from a nonlinear engineering beam model of one typical repetitive crossing point of the warp and weft threads singled out of the tissue.

This tissue model, incorporated into the finite membrane element of the program PAM-LISA, Fig.6, replaces at each integration point of a finite element the warp and the weft threads by nonlinear engineering beam elements, following the initial ondulation of the warp and weft threads, Figs. 7,8,9. At the cross point of the threads a short cross beam element with its axis perpendicular to the midplane of the fabric maintains the distance between the model beams and assures the cinematic coupling between the two families of threads, Fig.10 (the in-plane shear resistance of a coated fabric is mainly due to the low shear resistance of the coating material and it is modelled independently by an added orthotropic plane stress shear-only material property).

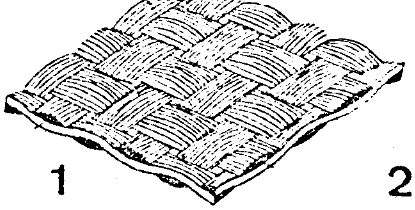
In the computer program the model simulates a membrane continuum by a substituting a small structure made of nonlinear beams, Fig.9, applied point by point throughout the continuum, and the response of a membrane element to e.g. imposed deformations will be obtained in a sequence of subiterations for equilibrium of this beam model at each point of interest.

The individual nonlinear beams of the model may have linear or nonlinear material properties. In the simplest case, the flexural rigidity is chosen linearly elastic as well as the axial extensibility. The model beams have also been provided with a nonlinear extensibility, characterized by a curved axial stress-strain diagram with possibly linear unloading, thus modelling, Fig.5, the nonlinear elastic or inelastic behaviour of the individual fibers of the tissue. Moreover, the cross beam element, keeping the distance between the warp and the weft beams, may be assigned an axial springiness to simulate the transverse elastic setting of the tissue threads, caused by the mutual compression of the threads due to the redirection of the tensile forces when the tissue is under biaxial loading. If given elasto-plastic properties, the cross-beam may partly account for the phenomenon of a permanent set encountered in most technical tissues, especially during the early cycles of loading history.

The model is believed to be able to carry further refinements, such as visco-elasticity or creep, etc.. and it has served as a valuable asset in practical studies of high demands.

Model Performances

Figs.11, 12, show the stress-strain curves obtained from technical tissues in the laboratory as compared to the stress-strain curves obtained by the proposed beam model indicating high accuracy of model description. The beam model parameters (geometry, axial and flexural stiffnesses) must be chosen judiciously in order to best fit the actual curves, a process which can be made to converge rapidly after a few tries. The beam model geometry is deduced directly from the weave's geometrical properties.



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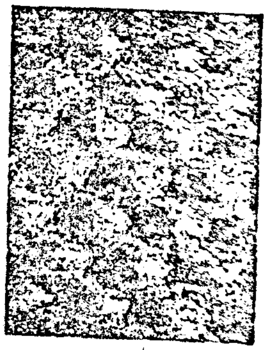

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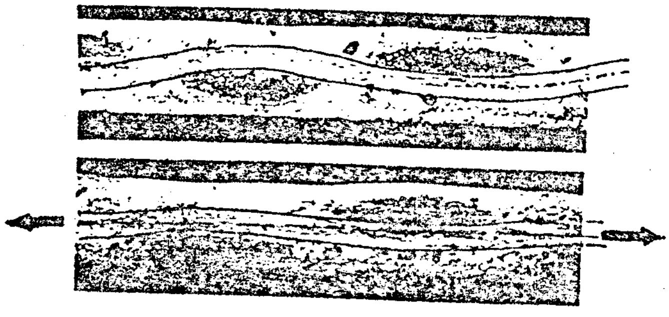

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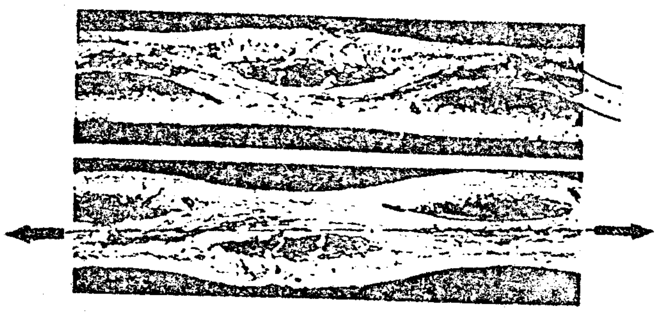

