# THE ARUP JOURNAL

OCTOBER 1980

# THE ARUP JOURNAL

Vol. 15 No. 3 October 1980
Published by
Ove Arup Partnership
13 Fitzroy Street, London, W1P 6BQ

Editor: Peter Hoggett
Art Editor: Desmond Wyeth FSIAD
Assistant Editor: David Brown

**Contents**

Front cover: Photo reproduced by courtesy of Heather Angel MSc FRPS
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# Lightweight structures: Introduction

## Peter Rice

Lightweight structures is a broad, if rather inappropriate, name for a group of surface structures made from fabrics or tension or compression nets. The structures are lightweight because the nets or fabric are the lightest available materials with adequate structural properties to span in two directions. Tents and nets have, of course, been in existence for a long time. Recently, however, stimulated by the early work of Frei Otto and others, a new understanding and vocabulary of possible shapes has emerged. Originally the research attempted to define the factors which made for efficient structural forms. In doing so it examined structures in nature, to see how they solved the relationship between form and efficiency. The most interesting and important work stemmed from a study of soap film surfaces, forms which are generated by the characteristics of the soap film itself, a uniform surface tension. Modelling techniques to generate soap film surfaces were developed. Model work led to an appreciation of the transient nature of the soap film surface; the surface form is dependent upon the load conditions acting upon it. It also led to the realization that modelling techniques generally were the best way to study and understand the relationship between geometry and equilibrium for these surfaces. The modelling techniques brought with them too an indication of the way in which real structures could be created. It is an essential part of the study of lightweight structures that the forms, the initial load conditions and the method of manufacture are wholly inter-related.

For engineers the philosophical base which underpins this study of lightweight structures has been a barrier to developing a mathematical understanding of their behaviour.

At the time these structures were being developed, computer techniques were emerging based upon the finite element and stiffness method of analysis. This is a static system of analysis which assumes that deflections are small and can be ignored when calculating structural equilibrium. One of the principal characteristics of lightweight structures is that this premise is not true. Indeed they change their geometry in response to each new load application. Consequently many devices were developed to mimic this characteristic and they were grafted onto the standard stiffness analysis programs. Recently, as Alistair Day explains in another paper, direct dynamic techniques have been developed which model accurately the way these structures respond to load in nature.

The development of lightweight structures has now reached the stage where the limits of what can be designed and built are the limitations of materials, the limitations of the designer's inventiveness, and not, as has been hitherto the case, the limitation of analysis and specification methods. When we talk of these structures we are talking of free forms, which must be in equilibrium with themselves and with a set of applied forces. Usually they are very light so that, in the initial condition, gravity loads are not very important. However, to counteract non-uniform applied loads, either snow or wind-induced, they are almost always prestressed, either by air pressure or directly through tensioning of the net and fabric elements. To understand the physical characteristics of any particular lightweight form it is still important to work with models. One has to learn through experience the vital relationship between stiffness, geometry or curvature and the stability of the surface under changing loads. One other important characteristic is that the surface is free of bending stiffness. For a fabric or tension net this is self-evident, but the consequence of this obvious characteristic is that the surface stiffness depends upon the prestress and the two-way curvature at any point. The modelling is used to help generate surfaces which have a balanced relationship between curvature in one direction and curvature in the other and between curvature at different parts of the surface. The prestress compensates for the lack of bending stiffness and helps eliminate flutter.

In order to be more precise in the discussions on lightweight structures, the structural forms are classified into five main types:

Tents, prestressed tents and prestressed cable networks

Air-supported structures

Pneumatic structures

Grid shells

Heavyweight cable roofs.

Prestressed tents and cable networks are doubly-curved saddle surfaces and are often developed from soap bubble models. The soap bubble, which is a uniform surface tension membrane, helps to ensure that surface curvature is adequate everywhere in the surface. Prestressing is achieved by stressing one set of cables or membrane fibres against another. The more curved the surface, the more effective the prestress as a means of providing surface stiffness. It follows, therefore, that large differences in curvature across the surface can lead to substantially different properties, e.g. a soft area or a stiff area, in different parts of the surface. It is also necessary to generate surfaces which can be prestressed. This is particularly important when dealing with stiff

**Fig. 1**
Soap bubble (Zambian settling tents)
(Photo : Ove Arup & Partners)

**Fig. 2**
Grid shell model
(Photo : Courtesy of Frei Otto)

**Fig. 3**
Aeroelastic model for Berlin roof project, a heavyweight cable roof
(Photo : Courtesy of Frei Otto)

**Fig. 4**
Cable net at Munich
(Photo : Joachim Schock)

materials such as *Teflon* fibreglass because they do not allow the fabric to redistribute the stress if locally overstressed areas occur. Surfaces which are easy to prestress are also surfaces which have a relatively uniform curvature throughout. The characteristic of low shear modulus which has been already mentioned is very important in detailing prestress nets and fabric tents. Shear distortion can lead to large displacements across the diagonal of the net members and can only be controlled by curvature and prestress. This shear distortion is one reason why cable networks are not more popular than they are. The category of prestress networks also includes radial cable trusses and prestress ring structures. Where they have shear or diagonal cable elements, as in the Jaworth system, they may be treated as normal structures when prestressed. This means that the prestress level should be sufficient to counteract normal working loads. Where shear diagonals do not occur, the behaviour is similar in character to normal cable networks. The geometry at any time is dependent on the loading as well as the member lengths. Various studies have been carried out on their behaviour[1] and the definition of the cable truss is done by models or by computer techniques as with cable nets.

One of the features to be noted with tensioned roofs is their response to dynamic oscillation, either earthquakes or wind buffeting. Usually their low mass and their high frequency puts them outside the range of most natural phenomena, and they do not present problems[2].

Air-supported structures are convex or cylindrical membranes which are prestressed through an internal air pressure. In this situation the crucial supporting element is the internal air itself, and the distortion of the air mass and structure under application of loads is clearly large and dependent upon the exact load distribution. A detailed treatment of air structures has been carried out elsewhere. It can be noted, however, that the dynamic modelling and analysis techniques developed for the prestressed tents are appropriate in air structures as well. The form of air structures is not as restricted as one might think from looking at those normally available. Modelling techniques show that by introduction of stiffer elements in the surface, free and unusual forms can be achieved. The stress levels in air-supported structures are generally substantially lower than the stress levels in prestressed nets and fabric tents. This means that they are not as sensitive to fabrication error or material quality and consequently the largest structures tend to be air-supported. Also because their geometry is a simple rounded pure form, they have a better controlled air flow over them and consequently can be influenced by their design and where they are situated in the landscape. They are, however, susceptible to wind buffeting. The natural frequency often falls within the dangerous range. One method of avoiding trouble which is adopted in practice is to change the internal air pressure if movement of the surface starts, thus changing the natural frequency and hence the response to buffeting.

