Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht

Band: 14 (1992)

Artikel: Tension structures: a brief review

Autor: Happold, Ted / Liddell, Ian

DOI: https://doi.org/10.5169/seals-853149

Tension Structures — A Brief Review

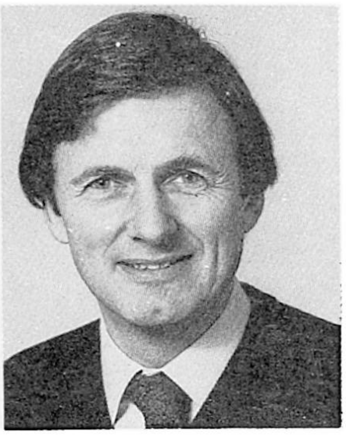
Structures en tension — brève revue

Zugtragwerke — eine Entwicklungsskizze

Ted Happold
Professor
Buro Happold
Bath, UK

Ted Happold is a Past President of the Institution of Structural Engineers, Senior Partner of Buro Happold, consulting engineers, and Professor of Building Engineering at the University of Bath.

Ian LIDDELL
Structural Engineer
Buro Happold
Bath, UK



Ian Liddell is the second partner of Buro Happold, consulting engineers. In the past fifteen years he has been responsible for a number of cable and fabric structures and other specialist engineering projects carried out by the office.

SUMMARY
This paper reviews design methods for surface stressed buildings and gives some design examples of the authors' current experience.

RÉSUMÉ
L'article passe en revue les méthodes de conception des bâtiments à couverture en tension et donne des exemples de conception tirés de projets actuels des auteurs.

ZUSAMMENFASSUNG
Dieser Beitrag untersucht Konstruktionsverfahren für oberflächenverspannte Gebäude und bietet einige Konstruktionsbeispiele aus den kürzlich gewonnenen Erfahrungen.

TENSION STRUCTURES - A BRIEF REVIEW

It is important to differentiate between the types of tension structures used in building. Bridge design has certainly influenced building. The concept of the suspension bridge is very old and building engineers such as Nervi, have employed the idea for a long time. Cable-stayed stiff roofs have been a substitution, with cables for the struts of propped cantilevers. The Forth bridge design of Fowler and Baker (Fig 1.1) expressed it clearly nearly one hundred years ago. Morandi copied it in prestressed concrete for his Maracaibo Bridge in 1957 and then developed the idea for his hangar roofs at Fiumicino airport in 1961. The stay cables support the beams along their length while uplift is counteracted by a combination of tie downs at the end, and the deadweight of the roof itself. A similar structural idea was used on the Sainsbury's store for Canterbury (Fig 1.2) in which we assisted Ernest Green and Partners. Indeed, we used a similar system for spanning the Tesco supermarket for Bristol (Fig 1.3).

As in bridge design, cables provide intermediate support to the roof beams along their length, and uplift from wind has to be counteracted either by tie downs at the end or by the deadweight of the roof. Although easy to analyse and with their structural behaviour easily understood visually, one has to pay extra for such masts and tie downs and, in the extreme, these masts have become cable-stayed flagpoles. Such a system is often not a structurally economic method of building, although can provide the basis for an effective and economic architecture.

It is the membrane action roofs, surface stressed structures, which have represented a new approach to design. The traditional approach in buildings has been to reduce deflections and deformations to preserve the integrity of the claddings and partitions, and so loadings have been resisted by increases in forces within the structure. Conversely, a surface stressed structure aims to achieve a minimum increase in force level, and thus a minimum need for expensive material, by distributing loading by an acceptable change of shape.

In surface stressed structures, the membrane is prestressed to form a load carrying system. This membrane can be either a coated woven fabric, a net of steel cables or an unreinforced structural foil. The prestress can be induced either by tensioning the surface via the boundary and supporting elements, or by pressure acting on one side; in which case it is a pneumatic structure. By using high strength materials in tension, surface stressed structures can provide a structurally efficient solution with a range of interesting architectural possibilities.

These structures are geometrically complex and have to be accurately prefabricated in their entirety (Fig 1.4). Consequently, the bulk of the work in the design office is spent on processing the geometry of all the components. Up until twenty years ago the only way to develop the geometry of a surface stressed structure was by physical modelling. However, to achieve sufficient accuracy this method took time and was expensive in terms of design resources. Improvements in the power of computers and developments in software have resulted in great advances in CAD systems for processing these structures rapidly and in a user friendly way (Fig 1.5).

However, it is still necessary to understand the physical principles governing behaviour of such structures and their materials in order to be able to utilise this software to advantage.

2 FORMFINDING

The process of formfinding is that by which the prestressed equilibrium form is developed. The objective is to create a model of the intended structure from which the geometry of the components can be found and in which the forces, stresses, volumes and environmental responses are known. As discussed