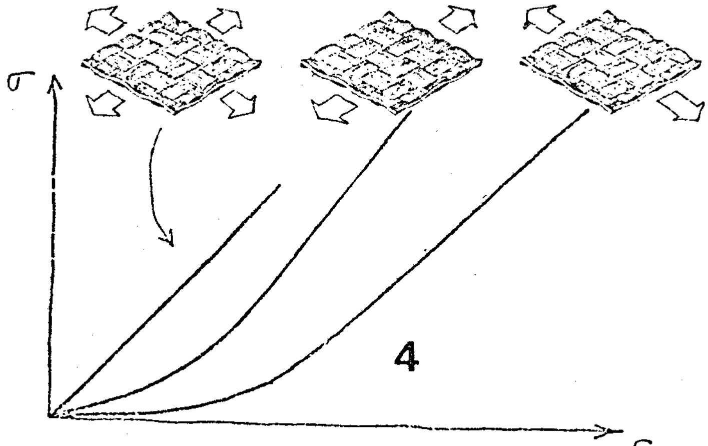

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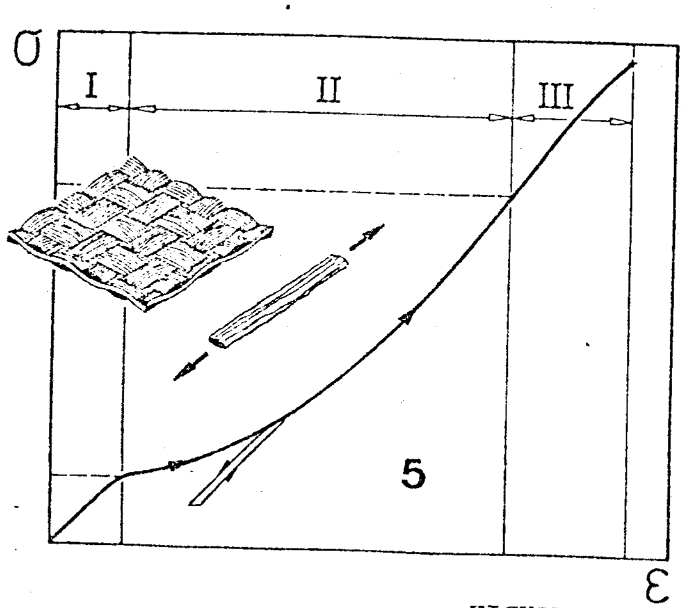

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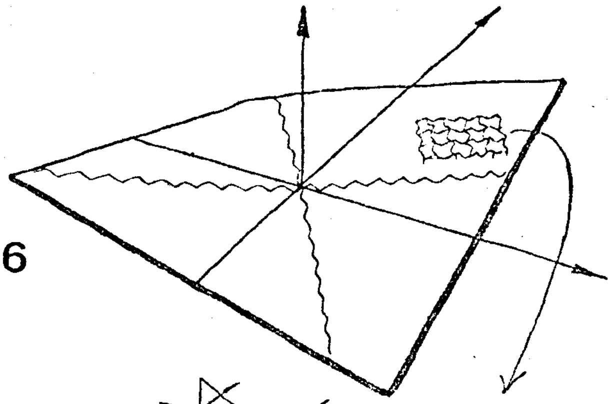

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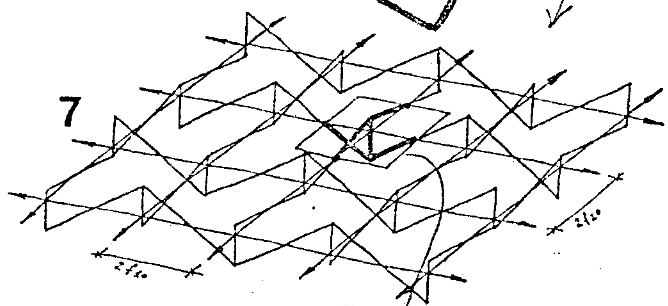

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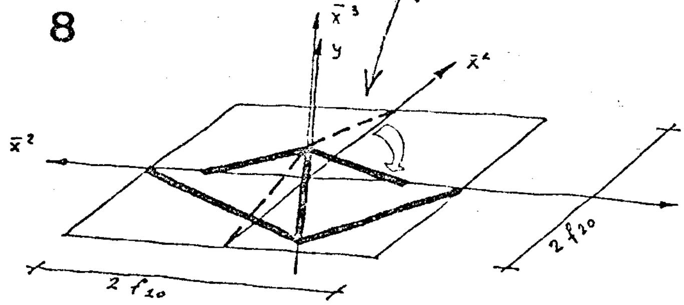

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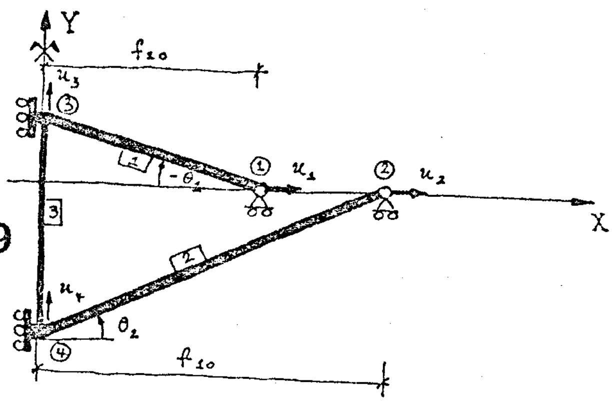

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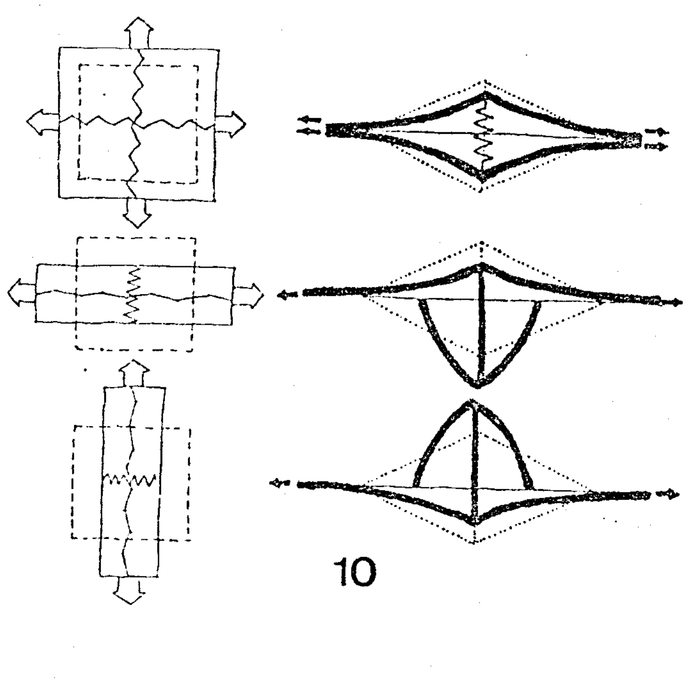