The other three structure types are considerably less important than tents or air-supported structures.

Pneumatic structures are pressurized tubes where the air prestresses the fabric, usually a stiff rubber fabric, in the same way as in a standard dinghy. Until the level of prestress in the fabric has been overcome, the tubes act as a rigid element. Generally the structures are designed so that for all normal working load conditions prestress is high enough to ensure no wrinkling[3] and others have suggested that the ultimate strength of a prestressed fabric rib is twice that at the onset of first wrinkling. Obviously this has got to be verified in particular cases as it depends upon the form of the structure. Structural forms are achieved in the same way as with other fabric structures. Because the air volume inside a fabric rib is relatively small and the pressure high, the system is much more sensitive to air leakage, as only a small amount of air loss is needed to effectively destress the surface. It is for that reason that special care has to be taken with the surface covering and, to date, the only membranes which have proved satisfactory for pneumatic structures are rubber-based membranes.

Grid shells are doubly-curved, convex surfaces which are generated by freely hanging chain networks. The system was first proposed by Frei Otto and was used by him to generate the Mannheim Multihalle. The funicular network is created under gravity loads and inverted and a bending stiff element is restrained to follow the geometry achieved. The critical problem with grid shells[4] is resistance to buckling under asymmetric load. For this a bending stiffness is necessary but in many cases this will not be sufficient and must be supplemented by an induced shear stiffness. In Mannheim this was achieved by laying cables over the surface and stressing them. It is also important to limit the shear distortion, otherwise cladding of grid shells can become very difficult and expensive. The concept that a funicular shape can be of importance in a compression structure which is deliberately kept light to reduce the weight is a controversial one. However, the mathematical modelling techniques now available enable one to choose a funicular shape which is best adjusted for wind and other applied loads as well as the self-weight, and this technique was adopted in the three Kocommas domes which we have recently designed.

The final structure type which is usually linked with lightweight structures is called paradoxically a heavyweight cable roof. The roof has hanging cables with straight bending stiff elements spanning between them, thus giving a surface which is flexible in one direction but stiff in the other. These structures have been included in the vocabulary of lightweight structures because the properties of the cables in the non-stiff direction are the same as the general properties of lightweight structures. The self-weight prestressing of these cables by a heavy load is usually designed to counteract uplift as well as reduce oscillation and movement caused by wind buffeting. The evidence to date suggests that they work very well although they should not be used in situations where wind pressure could build up underneath them. The general problems of form definition and specification for manufacture exist with heavyweight cable roofs as with other lightweight structures, although it is often possible to achieve a satisfactory result directly by drawing and computer modelling, without the use of physical modelling techniques. This is because the structures are singly curved and can be understood through plans and sections.

### Design and manufacture

When considering the design and manufacture of lightweight surfaces, one must return to an understanding of their physical properties as generated by the modelling techniques. Soap bubbles have a uniform surface tension which implies a uniform strength in each direction in the final structure. This is approximately true for most structural fabrics. The warp and weft strength of a structural fabric may not, of course, be the same, as is emphasized by Tony Read in a following paper. It is also true of an equally spaced cable network. To achieve this uniform property ,Otto originally proposed a prefabricated cable net with a 0.5m × 0.5m cable spacing and then distorted to form the surface. Because the net is shear-free it will distort into any curved form required, and the definition of the surface is created by its support points and its boundary cutting pattern.

With fabric and cable structures the essence of a good solution lies in the detailing. The problem of the detailing arises at the interface between the fabric/net and the boundary system, which is usually much stronger and stiffer than the surface elements. Strain compatibility problems arise and it is important to permit the boundary element to move independently of the surface or to arrange the strains in the boundary area so that they are compatible with the natural surface movements. In a fabric surface restrained at its edges by stiff elements, e.g. cables or rigid structures, it is important to minimize wrinkling of the surface. Wrinkling in the surface can lead to long-term deterioration in the fabric, particularly glass reinforced fabrics. One of the critical areas in all fabric and net structures is when two boundary systems intersect, e.g. at a support point where two boundary cables intersect. This can lead to critical cross stresses in the fabric in a zone where natural relaxation of stress is impossible because of the short straining distances involved. Clearly there are

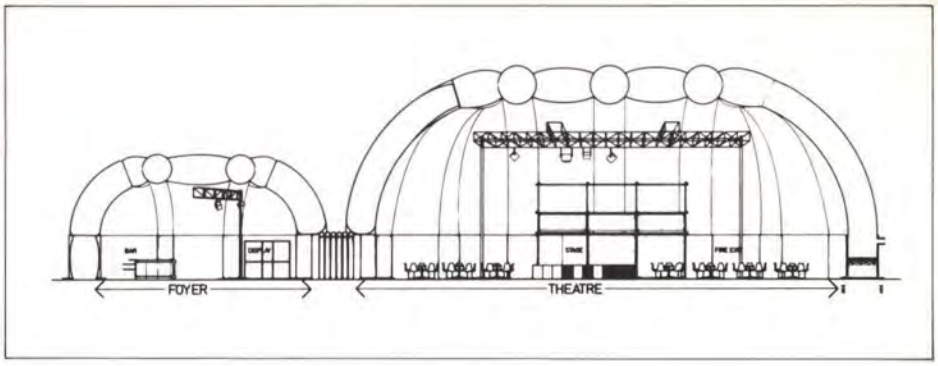

**Fig. 5**
Project for the Bubble Theatre in London

**Fig. 6**
Timber grid shell at Mannheim
(Photo : Ove Arup & Partners)

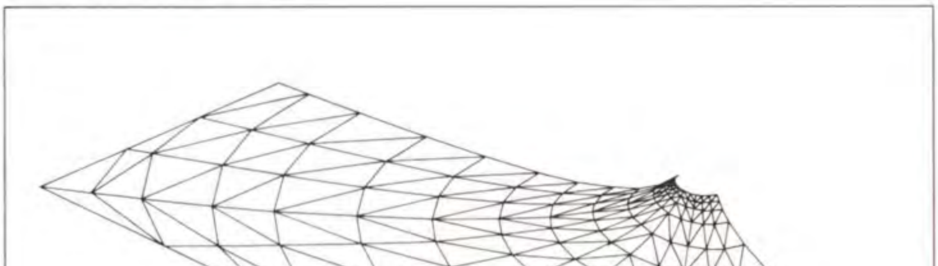

**Fig. 7**
Computer pattern generation for the Papal Canopy, Phoenix Park, Dublin

many detailed problems that have to be considered when talking of the detailing of fabric and tension net structures. However a substantial experience has been built up within the Lightweight Structures Group and by selected manufacturers.