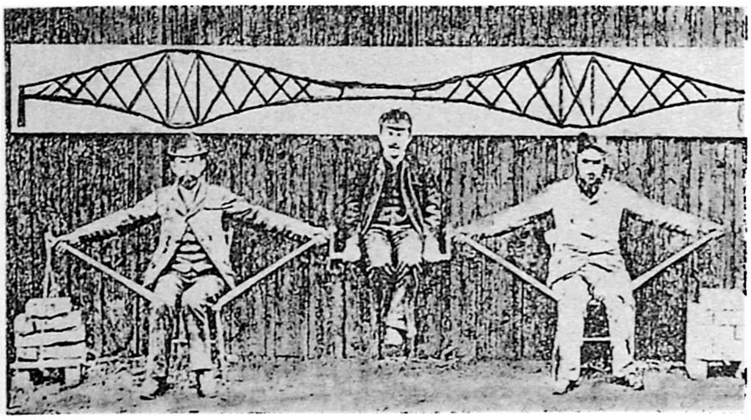


Fig 1.1 Fowler and Baker's Design for Forth Bridge

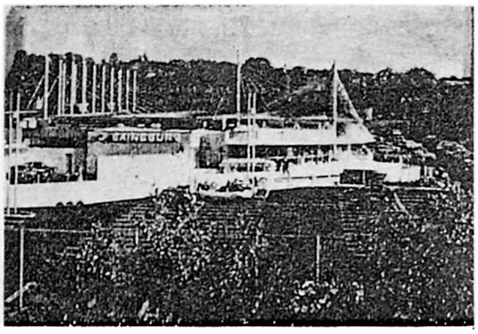


Fig 1.2 Roof at Sainsbury's Store, Canterbury

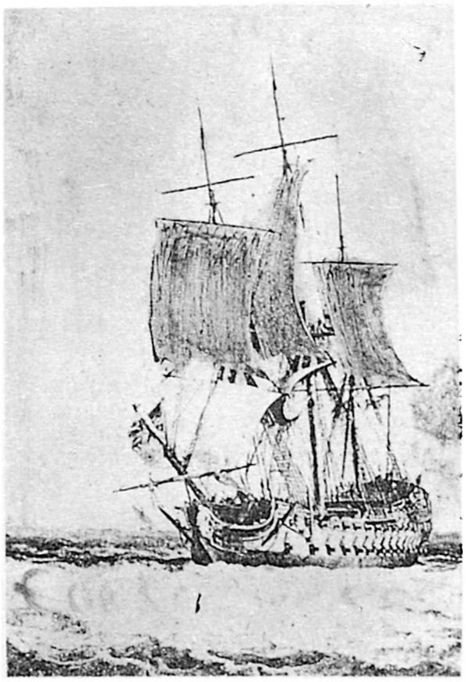


Fig 1.4 An early tension structure

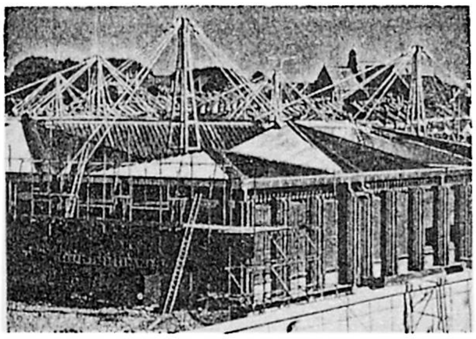


Fig 1.3 Tesco Supermarket Roof, Bristol

above, this can be done by physical modelling, geometrical calculations or by calculations involving static equilibrium of the computer.

Originally, accurate physical modelling for cable net structures was carried out using fine wire and small cable clamps. This method was used by Frei Otto for both the West German Pavilion at Montreal and for the swimming pool structure at the Munich Olympic Park [Ref 1]. All the component geometry was then measured from these models and the forces in the elements were all calculated by hand, generally using equation (b) of Fig 2.1. With experience and by choice of the appropriate formulae in Fig 2.1, one can make estimates of the forces in cables and fabrics supporting masts, and anchorages on the basis of the preferred form. In a real situation the stretch of the cables or fabric under externally applied loadings allowed the curvatures to change, usually reducing the forces caused by local 'high' load concentrations. Movement of the boundary cables caused by stretch in the anchorage system, or in an adjoining field has the same effect. Hence a full and accurate analysis can only be carried out using a non linear computer program which takes into account the displacements of the surface under loading and calculates the forces under the 'improved' geometry after deformation under load. Techniques used in our office are based on 'dynamic relaxation' the theoretical principles of which are given in Fig 2.2 [Ref 2].

2.1 Calculation of static equilibrium by computer

In this method the surface is modelled as a pattern of elements, usually triangles (or as bar elements in the case of cable nets). In the form finding mode, the membrane elements are set to have a constant predetermined stress no matter how much they change their size. Boundary cables can be modelled as elastic cables with a given length, or can be assigned specified tensions. Masts, tie backs, edge beams and arches can also be included in the model. The same model can be used for load analysis and for establishing the cutting patterns and cable lengths. The TENSYL suite is our office program and it is constantly being improved and updated [Refs 3, 4 and 5].

In TENSYL the shape is controlled by specific warp and weft stresses in the various areas of fabric, thus necessitating a trial and error procedure to get the required form. However, with the increasing capacity and speed of computers and the development of user friendly programs, the trial runs take less time, and data can be carried quickly so that the required form can be readily developed. The operator must nevertheless understand the physical principles involved.

These programs can also provide accurate analysis of the structure under loading. For this, the specified stress triangular elements of the formfinding are replaced by elastic elements with specified load extension behaviour appropriate to that selected for construction. These are then loaded with gravity or pressure loads, either singly or in varying combinations. User friendly graphics enable rapid evaluation of these results by both colour coded stress ranges and stress vector printout. Such computer aids make adjustment and improvement of the structure form easy and commercially possible without a severe setback to the design process, thereby enabling convergence on into the detail design of the components.

3 STRUCTURAL PERFORMANCE AS A FUNCTION OF FORM

A highly stressed membrane must be supported all round by a boundary which makes a closed, but not necessarily circular, ring. A uniform stress surface within a boundary is known as a minimum surface (Fig 2.3) - the minimal surface bounded by four cables with two masts.