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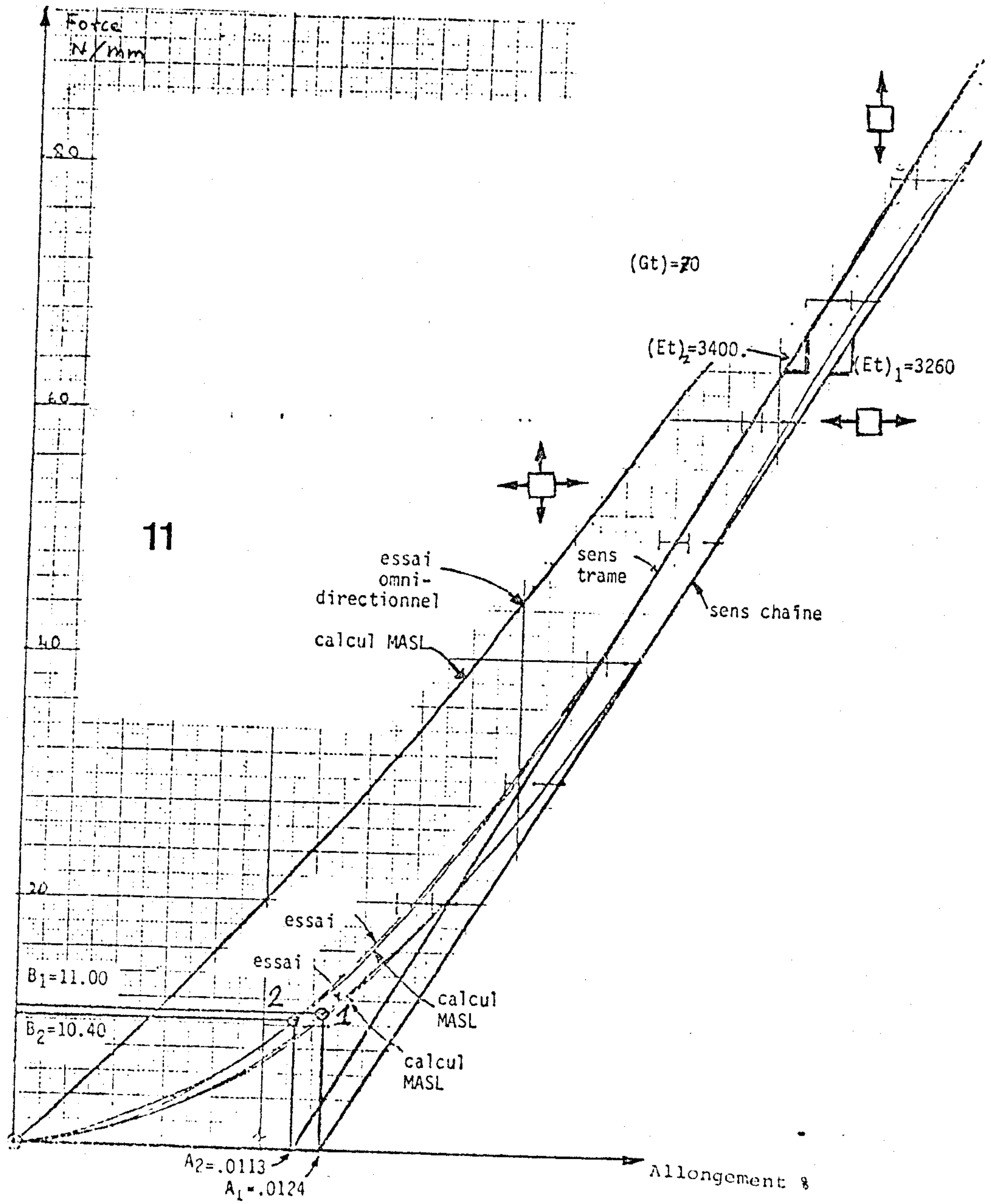
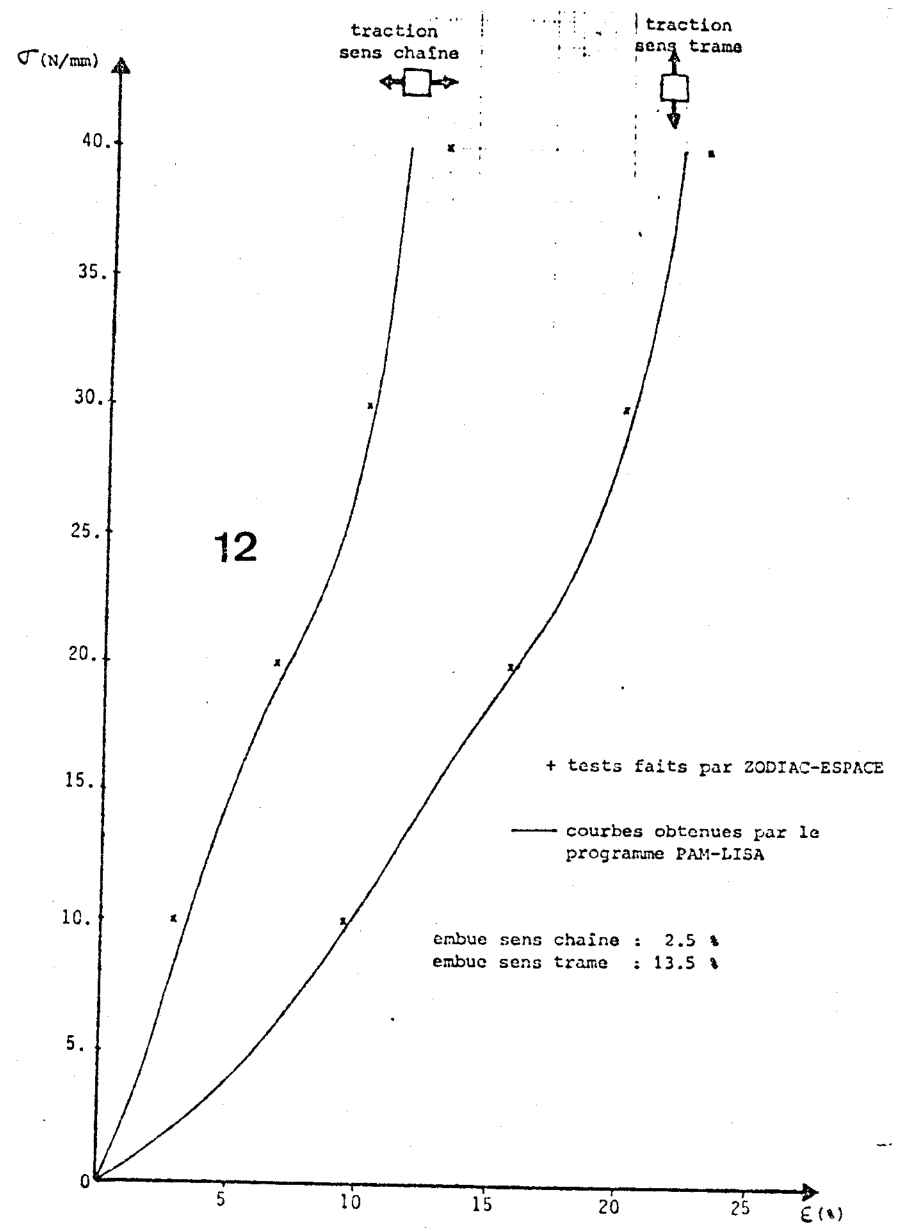