As has been stated elsewhere in the paper, the surfaces or nets are achieved by making patterns as in dressmaking which, when joined together, give the doubly curved surface. Traditionally this has been done by making accurate models of the surface, laying elements on this model and expanding the resultant patterns by a scale factor. The initial models may have been generated by soap bubbles which are accurately photographed to define their geometry and then subsequently re-made either as plaster models for fabric structures or as nets for cable structures. The process is complex and subject to error as each scale factor is increased. Modern techniques involve the use of computer pattern finding which eliminates the more laborious modelling systems but which can act as a screen between the designer and the final output, often inhibiting a true understanding of the surface characteristics. A mixture of modelling techniques is now recommended to aid in understanding the surface properties and computer analysis and definition for the final pattern shapes. Many considerations have, of course, to be taken into account at this stage, as the final surface must be taut in the prestressed condition. This involves allowing for the prestress strain in the surface, non-uniform and non-linear fabric characteristics in the case of fabric structures, and a clear understanding of the method of application of any prestress forces. The importance of these secondary factors increases as the scale of the structure increases and for large structures it is essential that a thorough understanding of the surface and fabric characteristics is included in any final shape.

To conclude this brief introduction to the essential features of the manufacture of lightweight structures, each of the five characteristic types is discussed in turn.

### Prestressed tents and cable nets

As already stated, a suitable geometry is doubly curved and anticlastic. The best geometries have the rate of curvature in either direction the same throughout the surface. For a typical surface the modelling starts with a soap bubble mode, in which the surface tension creates uniform tension in each direction. Using this as a basis, the model is photographed and reproduced with a fabric model or in wire and this is then carefully measured to get accurate cutting patterns.

This phase of the test procedure is very important. The most interesting feature is the accuracy with which these models can be made. They are often made in plaster as well when the surface has been defined and understood and the cutting patterns laid out on the surface. Model accuracy is adequate when working in flexible materials, cottons, pvc polyesters, etc., but not adequate when working with the glass reinforced *Teflon*, in which case computer modelling has to be used. The modelling phase has also been used to carry out structural testing. This is no longer necessary as computer programs are now well able to handle this part of the work.

For those not familiar with the soap bubble techniques, trial and error fabric models (using stocking net) can be made, where great attention is paid to achieving the curvature requirements. This will often suffice for a sketch scheme stage. When using simple fabric models the criteria of an adequate surface must be observed with care. It is extremely easy with fabric models to have large parts of the surface without adequate curvature as the stress levels in the fabric are not sufficient to create the curvature automatically. A special point by point assessment of the doubly curved nature of the surface has got to be checked at each development stage. For this reason fabric models, although extremely important and useful as an aid to the understanding of the nature and form of a surface, can only be used in broad structural terms and not directly as a means of fabric patterning.

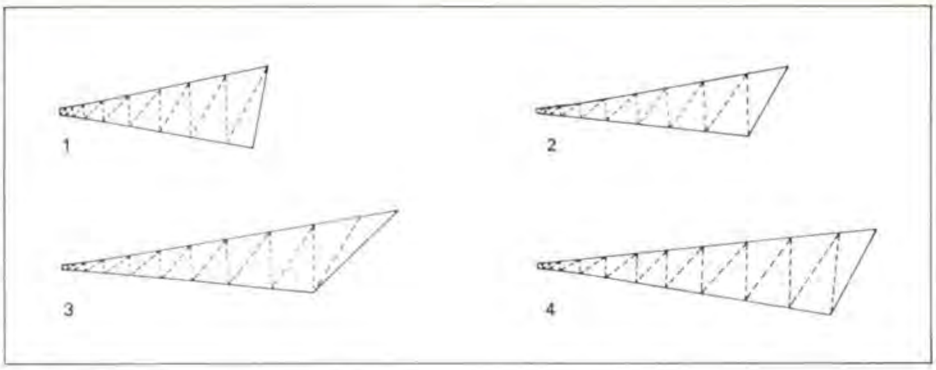

**Fig. 8**
Cutting patterns for the Papal Canopy

### Air-supported structures

Air-supported structures are doubly curved or cylindrical surfaces which are easy to understand in most normal conditions. They are surfaces which are in equilibrium with an internal air pressure and as such can be modelled in a number of ways. Although the ideal surface is spherical in shape, considerable variation from the sphere can be tolerated as the stress levels are normally not high. The critical factor in the decisions on the shape is to avoid instability under unsymmetrical applied load such as snow or dynamic instability under wind buffeting. The surfaces can be generated by soap bubble or rubber models which are translated into a plaster equivalent or modelled directly by the computer. Cutting patterns have the same constraints as with tension nets, though as the stress levels are considerably less, the effects of elasticity and fabric movement are reduced.

### Pneumatic structures

These are much more like rigid structures in their basic properties, because the level of prestress is high and the materials used must be strong and hence are very stiff. They only become significantly non-linear when the prestress load has been exceeded. The form-finding of the basic shapes is that of the definition of an essentially rigid structure. Once a structure in equilibrium has been defined then the form can be defined physically. It is usually not necessary to allow for strain effects in the surface as these are low.

### Grid shells

These are generated by hanging chain models. This ensures that the surface form is funicular under dead load. Although this can have a considerable benefit where the self-weight is large when compared with live loads, it may not be too important in real structures which are usually made with a lightweight cladding. This leads to a clear separation between the problem of surface definition and the subsequent structural analysis.

Surface definition is carried out by the funicular model. Usually the chain net has equally spaced members, either in a square grid, or as in the case of Kocommas an hexagonal grid. This corresponds with a simple method of manufacture. The subsequent structure is then defined by defining the grid boundaries and support points.

The surface covering itself can be patterned directly by making a model from the photographed chain model or indirectly through computer modelling.

The structural analysis of the grid shell is very important. Non-linear analysis is essential as the in-plane shear stiffness achieved by the bending elements is necessary to prevent buckling of the surface under partial loads and unsymmetrical loads.

### Heavyweight cable roofs

Modelling is rarely used except for architectural understanding. This is because the interaction between the bending stiffness and the cables is almost impossible to reproduce in model form. Individual cables want to take up a profile consistent with their loaded form. As adjacent cables may have a loaded form which is different, they have incompatible shapes which are adjusted by the bending stiffness of the rafters. Various computer methods exist for doing this. Furthermore, the heavyweight roofs are the most easily understood through drawing. They are not a much used form of structure.

### Conclusions

Lightweight structures are a group of structures united by two characteristics. The surface covering is usually very light and flexible and without bending stiffness which can be patterned into any three-dimensional shape. In addition the shape and equilibrium of the surface at any given moment are dependent upon the load conditions acting upon it. This derives from the low bending stiffness and low shear stiffness of the surface and means that normal techniques of structure definition and structural analysis are inadequate. Methods exist at present to solve these and are being developed with a clarity and sophistication which copies directly the way the structures behave in nature. Modelling techniques, which have been initiated and are being developed by Frei Otto in Stüttgart, and computer techniques, using the on-line drafting methods available in modern computers, are equally important. The structures require an open approach from designers and a willingness to recognize that the methods which must be used to understand the correct form or shape are physical.