A minimal surface, within a given defined boundary, has the least possible surface area and the minimum strain energy; hence it can be said to have maximum structural efficiency. It is possible to modify the surface by changing the ratio of stresses in the prestressed condition. From the point of view of overall design requirements, it may be desirable to do this to improve the headroom in the building,

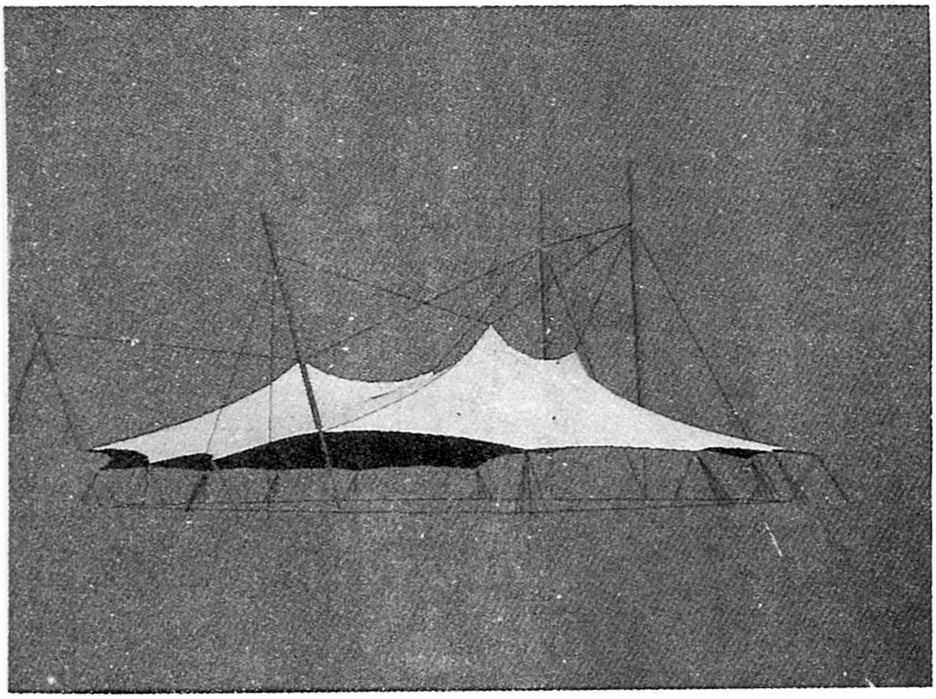
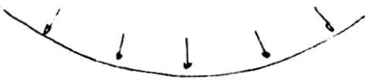


Fig 1.5 CAD Representation of a Surface Stressed Structure

Approximate Methods of Calculation

Cylindrical membrane strip of unit width under pressure loading



w = Load / unit length
R = Radius of arc
T = Tension

$T = w \times R$ --- ①

2. Forces in hanging cable under uniform vertical load

s = SPAN
d = Central dip
ℓ = length of cable

Cable hangs in a parabola such that

$$y = \frac{4d}{s^2}(sx - x^2)$$

Horizontal force $H = \frac{ws^2}{8d}$
Vertical force $V = \frac{w\ell}{2}$
$T = \sqrt{H^2+V^2}$ --- ②

Fig 2.1 Basic Geometry of Surfaces

Approximate Methods of Calculation

Cylindrical membrane strip of unit width under pressure loading

w = Load / unit length
R = Radius of arc.
T = Tension.

$T = w \times R$. — ①

2. Forces in hanging cable under uniform vertical load.

s = SPAN
d = Central dip
ℓ = length of cable.

Cable hangs in a parabola such that

$$y = \frac{4d}{s^2}(sx - x^2)$$

Horizontal force $H = \frac{ws^2}{8d}$
Vertical force $V = \frac{w\ell}{2}$
$T = \sqrt{H^2+V^2}$ — ②

Fig 2.2 Equations of Equilibrium

to modify the visual appearance of the surface, or to improve the performance of the particular structure to the range of loadings it must resist.

If this surface is made from woven fabric or an orthogonal cable net, there are two sets of tendons at right angles to each other which ideally would follow the lines of principal curvature so that they then have opposing curvature. Prestress is required to stiffen the surface against deflection. If the surface is flat, then prestress provides the only resistance to deflation. If it is well curved, then the elastic properties of the membrane provide the resistance to deflection regardless of the level of prestress, up to the point where yarns go slack in one direction, or where under a local load the curvature becomes synclastic. This effect becomes very important under snow loading.

3.1 Behaviour under load

Wind loading on such a surface consists of a random and varying set of surface pressures in which uplift generally dominates. The downward pressures are taken by the sagging set of tendons and the uplift pressures by the hogging tendons. The tension along any particular tendon remains sensibly constant so local high pressures are taken by the surface deflecting. The radii of curvature consequently change and the equations of equilibrium are satisfied. This means that a stressed surface is a load averaging system - the maximum tension in a particular hogging tendon is caused by the maximum average uplift pressure in the area of the tendon.

The same principle applies for down loads. Snow loading tends to slide down the steep slopes and remain on the flatter slopes. This results in high local patch loading on the horizontal areas, with high local load producing large local deflections. As discussed above, the local tensions are not particularly high. The increase in tension is spread over a large area of the structure with a corresponding strain in the fibres. This results in a large increase in strain energy in the structure which must be balanced by the decrease in potential energy, such as the local load times its deflection.

Within the limits tolerated by the chosen cladding system, deflections of large magnitude are not themselves a problem provided they are not accompanied by severe local changes in shape or excessive in-plane shear distortions. However, a large deflection can cause problems with ponding if it is such that there is no longer any drainage away from the deflected pocket. Once this occurs, any additional rain or melt water will run into the pocket which will become larger and larger until the fabric tears or the supporting structure collapses. On a tensioned fabric structure, the problem of ponding can be avoided by ensuring that there are no flat horizontal areas. On canopy structures which are used primarily in the summer, it is a sensible precaution to install drainage grommets in areas where ponding can occur.

Air supported structures also suffer from ponding if the local snow load exceeds the inflation pressure. Stadium structures with a primary net of cables are particularly sensitive to ponding since the snow tends to drift into the cable valleys. A means of preventing ponding therefore needs to be considered in the design stage.

3.2 Dynamic behaviour

Surface stressed structures tend to have large deflections compared with bending stiff structures. They also have natural frequencies of oscillation which could theoretically respond to wind flow or turbulence to produce dangerous freed oscillation. This behaviour has been studied extensively by Davenport and others [Ref 6] but in practice coherent wind induced oscillations have not been observed in properly tensioned prestressed membrane structures.