FIGURES D11 - D12

PART IV : TECHNICAL APPLICATIONS

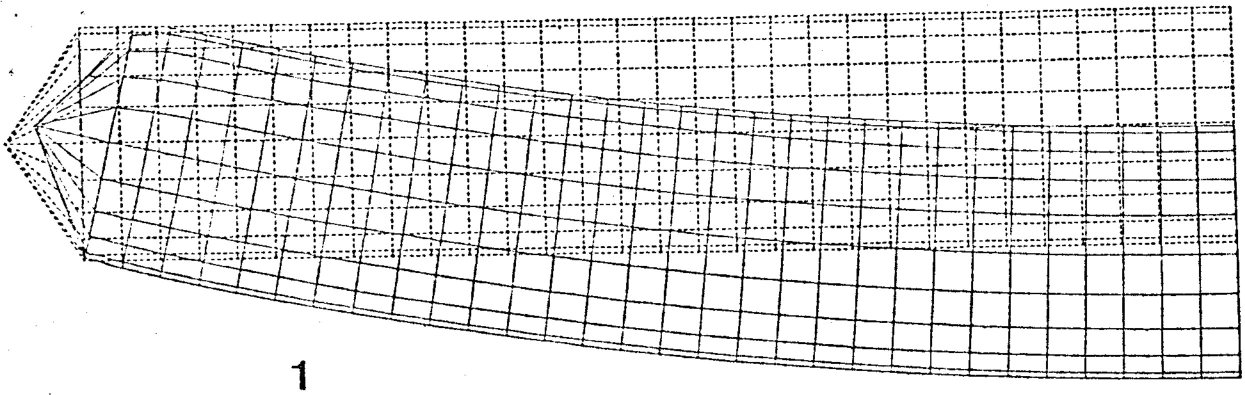
INFLATABLE BEAMS (Figs. E1-E4)
(Reference 28)

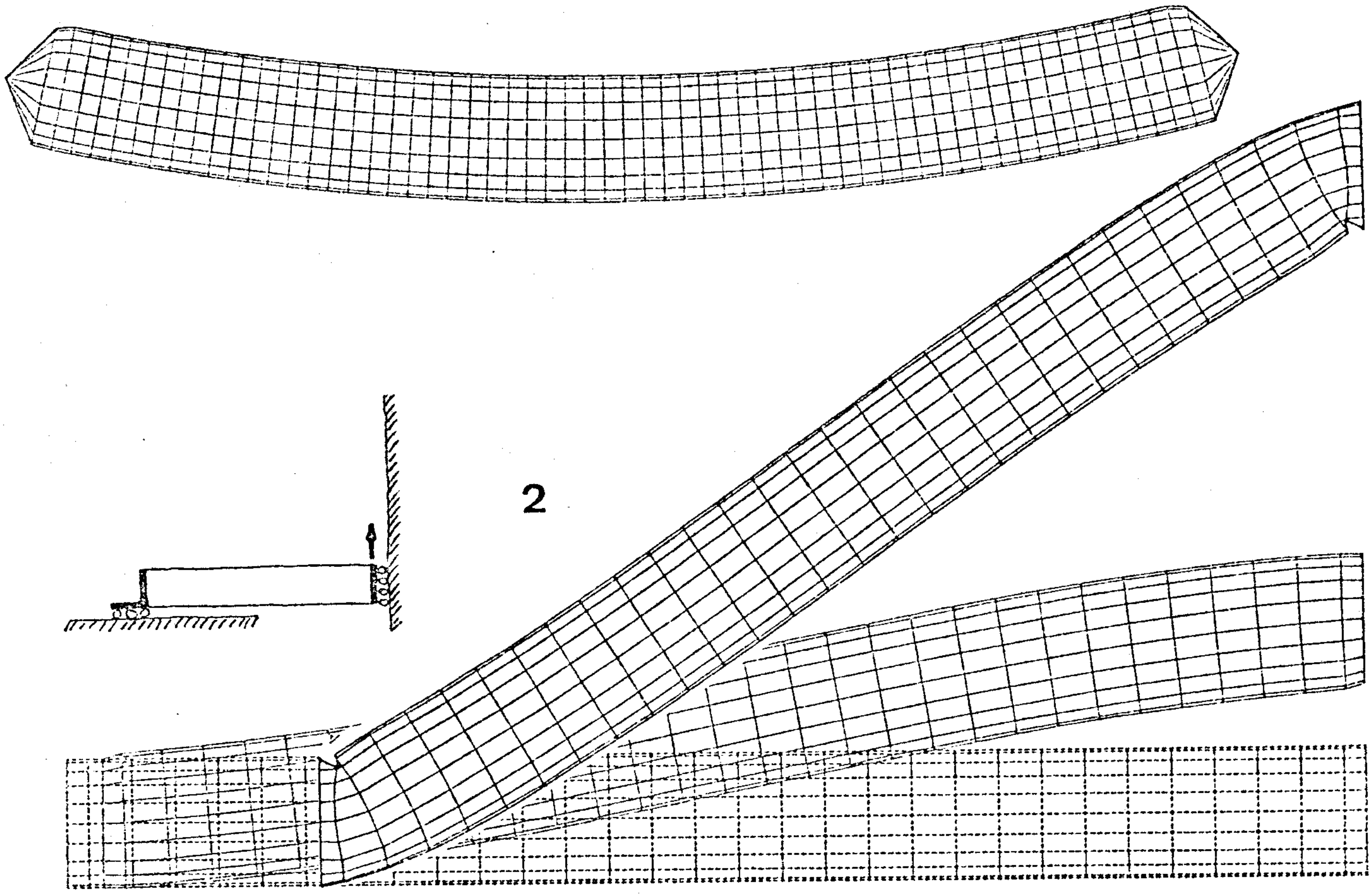
A simple pneumatic tube with a diameter to length ratio of 1 : 10 has been analyzed for simple load cases with PAM-LISA and it has been compared successfully to some tests carried out in the laboratory. The four basic load cases studied were an inflating pressure together with axial compression, flexure, shear and torsion. Due to the large displacements and deformations of the tube the results differed in the last three load cases when the axial deformation of the pneumatic tube is either prevented or permitted to take place.