### References

(1) RICE, P. Notes on the design of cable roofs. *The Arup Journal, 6* (4) pp. 6-10, 1971.

(2) DAY, A. A general computer technique for form finding for tensile structures. IASS Conference 'Shells and spatial structures: the development of form' Morgantown, West Virginia, USA, August 1978.

(3) BULSON, P. S. Structural behaviour of a 30ft. span inflated bridge. IASS Pacific Symposium on tension structures and space frames, Tokyo and Kyoto, Japan, 1971. Proceedings, pp. 461-471, Architectural Institute of Japan, 1972.

(4) HAPPOLD, E. *and* LIDDELL, W.I. Timber lattice roof for the Mannheim Bundesgartenschau. *Structural Engineer, 53* (3), pp. 99-135, 1975.

# A brief history of cable and membrane roofs

## Brian Forster

Membranes are thin sheets of material possessing a high degree of lateral flexibility so that, when loaded laterally, they do not develop bending stress. They can only develop in plane tensile and shearing stresses. Similarly, chains and cables are highly flexible and in supporting load, only develop tensile stress.

### Before the 19th century

Whilst by far the major development of technology and theoretical understanding has taken place since World War Two, membrane and cable structures existed several centuries before Christ. There is evidence from the fifth century BC of bridges suspended by 'ropes' of liana, and also bamboo. Stone reliefs carved during the Assyrian, Egyptian and Roman civilizations depict army tents consisting of animal skins or woven fabric pulled over a framework of bars. Copper wire cable has been excavated at Nineveh and bronze wire cable from Pompeii. Suspension bridges are known to have been built in China since AD 90. The cables were made by plaiting bamboo; planks laid directly onto a group of cables formed the pathway and the majority of such bridges in West China have spans 40-80m using 6-12 cables. Wrought iron chains were introduced for some crossings in the sixth century AD.

In Roman times, spectators in amphitheatres were shaded from the sun by linen fabric slung between natural-fibre ropes. These awnings, called 'velaria', were surprisingly large; frescoes in Pompeii dating from 59 BC show part of an auditorium covered with a fabric awning. Around the top storey of the Colosseum in Rome there are attachment points for masts to support the network of ropes. Velaria were also used to cover Roman theatres because the spans were beyond the capacity of rigid wooden roofs of that period. Similar awnings called 'toldos' have been used over Spanish streets since the 16th century (Fig 1). The Romans (amongst others) made inflated bags from animal skins sealed with gum and preserved with salt. These were used as flotation devices for steadying boats and animals on difficult water crossings. Inflation was necessary not just for buoyancy but to maintain the skin in a stable shape. Gold beater's skin, a fine membrane from the intestine of an ox, was also used.

However, none of these civilizations can be thought of as having really developed a membrane or cable structure for the purposes of enclosing living space. Their buildings were in the main constructed of heavy, rigid materials such as stone and brick which satisfied, amongst other things, the desire for physical security. It is to the world's nomadic groups that one must look for the first proper membrane building. Nomads through necessity have developed forms of shelter which are easy to carry, assemble, and dismantle, and which are adaptable to climatic change. They are composed only of materials readily available, and utilize the craft-skills which their makers have developed and by which they survive. A number of these skills involve the stretching of woven fabrics or skins over a simple framework of timber poles, e.g. the North American Indian teepee, and the Mongolian yurt. The Bedouin tent, however, is the most satisfying example—one in which the function of structure is provided simultaneously by the element that provides shade and protection from the weather. The Bedouins subsist on the products of their flocks of sheep and goats. Weaving is their only developed craft and is carried out on simple handlooms laid out on the ground. Their tents are made by sewing together long strips of goat-hair fabric. Each tent is arranged in plan as a series of squares, each up to 4m square, placed side by side. Individual tents are typically 12m long by 4m wide, but they can be longer or shorter according to the size and wealth of the family. The interior space is subdivided by decorated fabric strips stretched between edge poles. A central line of taller poles, each with carved bearing plates is used to give the roof a fall each way, the fabric hanging in shallow catenary between edge and centre poles. Ropes are pulled down over the edge poles and staked into the ground. Woven goat hair straps are sewn on along the edges and reinforce the area of the poles and guys, also forming a decorative motif. The side walls are made of strips which are joined to the roof fabric by large wooden pins. This simple technique permits adjustment or removal according to the need for shade, ventilation or warmth. Similar tents are used throughout the Muslim world by other nomadic and pastoralist groups.

From the time of the Romans to the end of the 18th century, the tent as a form of construction developed very little. Its principal application continued to be short-term accommodation during military campaigns. This lack of development might be partly explained by the facts that woven fabric had limited tensile strength, and that there were difficulties in making joints capable of transmitting significant force. It would have been recognized that thin, singly-curved surfaces are unstable in high winds. Techniques of stabilizing membranes by any method other than by adding weights to the surface do not appear to have been explored during this period. There was a similar lack of development in cable-supported structures. Machine-drawn wire had, however, made its appearance in 14th century Europe.

### 1800-1945

For membranes and cables to be effective in supporting laterally-applied load, they must either be initially curved or be capable of developing curvature under load. The particular degree of curvature is dependent on applied load and, if unrestrained, the curve will adjust according to any change in the nature of applied load, e.g. early rope bridges. The dynamic stability of a cable roof having only a single, downward, curvature is dependent upon the level of mass that it supports, combined with a system of bending stiffness, secondary in nature. The provision of mass and stiffness is not always desirable and a second method of ensuring stability is by the use of anticlastic surfaces. Because the curvatures are mutually opposed to one another, anticlastic surfaces can be prestressed. A third method of ensuring stability is by creating a sufficiently large pressure difference between the inner and outer surfaces of the membrane, as for instance in balloons, blimps, and in a wide variety of other air-inflated items including the car tyre. Again the surface is prestressed and the level of prestress is related to frequency of vibration.

Up to 1800 it would seem that cable and membrane structures were only constructed with single curvature and were either of short span or supported sufficient weight for them to be stable. From 1800 three distinct lines of structural activity developed, one in building, one in bridge engineering, one in aeronautics – each one involving the use of one of the above methods of ensuring stability. During the 20th century the technology developed in each became applicable to the design of a wide variety of membrane buildings and cable roofs.