The same is not true of air supported structures. In this case it is the mass of enclosed air which controls the oscillation of the roof. If the shape of the roof is such that the roof is locally deflected inwards, this can activate oscillations of the internal air which can become resonant. For large and important

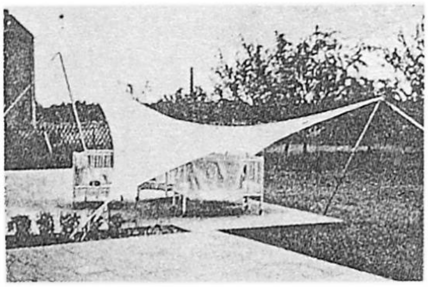
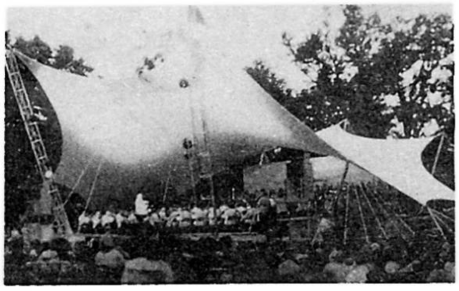


Fig 2.3 Minimum Surface Bounded by 4 Cables and 2 Masts

g 4.1 Eye Loops, Boundary or Ridge Cables on Masts



g 4.2 The Washington Symphony Orchestra Tent

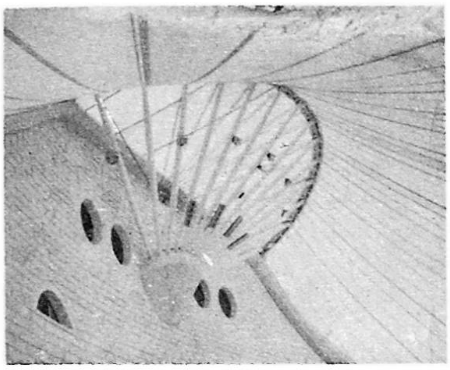


Fig 4.3 Conical or Pseudo Sphere Form

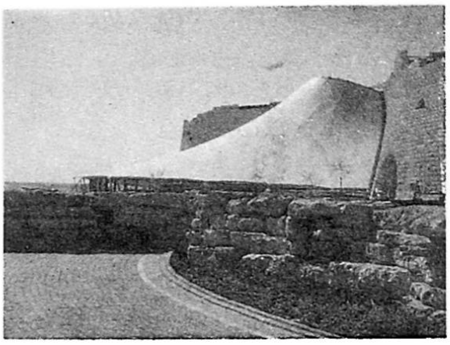


Fig 4.4 Diplomatic Club, Riyadh

Fig 4.5 The Heart Tent, Diplomatic Club, Riyadh

structures this effect should be studied in a wind tunnel during the design stage.

4 EXAMPLES OF FORM

Each field of fabric within a whole structure which may be composed of a number of such fields must be bounded and determined by the type of supporting elements at its structural boundary. These can be rigid elements such as beams, walls, arches or flexible cable elements such as eye loops, boundary or ridge cables on masts (Fig 4.1). As it is difficult to form a useful space with a single 'saddle' surface, a building will usually consist of a number of fields arranged together and anchored to a range of boundaries. The correct determination of the boundaries from the range outlined below is probably more significant to the overall success of the design than choice of the surface itself.

4.1 Masts and ridges

A membrane cannot be supported by a point. Generally at a mast point there will be two ridge cables, sometimes three or four, which transfer the uniform stress in the fields to the concentrated load at the mast. A recent example of a tent with such masts and ridges which has been developed by the Practice is the Washington Symphony Orchestra Tent (Fig 4.2).

4.2 Conical forms

With conical or pseudo sphere forms, there are often a large number of radial cables coming together at the mast (Fig 4.3). These usually lay freely under the fabrics, the tension is constant and the fabric can slip over the cables. Typical examples of these forms from the Practice are found in the Diplomatic Club, Riyadh (Fig 4.4), with its Heart Tent (Fig 4.5) and the Munich Aviary (Fig 4.6).

4.3 Ring supports

A single membrane can be supported by a large ring. Again, soap film modelling demonstrates the problem. If a film is created between an inner and an outer ring, the inner ring can be lifted to form a doubly curved surface. If the rings are moved further apart, it will be found that at a certain point the film will always burst. This happens because the meridional radius of curvature becomes greater than the circumferential radius. At this point the conditions of equilibrium cannot be met so the film bursts. With a real fabric, the meridional tension can be greater than the circumferential tension, and reinforcement can be added by doubling the cloth or by broadseaming so that the ring can be smaller than that which the soap film theory predicts. Even so, a relatively large ring is still required. An example of this technique can be seen in the permanent structure for the new Mount Stand at Lords (Architects: MHP/Engineers: OAP).

4.4 Humped tents

Originally this system, which does not use cutting patterns, was devised by Frei Otto. The woven fabric is made up flat and without shaping along the seams. During erection the fabric is supported on domed supports so that the angle between the directions of weave are changed, so allowing it to distort into a doubly-curved surface over the support. The Staffordshire House atrium roof (Figs 4.7 and 4.8) is a humped tent with a fully patterned membrane.