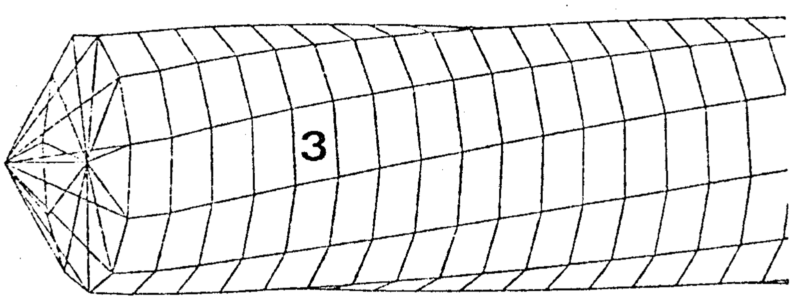
Figs. 1-3 show the resulting deformed finite element shapes due to simple bending, transverse shear and torsion, respectively, in true scale.

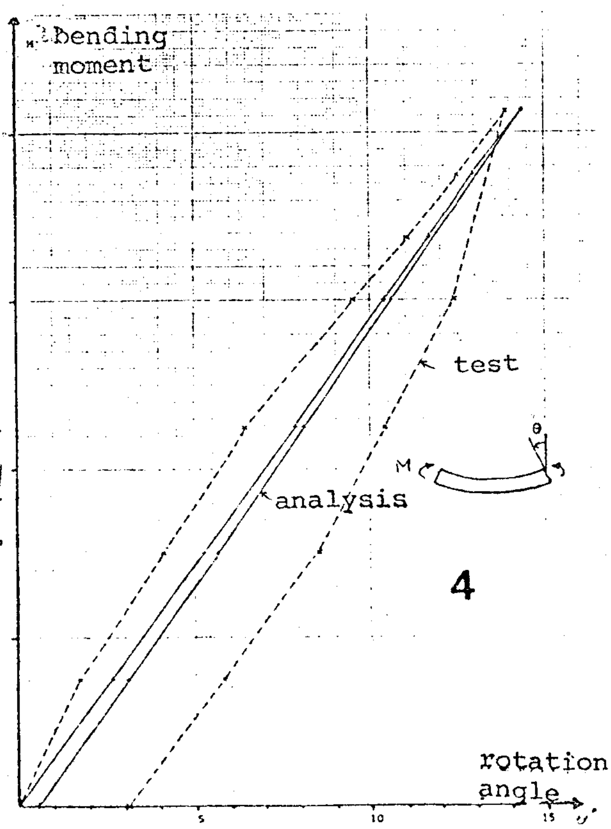
Fig. 4 shows the good agreement between analysis and experiment for example in the case of pure bending. The greater hysteresis of the lab tests is due to some friction in the mechanical joints, assumed perfectly frictionless in the analysis.

The computer models comprised about 300 membrane elements. The pneumatic tubes were made of a commercialized neoprene coated polyamid weave. The possibility of wrinkling of the skin material near the ends of the tubes is automatically accounted for in the analysis program, as seen in Fig. 2 , where the wrinkles become visible in the deformed finite element mesh. The geometry of wrinkles may remain invisible in mesh plots, because they may occur inside a finite element, being not permitted to transmit compression in any direction.









FIGURES E1 - E4

VENUS BALLOON (Figures F1-F10)
(Reference 22)

In a pilot study carried out for the French Space Agency, CNES, a balloon of about 9 m diameter having a volume of ca. 400 cubic meters, made of a very thin lightweight and highly complex composite skin consisting of a high strength weave, with several coatings, reflective and protective layers, intended to be launched into the atmosphere of the planet Venus, has been studied with the aid of the computer program PAM-LISA.

In this Russian-French joint project the balloon was to be built in France and it was to be transported by a Russian space vehicle into an orbit around Venus. The balloon was to be released from the transporting vehicle,surpressu-rized to about 50 millibar and the studied balloon was to carry an instrument mass of about 250 kg. The entire mass of the balloon + payload was roughly 370 kg, the mass of the membrane envelope about 75 kg. The relative atmospheric pressure gradient at the cruising level of the balloon within the Venus atmosphere was roughly 0.8×10^{-9} Newton/cubic millimeters, resulting in the buoyancy needed to balance the total weight inflicted on the mass of the balloon under the influence of Venus' field of gravity at cruising level.