### Development of the circus tent

The Industrial Revolution, starting in Britain, and then spreading into Europe and North America, brought mechanized spinning of yarn and weaving of cotton, wool and linen textiles. During the 19th century the railways spread and also the populations of the industrializing countries had multiplied dramatically. From 1800 the circus began establishing itself as a major form of popular entertainment. Performances took place inside large halls of permanent construction in major towns and cities. Then in the 1860s a radical departure occurred in the USA. Circus companies began travelling by rail to perform in towns without such halls, and of necessity developed structures which could be quickly assembled and dismantled at each stop. So the large circus tent began to flourish. A visit to Paris in 1867 by the 'First American Railway Circus' complete with its tent and technical apparatus aroused great public excitement and led to the formation of mobile groups in Europe. The tents, such as the classic 'Chapiteau' were up to 50m in diameter and made from machine-woven linen or hemp canvas. The Chapiteau is supported near the centre by four King poles situated around the circus ring. The canvas hangs from these to frequent perimeter poles. By virtue of this and the circular plan shape, slight double curvature exists in the fabric. Between the King poles and the perimeter there is a ring of lighter Queen poles inclined at approximately 60° to the ground which are used

**Fig. 1**
'Toldos' over a street in Seville, Spain (Photo: Courtesy of IL Archiv)

**Fig. 2**
M. Poifevin, Equestrian Aeronaut, at Champ de Mars, Paris, 1850
(Photo: *Copyright* Mary Evans Picture Library)

primarily to pre-tension the membrane. Even though these structures are geometrically simple, considerable knowledge in terms of cutting patterns, joints and craft skills were developed and passed on by successive generations of tentmakers. The Stromeyer Co., established in 1872 in Germany, continued the practice of large tent-making almost to the present day.

The Industrial Revolution also brought the development and production of wrought iron as a structural material. In the early 19th century, bridge engineers, notably Finley in the USA and later Telford and Brunel in Britain, exploited the material's high tensile strength by using wrought iron to make chains. Claude Navier published in 1823 theoretical studies on the analysis of suspension structures. At much the same time wire rope made with malleable iron wire became available. In 1829 Sequin and Lame designed a suspension bridge in France using continuous wire ropes rather than a chain of wrought iron bars. Vicat invented an insitu method of spinning wire to form the ropes.

During the next century there were collapses of suspension bridges which are now attributable to aerodynamic excitation. J. M. Rendel investigated the collapse of the Montrose bridge in 1838 and observed that control of undulation and oscillation of bridge decks required torsional as well as bending stiffness. The 330m crossing of the Ohio River at Wheeling, Virginia, was completed by Ellet in 1849. Unfortunately it collapsed in 1854 during a severe storm and John Roebling rebuilt it, modifying the design in two respects. Firstly he recognized that in making the cable, the wire strands had to be compacted tightly to prevent rubbing between individual wires and the whole bundle then wrapped in a continuous helix of coated wire. Secondly he incorporated radial stays between the tower top and bridge deck. With the Pittsburgh bridge (347m) in 1860, Roebling made the first use of travelling sheaves to spin the cables. Already in 1855 he had built a 269m span double decker road-rail suspension bridge across the Niagara. Stiffness was achieved with stays, counter stays and deep trusses. His crowning achievement was the Brooklyn Bridge with a span of 523m and this made the first use of steel wires. Less reliance was placed on stays and more upon deck stiffness.

Following the example of bridges, some roofs were suspended from cables. The Naval Arsenal at Lorient, France, designed by Laurent in 1837 had a central span of 42m with two lines of suspension chains supporting longitudinal and transverse trusses.

In 1896 V. G. Shookov presented four steel tent structures at the All-Russian Exhibition in Nizhniy-Novgorod. His ideas on form and construction were advanced and were without equal until the 1960s. Flexible nets were formed from strip steel onto which thin steel sheets were assembled and formed unprestressed anticlastic shell surfaces. It is worth noting that Shookov took the tent as his model rather than the suspension bridge.

A third field of activity related to the development of membrane structures was opened up in the 18th century. In France, the Montgolfier brothers performed their celebrated experiment of inflating, with hot air, an 11m diameter balloon made of linen and paper. In the same year, 1783, Meusenier designed a hydrogen-filled airship. Interest continued during the 19th century (see Fig. 2) and by the early part of the 20th century a body of practical and theoretical knowledge had been built up which permitted the operation of large passenger and cargo carrying airships.

### The 20th century

In 1917, an English engineer, F. W. Lanchester, registered a patent for 'An Improved Construction of Tent for Field Hospitals, Depots and like purposes'. In the patent, Lanchester states 'The present invention has for its object to provide a means of constructing and erecting a tent of large size without the use of poles or supports of any kind. The present invention consists in brief in a construction of tent in which balloon fabric or other materials of low air permeability are employed and maintained in the erected state by air pressure and in which ingress and egress is provided for by one or more air locks'. He had in fact invented the 'air-house' in which spherical or part-spherical and semi-cylindrical membrane surfaces are supported and stabilized against wind and snow loads by maintaining a pressure difference between the air enclosed by the membrane, and the air outside.

Unfortunately Lanchester's own designs were never realized. This was perhaps partly due to public opinion and also due to the lack of a sufficiently durable membrane material.

When Lanchester died, in 1938, synthetic fibres such as nylon had been developed and during World War II improvements in the coating of fabrics were made for the construction of barrage balloons, blimps, inflatable life-saving devices and deception devices such as inflatable dummy tanks. Shelters supported by air-inflated tubes were also used in the Western Desert.

### Post 1945

World War II and the subsequent emergence of the Super Powers promoted considerable developments in aeronautics, radar and weaponry which lead into spaceflight nuclear power and computers. From these fields the construction industry gained substantial advances in materials – metals plastics and adhesives, and in engineering analysis techniques – matrix methods coupled with the electronic computer. Also the dynamic stability of suspended structures became more properly understood following the collapse of Tacoma Narrows suspension bridge in 1940.

Since 1950 many engineers and architects have developed the field of cable and membrane structures. However, there are two individuals who may be singled out as having made significant contributions to our knowledge continuously since 1950. These are Frei Otto, architect and Professor of Lightweight Structures in Stüttgart, and Walter Bird, engineer and contractor in Buffalo, USA.

At his Institute Otto has researched form possibilities and parallels in nature. Frei Otto's constructed work includes tents and cable nets of all shapes and sizes. Early in the 1950s he formed an exceedingly fruitful collaboration with Peter Stromeyer, the tent

**Fig. 3**
Ceremony tent for BP, Aberdeen, Designers : Frei Otto, Design Research Unit, Ove Arup & Partners (Photo : Ove Arup & Partners)