4.5 Funicular arch support systems

It is possible to support a membrane by an arch which has no bending and is itself stabilised by the membrane. This form finding process can only be carried out using an equilibrium computer process. The arch is only moment-free under ideal prestress conditions. Under imposed loads, moments are generated and there are stability problems requiring the addition of bending stiffness. Recently engineers

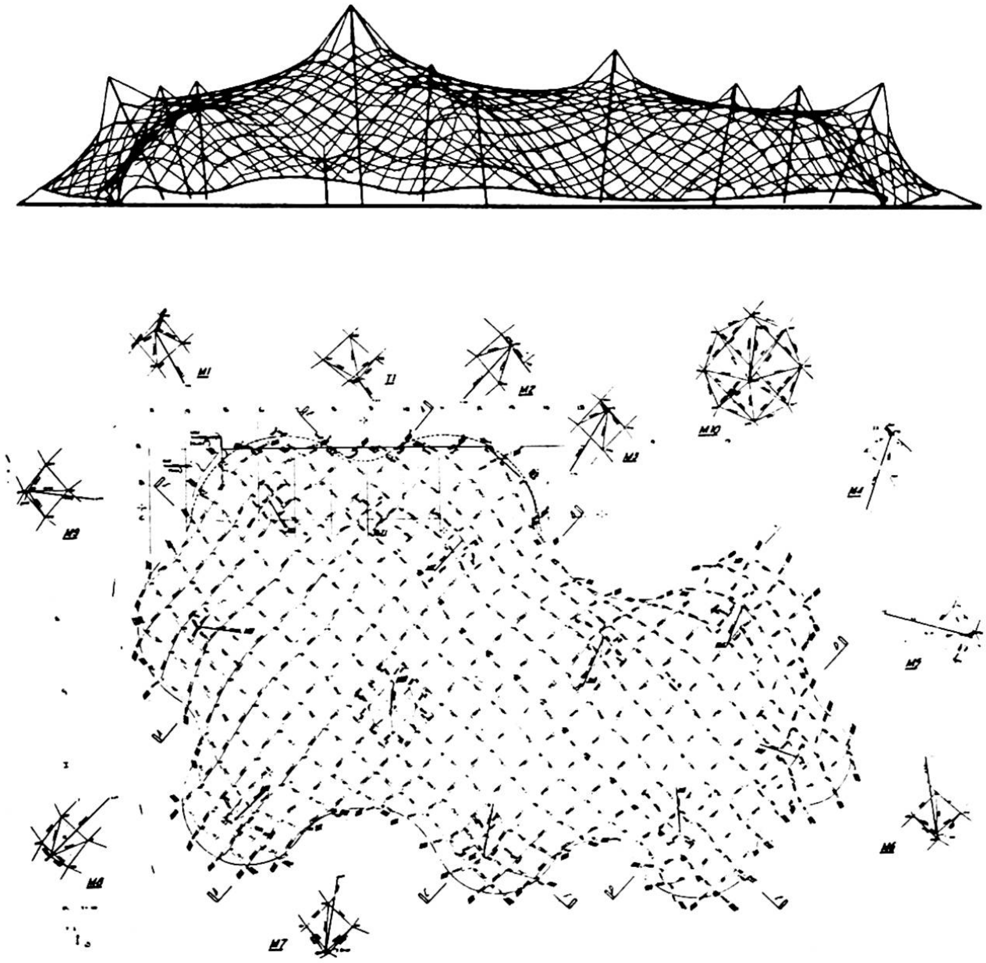


Fig 4.6 Munich Aviary

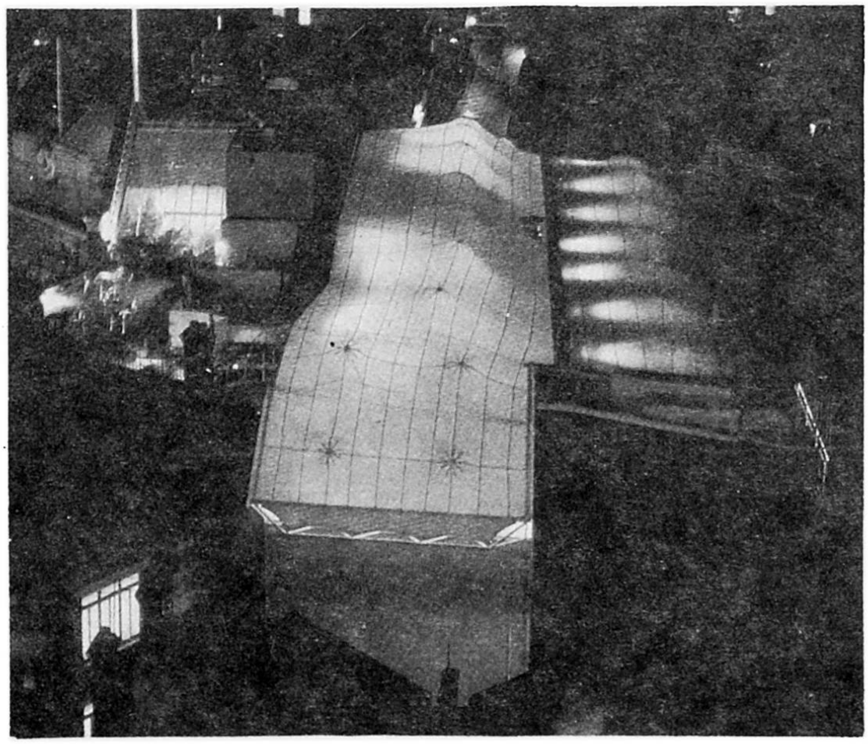


Fig 4.8 Staffordshire House Atrium Roof

Schlaich and Partners at Munich Skating Arena, and we ourselves at Stoke Garden Festival (Fig 4.9) have preferred the self-stabilised trussed arch form.

4.6 Surfaces supported by compression ring beams

A system of boundary arches to the net has been used for a roof at the Calgary Olympic Saddle Dome (Fig 4.10) engineered by Jan Bobrowski and Partners, for which Buro Happold were the proof engineers. In these examples the cladding is of reinforced concrete plates and the finished structure becomes a concrete shell. The Tsim Sha Tsui Cultural Centre Roof in Hong Kong is of this type.

4.7 Air supported cable restrained roofs supported on a ring beam

For the US Pavilion at Expo '67 at Osaka, Davis and Brody, the architects, as a cost saving exercise, adopted a low profile cable restrained air supported roof enclosed by an earth berm - an idea which had been promoted by the father of air supported structures, Wally Bird. To solve the problem of anchorage, the engineer David Geiger proposed to use a moment free compression ring. With the diagonal cable arrangement this ring became elliptical in form. The roof material was, in this case, PVC coated glass fibre cloth laced to the cable net.