The balloons membrane enveloppe, Fig. 1, was to be fabricated from 32 identical meridional sheets of material, glued side by side via 32 fabric ribbons, 5 centimeters wide, which are running from the north pole of the balloon to the south pole. The ribbons were made of the same basic skin material but in such a way, that the ribbon added virtually no strength in the meridional direction.

The high strength tissue of the composite skin (KEVLAR, MYLAR, ..) was woven such that the uniaxial tension test curves in the warp and weft directions, see Fig. D11, differed as little as possible, assuring almost equal stiffness and strength in both tissue directions (this is not true in many commercia-lized fabrics, exhibiting a greater stiffness in the warp direction whose threads are straighter initially than the threads in the weft direction, fig. D12).

At both poles of the balloon rigid metallic polar caps with diameters of about 0.7 and 1.0 meters served to capture the oncoming meridional membrane sheets.

The task was to find a shape of uniform stress, to replace the shape by a skin of given properties with the minimum possible deviations in shape and stress, and to study the obtained balloon for various load cases.

To this end the membrane design methodology, outlined previously, has been applied with the obvious omission of STEP 3 (Pattern Finding), since the meridional sheets of the balloons cutting pattern are geodesic strips.

Due to the symmetry conditions of each of the 32 repetitive sections, only one half of such a section was actually modelled. The finite element model of the studied half comprised a total of 732 membrane elements, namely 176 elements along a meridian and 4-5 elements across the studies half of the section, Fig.2. Near the polar caps of the balloon a few rigid elements have been added in order to simulate the metallic plates bordering the membrane of the balloon.

In STEP 1 of the applied design methodology (Shape Finding) the soap film shape of the balloon under the combined action of the internal inflation pressure, the linearly varying external atmospheric pressure, the suspended pay load, the dead loads at the poles and with a soap film stress, such that the final volume of the balloon corresponded precisely to the volume required for stationary floating at the projected cruising altitute, has been found, Figs. 3,4. The resulting uniform membrane skin tension was about 10.8 Newton/ millimeters.

The program then performed STEP 2 of the design methodology (Substitution under Stress) and it replaced automatically each of the 732 soap film elements by an element of the real, nonlinearly elastic, coated fabric material, such that each real fabric element had the precise uniform target elastic stress state of 10.8 Newton/millimeters while occupying the exact positions of the respective soap film elements.

The shape and stress state of this elastic substitute membrane under pressures and loads are identical to the shape and stress of the soap film membrane.

This is not true, in general, if STEPS 1 and 2 of the design methodology are not followed, as it is shown in Figs. 5,6, representing the cross section through a balloon fabricated from a cutting pattern simply designed after the geometry of a perfect sphere. The shape after inflation enlarges, and the suspended payload introduces stress perturbations, Fig. 9 .

In STEP 4 of the design methodology (Cut out Pattern) the elastic pattern skrinks by the elastic stretches and it becomes a totally stress-free piece of doubly curved surface of fabric material in space.

This surface of fabric skin is made flat in an extra computer run as described in STEP 5 of the design methodology (Flattening), hereby introducing inevitable but minimum parasitic internal stresses whose maxima remained below $\pm$ 30 % of the final stress state of roughly 10.8 Newton/millimeters. The highest parasitic stresses occur near the balloons equator in the meridional direction due to the elastic deformation of the doubly curved fabric surface into a flat piece of fabric. They are the minimum possible ones, because the flattened pattern is not supported laterally. Their magnitude is a function of the size of the pattern and of the stiffness of the fabric material.

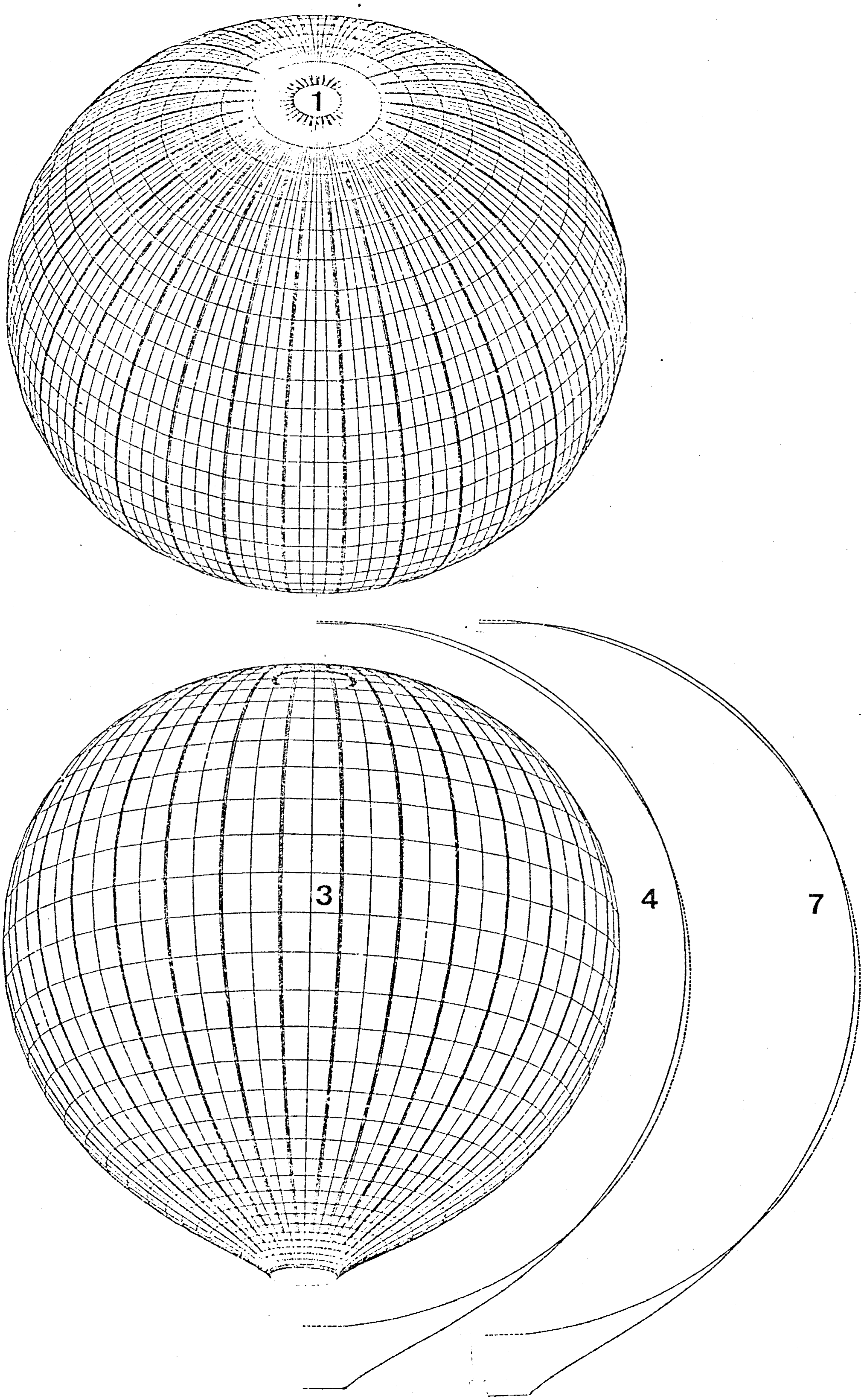
The form of the flat, plane sheet is now used as a cutting pattern in order to cut out an identical sheet from totally stress-free material according to STEP 6 of the design methodology (Cut out of Final Pattern).