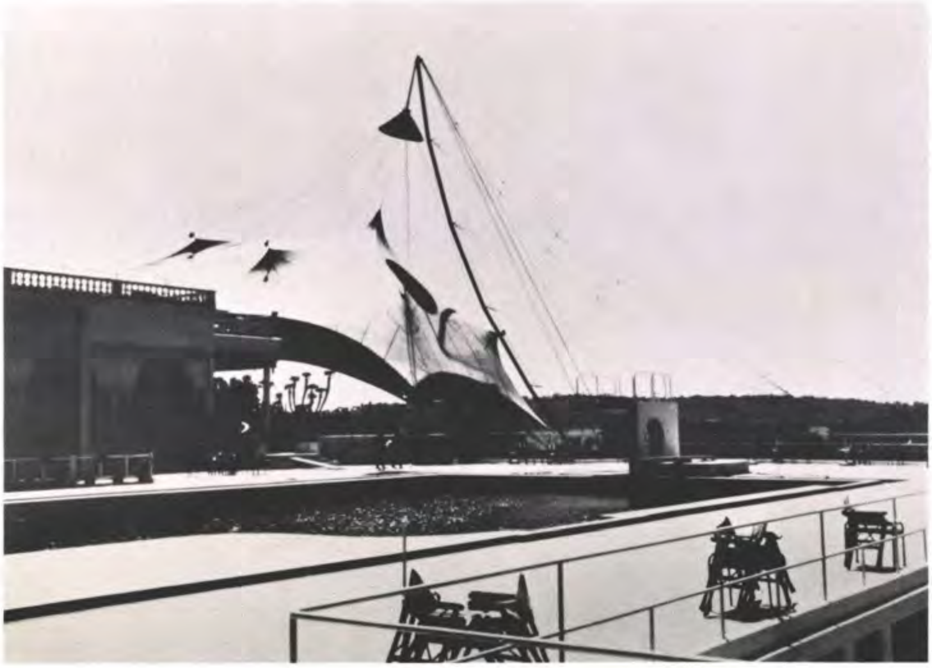

**Fig. 4**
Retractable roof in Cannes. Designers : Roger Taillibert, P. Stromeyer, Frei Otto, S. du Chateau (Photo : Courtesy of IL Archiv)

**Fig. 5**
Fuji Pavilion, Osaka Expo 1970. Designers : Murata & Kawaguchi (Photo : Courtesy of Taiyo Kogyo Co.)

maker. Between 1955 and 1965 many free form, doubly-curved tents were designed and made for various Federal Garden Shows, trade shows and national exhibitions such as at Lausanne in 1964. Each one introduced new ideas about shape, erection and stressing technique and experimented with different kinds of cloth and jointing. Also during this period Stromeyer and Otto, amongst others, were studying the problems of making retractable roofs. Taillibert, in France, gained government sponsorship for the idea of covering swimming pools with a membrane bunched at the top of an inclined stayed mast (Fig. 4). The membrane was developed by miniature cable tractors travelling down cables radiating from the mast to the boundary. Queffelec, in France, developed the cable tractors and their control systems, whilst Stromeyer and Otto developed the membrane and cable systems. A number of such roofs, typically covering 60m× 30m, were built in 1965-70 in France and in Germany. In 1970 Frei Otto proposed a retractable roof 300m in diameter. Taillibert's 1976 Olympic Stadium at Montreal will finally be completed with a retractable membrane roof made of aluminized *Kevlar* fabric, one of the new super high strength, synthetic fibres.

Between 1960-70 the tent industry in Japan flourished with the Taiyo Kogyo Co. producing a spectacular array of membranes at the Osaka Expo 70. Walter Bird has promoted the use of woven glass membranes coated in *Teflon* and currently the world's largest tent structure is being constructed in Jeddah. The first phase covers 50,000m$^2$.

### Air supported structures

The development of air-supported structures was taken up seriously by the US Military towards the end of World War II. In 1948 a team under Bird at Cornell Aeronautical Labs had completed full-scale prototype testing of a radome 15m diameter by 12m high.

This work was initiated by the need for non-metallic covers over long range radar antennae. During the '50s the DEW Line radomes were built, along with 'Telstar' communications satellite tracking stations. The largest of these structures was built in Maine and measures 65m in diameter and 50m high and was designed for a basic wind speed of 45m/sec. Similar radomes were built at Fylingdales and at other sites in Europe. In 1956 Bird *et al* formed a company to fabricate air structures. As military applications for air-supported and air-inflated structures expanded, commercial interest began to be shown, first with warehouses and later with swimming pool and tennis court covers. Similar markets developed during the 1960s in Europe and Japan. However, US architects working with Bird were the first to exploit the geometrical possibilities of thin membranes supported by air; Carl Koch with a 44m diameter lenticular pillow roof over the Boston Arts Theatre (1959); Victor Lundy with the beautifully undulating 'Atoms for Peace' travelling exhibition – a double wall structure 90m long and 38m wide (1960); Victor Lundy again, with 25m high and 15m diameter clusters of bubbles for the New York World Fair (1963).

In 1966 Frei Otto published the 2nd volume of *Zugbeanspruchte Konstrucktionen* which revealed many more possibilities for the geometric form and span of pneumatic structures.

Murata and Kawaguchi excited visitors to Expo 70 at Osaka with their Fuji Pavilion (Fig. 5) composed of 16 air-inflated arches, each 4m in diameter and 72m long connected to a concrete ring foundation 50m in diameter. Pressure was adjustable to cope with typhoon conditions. The US Pavilion at Osaka was an air structure designed by Chermayeff, Geiger and Bird. This roof, with a clear span of 135m, had a very low profile and blended smoothly into a perimeter earth beam. This shape secured uniform attached flow conditions, thereby minimizing aerodynamic loading. This structure has formed the archetype for a series of roofs built since 1974 over sporting arenas in North America, the largest being the 220m span Silverdome in Michigan. Arups are designing a similar roof in Aberdeen (Fig. 6) (200m). An interesting development in Canada is the welded stainless steel skin at Dalhousie by Sinoski.

Also in the '70s Otto and Arup studied the problem of covering whole cities built in the Arctic with multi-layer air supported cable/membrane roofs with clear spans of 2km (Fig. 7). This collaboration continues into the '80s with a proposal to build a roof of similar area in Alaska.

The idea of building pretensioned cable structures may have been in a number of engineers' minds since Sir George Cayley patented the tensioned spoke wheel in 1803. But the practical realization of such systems did not occur until the 1950s when David Jawerth in Sweden patented a shear stiff prestressed cable truss which has found application throughout the world during the last 25 years, e.g. in the UK at Billingham, and at Schipol Airport with a 77m span hangar and in Stockholm with an 83m ice rink. In the United States, Lev Zetlin solved problems of wind-induced flutter of bicycle roofs with his design for the Utica Auditorium, 80m in diameter, built in 1959.

Slung cables were also used by a number of designers in conjunction with the mass and stiffness of concrete. Saarinen with the Dulles Airport Terminal roof (1958) and Viera *et al* with a 95m diameter roof in Montevideo (1958). The slung cable roof with single curvature has been taken furthest in terms of minimum mass and support geometry by Otto, Gutbrod and Arup with the 46m span Mecca Conference Centre roof (Fig. 8).

The development of roofs stabilized by double curvature and pretensioning was stimulated by the completion in 1963 of the Raleigh Arena (North Carolina) by Nowicki and Severud (Fig. 9). A saddle-shaped net of 20 and 30mm diameter cables spans 95m between a pair of reinforced concrete arches which are inclined in opposite directions to one another at 20° to the horizontal. Flutter of flat areas around the perimeter was prevented by straight guys which rake down onto perimeter columns.