Bird and Geiger realised that this form of construction could be used for covering stadia. The development of teflon coated glass fibre cloth which met the US fire requirements allowed the design of these structures to proceed. The first developed was the Unidome, followed by the Silver Dome at Pontiac where the air supported roof was adopted after construction of the stadium had commenced. A similar development was anticipated by our own project at 58°North (Fig 4.11).

Subsequent developments in the USA have been aimed at minimising first costs by using larger panels of cloth, with performance in service however, being neglected. Some of these stadia in the northern half of America have experienced problems with snow drifting in the valleys causing local inversions which can lead on to damage and total deflation of the roof. The failure of one at Minneapolis will be discussed at the Conference.

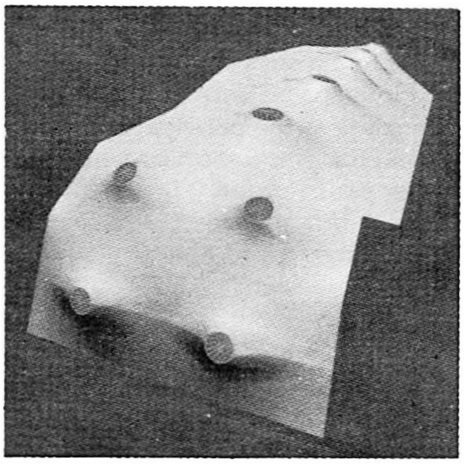
The cure lies in the use of smaller panels, a higher inflation pressure and greater snow melt capacity, together with better form determination and patterning - all of which increases the initial cost. Air supported structures however, remain the most economic structural type of enclosure of large spans but they require to be properly detailed and managed.

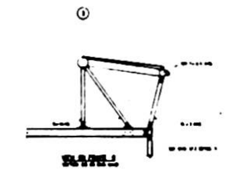
5 ONGOING DEVELOPMENT

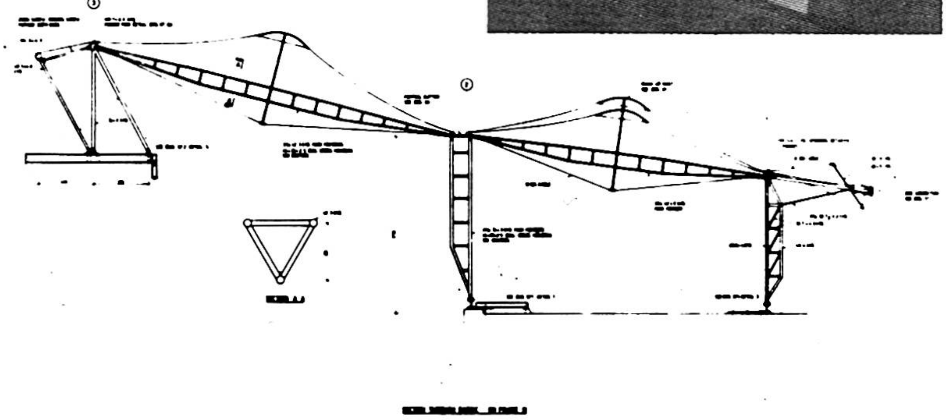
The currently used textiles for architectural purposes are PVC-coated polyester fabric and PTFE-coated glassfibre. New fluoropolymer coating materials offering improved performance are being developed all the time and we are currently working with pure woven PTFE fabric for flexible membranes for folding structures. We are also developing ways of supporting glass on cable nets and new ways of generating nets so that the meshes are flat without twist.

As a development from 58°North foils and films of polymer without a structural fabric are of growing interest to us. The ETFE and FEP foils available have completely different mechanical properties from fabric supported membranes, being isotropic, and of low stiffness, yet having a fair resistance to tear propagation. To date, such foils have been used to admit a high measure of vector modelled light for leisure activities, swimming pools and horticultural uses by way of individual inflated cushions up to 5.0m or so in size, restrained by small stainless steel wires and held within an overall structural grid. They are highly translucent and very inert.