According to STEP 7 of the design methodology (Erection), in a final computer run the final sheet is brought into its spatial position, and it is reloaded by the original internal pneumatic pressure plus the other loads responsible for the initial soap film shape. This step corresponds to the physical assembly of the final cutting pattern and the putting the balloon into service conditions.

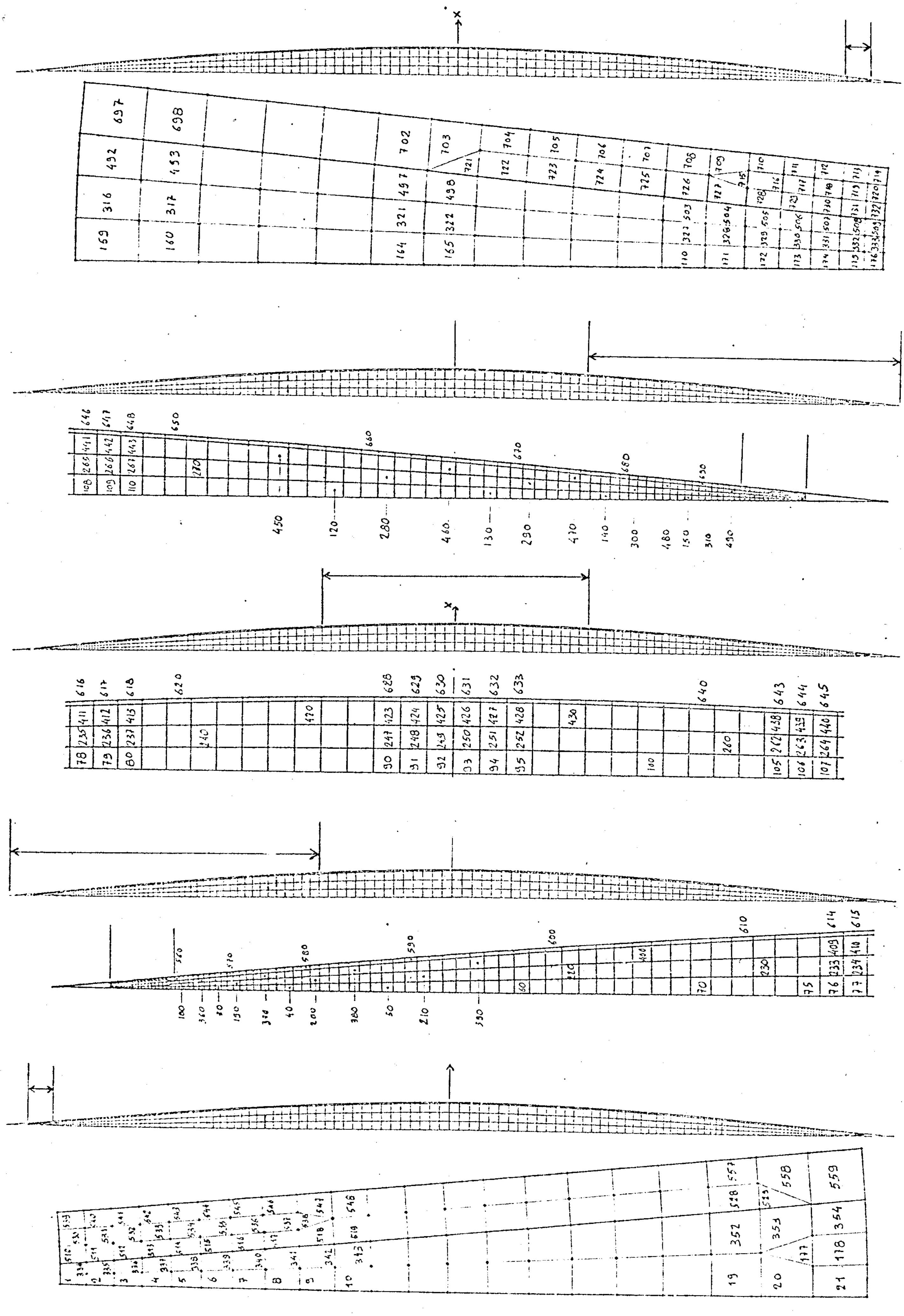
During the process of reloading, the flat final sheet is deformed elastically into a doubly curved three dimensional fabric surface. The corresponding elastic surface deformation will generate inevitable, but minimum, parasitic stresses of maximally $\mp$ 30 % of the average uniform target soap film stress state of about 10.8 Newton/Millimeters. The parasitic stresses of reversed sign are again maximum near the equator of the balloon. The final shape of balloon generated this way differs very little from the original soap film shape, as shown in the cross section through the final balloon, Fig. 7.