**Cable roofs**

The Raleigh Arena formed the archetype for a great number of cable roofs built throughout Europe, the Eastern Bloc and USSR, and USA. A recent example is the Milan Palasport by Valle and Romana with a clear span of 135m.

In 1954, working in Brazil, Borges and Alliana produced a delightful exhibition pavilion, 60m × 100m, in Sao Paulo. Here the net was given much more curvature and was stretched between vertical arches with inclined tie backs from the arches taken into ground anchorages. 1958 saw the completion of the Yale Ice Hockey Rink. Saarinen and Severud used a third arch as central spine to support a cable net covering 70m × 55m. In Melbourne, Yuncken, Freeman and Irwin covered part of an open air music bowl with a cable net supported by edge catenaries and 20m high steel masts 60m apart. At the Brussels Expo 58, Rene Sarger engineered two pavilions with double curved cable nets supported by masts and ridge cables. The largest of these, the French Pavilion, had a span of 100m.

Frei Otto, inspired by Nowicki's achievement, has taken the concept of the cable net supported by masts furthest in terms of lightness, geometric shape and elegance.

**Fig. 6**
Bridge of Don, Aberdeen.
Designers: J. Arnott, Grampain Regional Council Architect, and Ove Arup & Partners
(Photo: Harry Sowden)

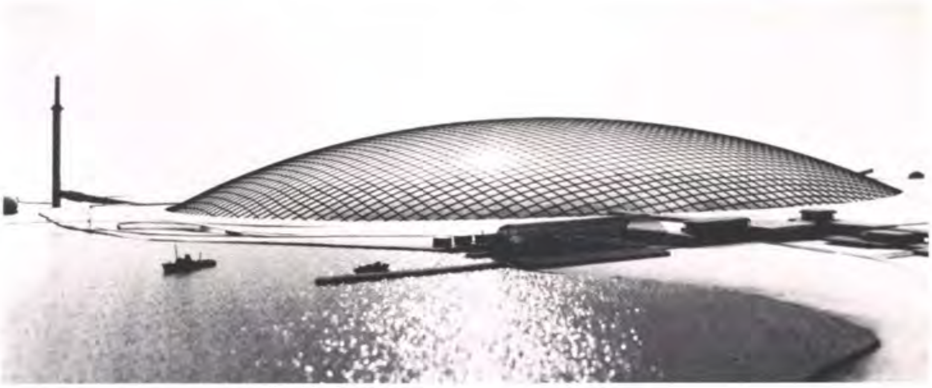

**Fig. 7**
Arctic City. Designers: Frei Otto and Ove Arup & Partners
(Photo: Courtesy of Frei Otto)

**Fig. 8**
Mecca Conference Centre.
Designers: Rolf Gutbrod, Frei Otto and Ove Arup & Partners (Photo: Ove Arup & Partners)

**Fig. 9**
Livestock Arena at Raleigh, North Carolina.
Designers: M. Nowicki and F. Severud
(Photo: Courtesy of Architectural Association)

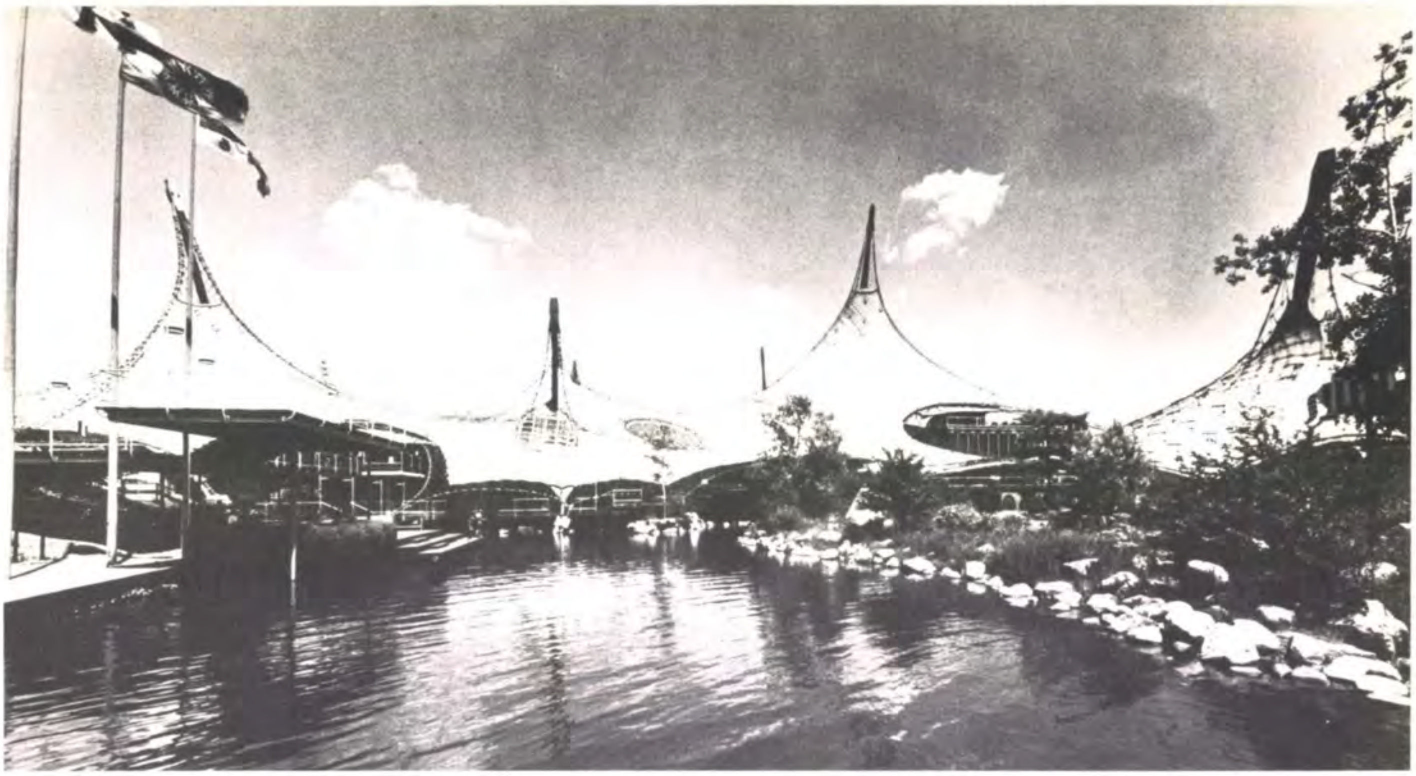

**Fig. 10**
German Pavilion, Montreal Expo 1967.
Designers : Rolf Gutbrod, Frei Otto,
Fritz Leonhardt
(Photo : Courtesy of IL Archiv)

**Fig. 11**
Cooling tower at Schmehausen,
West Germany.
Designers : Leonhardt & Andrä
(Photo : Courtesy of IL Archiv)

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The first of his major designs was the German Pavilion at Montreal Expo in 1967 covering 10,000m$^2$ with an underslung polyester membrane (Fig. 10). In 1972 Otto collaborated with Leonhardt on 75,000m$^2$ of covered arena for the Olympic Games in Munich, and most recently the cable net with two polyester membranes covering the Jeddah Sports City.