Fig 4.9 Staffordshire House Atrium







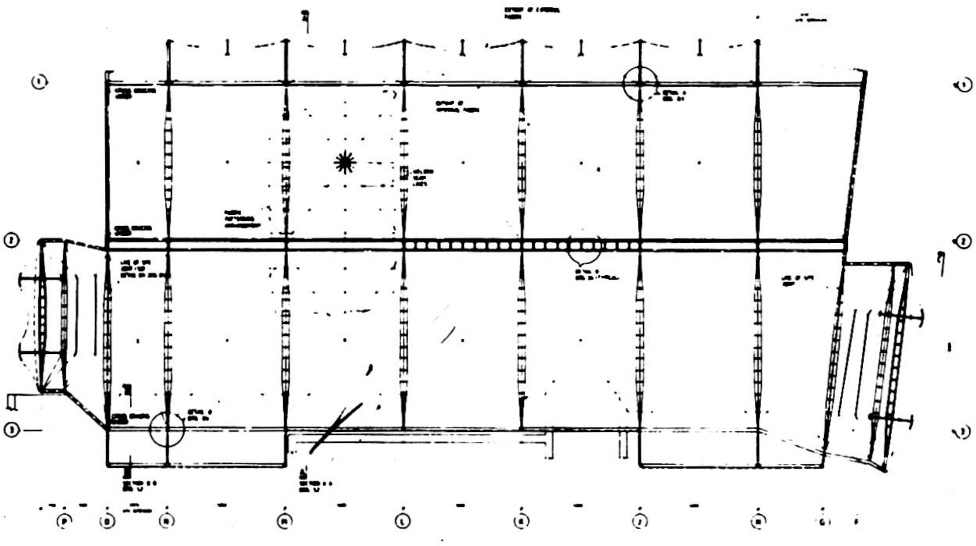


Fig 4.7 Staffordshire House Atrium Roof

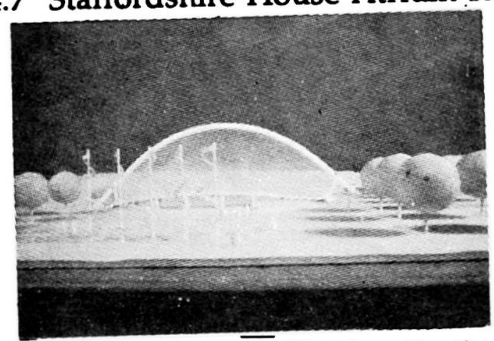


Fig 4.9 Stoke-on-Trent Garden Festival

Although clearly not as versatile as more conventional fabric based materials, they are highly appropriate where a support matrix can be provided. Indeed because these cushions also provide a thermal performance rather better than double glazing for approximately a quarter of the weight, we proposed their use as the principal covering element to the 58°North project. As a development of this earlier proposal the Practice is now working on a design for an atrium for a new hospital in London with architects Sheppard Robson (Fig 4.12). This will use 4.0m^2 inflated cushions of a clear foil material, ethylene tetra fluoro ethylene (ETFE), supported within a grid shell of GRP ribs. This will ensure a light transmission equal to that of glass, yet will require a far less heavy support system across the atrium.

And finally an airship (Fig 4.13).

ACKNOWLEDGEMENTS:

The considerable advance in the base technology of this whole field has been made through the interaction of designers of practical problems within our firm, and from outside in practices with the thoughts and efforts of researchers both in Stuttgart, at the Sonderforschungs Bereich SFB 64 Weitgespannte Flachentragwerke (Long Span Structures Group), and closer to home with the Wolfson Flexible Structures Group at the University of Bath and at City University, London .

REFERENCES:

(1) OTTO F, HAPPOLD E, RICE P et al 'Frei Otto at Work' Architectural Design March 1971

(2) BARNES M R 'Applications of dynamic relaxation to the design and analysis of cable, membrane and pneumatic structures' Second International Conference on Space Structures Guildford 1975

(3) 'Air Supported Structures - The State of the Art' Conference Institution of Structural Engineers June 1980

(4) 'The Design of Air Supported Structures' Conference Institution of Structural Engineers July 1984

(5) AFSF Proceedings of a Conference on Architectural Fabric Structures Orlando 1984

(6) DAVENPORT A G 'The response of tension structures to turbulent wind - the role of aerodynamic damping' First Oleg Kerensky Memorial Conference Institution of Structural Engineers June 1988