The quality that may be achieved through the use of the proposed design methodology is demonstrated by comparing the final stress states near the south poles of the balloon designed after the methodology, Fig. 8, and of a balloon made from sections cut out after the geometry of a perfect sphere, Fig. 9. The stress contour plots show meridional tensions of 21.5 to occur in the spherical balloon, while the stresses in the well designed balloon membrane remain very close to the target value of 10.8 Newton/millimeters.

Finally, the balloons stress state due to hypothetical repetitive inaccuracies in the width of the cutting pattern has been studied. To this end a sinusoidal gap of 0.3 millimeters in amplitude and about 200 millimeters long has been introduced at the least favorable position in the calculated cutting pattern near the north pole of the balloon. The resulting maximum elastic stresses of 27.0 Newton/millimeters in the circumferential direction, Fig. 10, exceed considerably the target stresses of 10.8 Newton/millimeters, indicating that a high precision in the evaluation and the fabrication of the cutting pattern is a prerequisite for the use of modern stiff, high-strength fabric material.



FIGURES F1, F3, F4, F7



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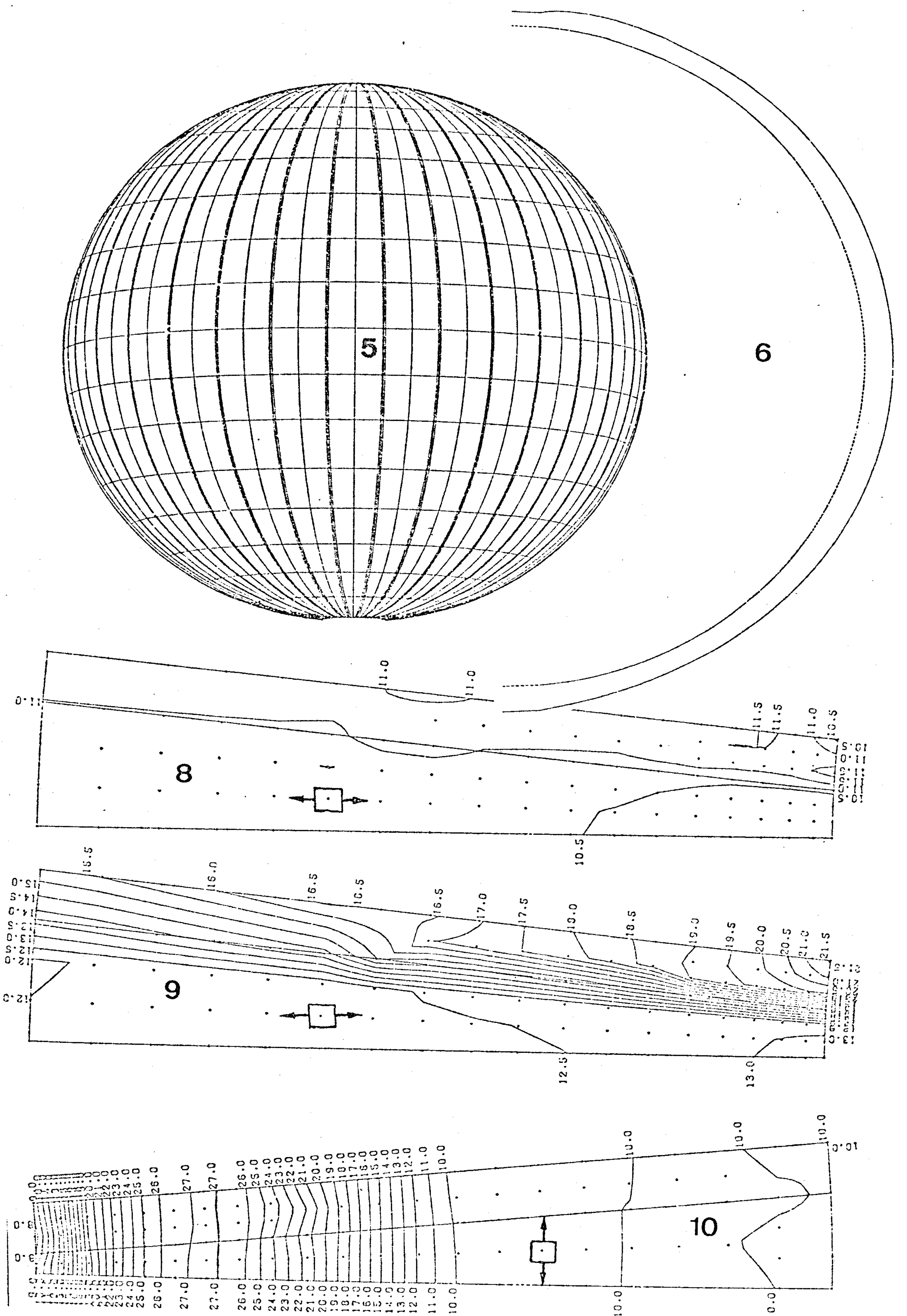
FIGURES F2



FIGURES F5, F6, F8 - F10

CONCLUSION

The paper tried to give an overview on the design and analysis of pneumatic structures using a modern numerical tool.

The program in question, PAM-LISA, permits the complete design of lightweight structures, ranging from simulated soap film forms over precise cutting patterns to the analysis of the resulting structure under loads.

Special emphasis has been given to a general design methodology of membrane structures, permitting the best possible design and introducing a universially applicable, rational, method for the tricky subject of cutting pattern evaluation.

The feasilibity and success of the tool and the methodology have been demonstrated in two demanding examples in industry and space projects.

The proposed tool and methodology are believed to be the missing link in the rational, efficient and widespread use of high technology materials in the engineering and architectural design of permanent pneumatic and tent structures.

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