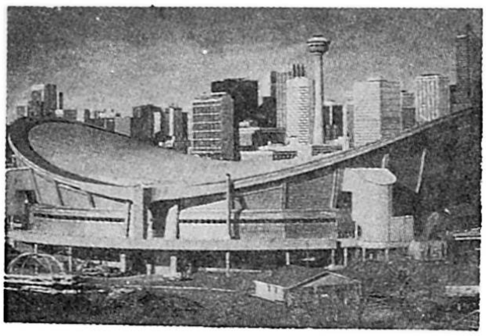


Fig 4.10 Calgary Olympic Saddle Dome

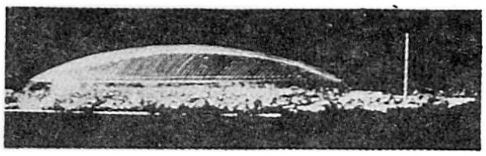


Fig 4.11 58°North

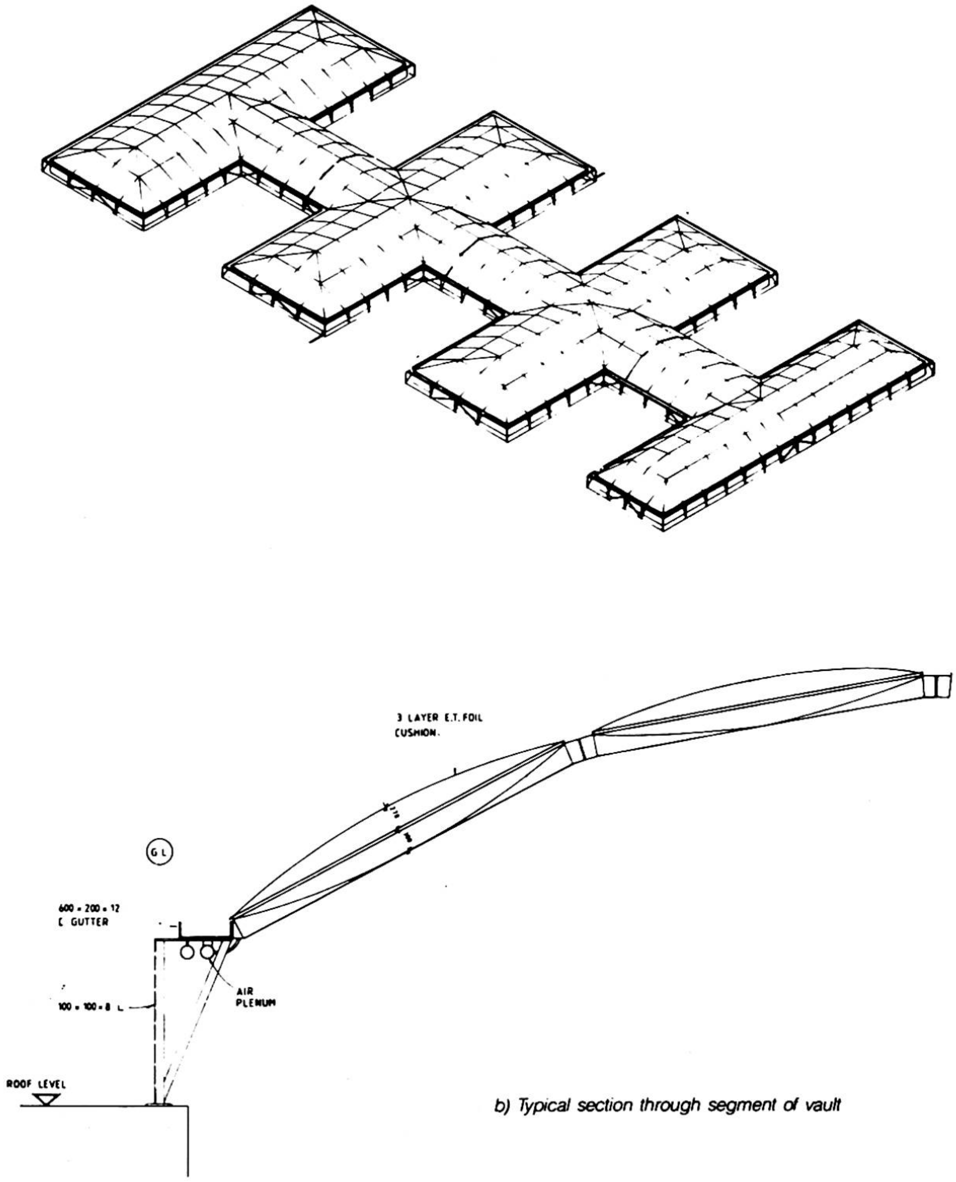
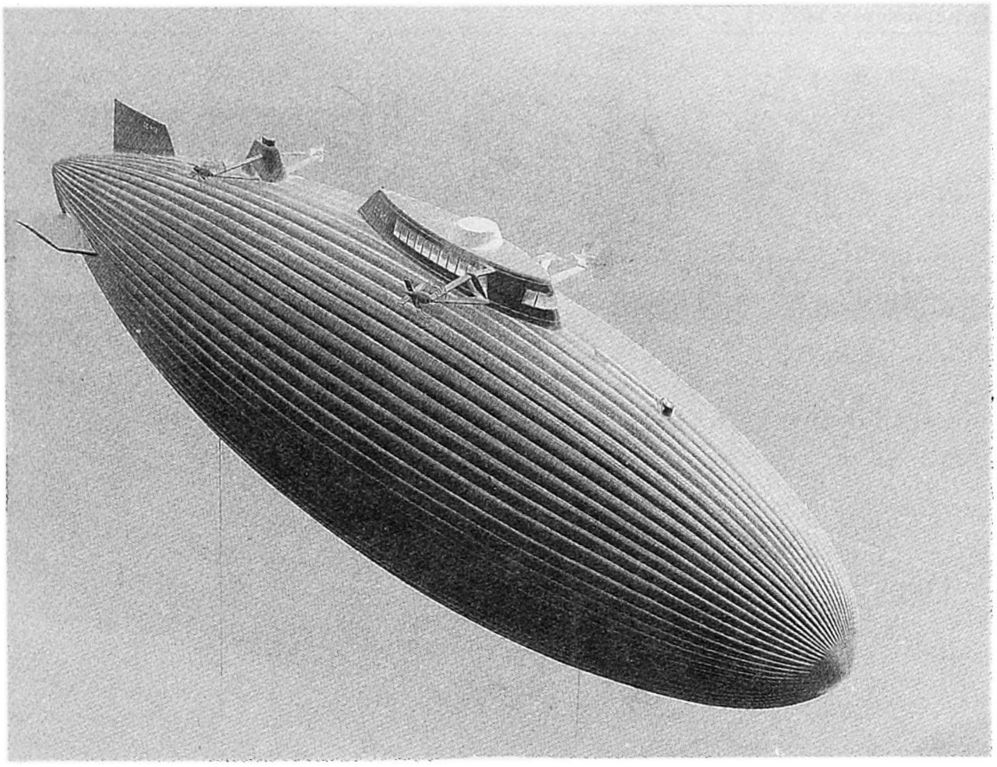


Fig 4.12 Westminster & Chelsea Hospital Atrium Roof



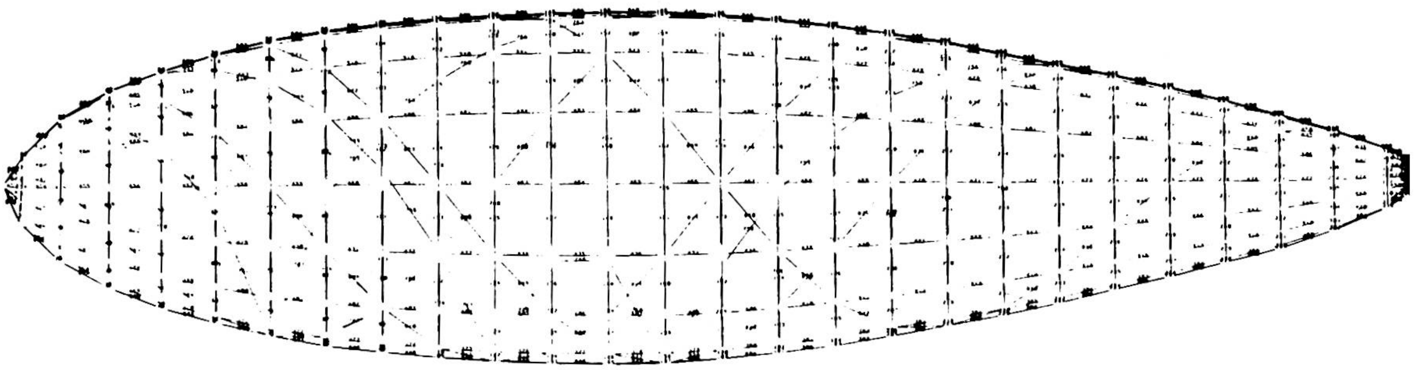


Fig 4.13 Airship