But perhaps the most stunning cable net structure to have been built is that for the 140m maximum diameter× 180m high cooling tower at Schmehausen, designed by Leonhardt and Andra (Fig. 11). This was completed in 1975 and its hyperboloid form echoes Borges' simple pavilion of 1954. It does perhaps point the way to new fields of use for cable and membrane structures.

# Air-supported structures: fire and smoke hazards

Margaret Law

### Introduction

In the design of fire safety for an air-supported structure, the objectives can be summarized as follows:

Protection of people – occupants and fire fighters

Protection of nearby buildings

Protection of structure and contents.

The measures adopted to meet the objectives cover fire prevention, designed to reduce the risk of fire occurring, and fire protection, designed to mitigate the effects of fire should it nevertheless occur. The mix and balance of measures adopted depends on the particular circumstances.

What are the special aspects of an air-supported structure which affect the fire safety design? First the susceptibility to collapse due to loss of pressure caused either by destruction of part of the membrane by fire or by the opening of a large number of exit doors, or by both. Secondly the turbulent effect on smoke which in the initial stages would normally tend to form in layers at high level but may be stirred up by the collapsing membrane – particularly on a windy day – and by movement of escaping air towards the exits. Thirdly, the vulnerability of the structure to external fires.

Experimental fire tests have demonstrated that, should the membrane of an air-supported structure be exposed to a small fire source, it is likely to suffer only localized damage, and buoyancy from the fire may delay the collapse due to loss of pressure[1–6]. However, should the fire grow, the membrane is likely to suffer irreparable damage and collapse may be swift. In these circumstances the primary objectives are to safeguard the people using the structure and to make adequate provisions for the fire brigade to tackle the fire and to prevent spread to adjacent property.

The approach to designing fire safety for the people inside may be affected by whether the structure is considered as a building or as an enclosure of an open space. Must one aim to apply the building regulations or should one try to ensure that the fire hazards are not significantly greater than if the activities were carried out in the open air? The answers to these questions ought to take into account the risk of fire occurrence, the type of activity carried out and the size of the enclosure. For example, in an automated warehouse there is a low risk of fire occurrence and a low risk to life safety; in a fairground there may be many sources of ignition and many people at risk; in a covered sports stadium there will be a low risk of fire occurrence and the size of the enclosure could be so large in relation to the size of the fire that for a period the conditions would be similar to those in an open-air stadium.

Where fire safety of the structure is concerned, because the membrane is so vulnerable if directly involved in fire, the best cure is prevention.

### Fire prevention

Fire prevention is an important aspect of management, maintenance and surveillance procedures. As far as design is concerned, particular attention may need to be paid to the following:

(a) Elimination or isolation of potential sources of ignition. If 'hot' processes cannot be placed outside, they should be enclosed or where appropriate the membrane should be suitably shielded. If collapse of the structure begins, because of a tear or a fan breakdown, then the membrane needs to be kept clear of any hot surfaces.

(b) Preservation of the integrity of fuel and electrical systems which might be affected by structural movement.

(c) Use of non-combustible materials wherever possible.

(d) Provision of an efficient rubbish disposal system to avoid accumulation of refuse adjacent to the structure.

### Structural considerations:

### Membrane material

In general the membrane material is a coated fabric, although stainless steel has been used.[7] The Draft for Development, *DD50*[3], recommends that the membrane should not 'readily support combustion when used for an air-supported structure'. However some membrane fabrics which would not meet the *BS 3120* 'Performance requirements of flame proof materials for clothing and other purposes' nevertheless perform satisfactorily when pneumatically stressed because small fires adjacent to the fabric penetrate quickly and flames are carried outwards with the escaping air. Under these conditions there is generally no tendency for the flames to spread across the fabric[2]. Under building regulations the highest standard of performance for the surfaces of walls and ceilings is judged by the results of two tests, *BS476: Part 7* 'Surface spread of flame test' and *BS476: Part 6* 'Fire propagation test', the basic objective being that the surface should not increase the rate of flame spread over that which would occur if the surface were non-combustible. It is clear therefore that, when inflated, most membranes would meet the requirements of *DD50* and, by venting the fire, would be superior to many surfaces in buildings. It is when the membrane is in the collapsed position that the degree of flammability is likely to be more important. Most of the membrane materials do not remain sufficiently rigid to be tested according to *BS476*, and the appropriate test is thus *BS3119* 'Method of test for flameproof materials'.

The flame performance of a coated fabric is governed almost entirely by the characteristics of the coating but the nature of the fabric does also have some influence. Both PVC coatings and rubber coatings are flammable and require the addition of large amounts of flame-retardant materials to achieve the highest flame performance. With *Neoprene* coatings on nylon, the fabric and the coating adhesive make a significant contribution to the overall performance. Thick coatings of rubber with high levels of fire retardants are required to smother this effect in order to achieve high performance. PTFE-coated glass fabrics have a significant advantage over other coated fabrics because the combustible content is significantly reduced. The fabric remains intact after flaming and so it can be tested to *BS 476: Part 7* to achieve a Class 1 surface spread of flame. It is also classified Class 0 to *BS 476: Part 6* 'Fire propagation test of materials' and flameproof to *BS 3119 and 3120*. No special flame-retardant materials are added to the coating.

In assessing flame performance it must be remembered that under real fire conditions other factors may be as important as this, such as smoke generation, toxic fumes and integrity of seams, although the smoke and toxic hazard may be less than inside a building because of the direct ventilation to the open air.

### Exposure hazard

Once a fire inside an air-supported structure becomes fully developed the coated fabric will be destroyed and nearby buildings will be exposed to the risk of fire spread by heat radiation and flying embers. In the context of building regulations, therefore, the whole external wall would be defined as 'unprotected area' and spaced accordingly from the boundary. The boundary distances in regulations are based on an assumption that the maximum acceptable intensity of radiation falling on the outside face of an exposed building is $12.6\text{kW/m}^2$, this being the critical intensity for ignition of dry wood in the presence of a spark or brand[8]. How this applies to air-supported structures is less clear; probably the brand would have to be large before it burnt a hole in the membrane, assuming it could lodge there. It could then fall inside to start a fire, while the membrane itself would start to deflate. Any such extra risk of fire spread from an adjacent building should therefore be taken into account when siting an air-supported structure and people inside should be aware that they may not have the same degree of protection as from a conventional enclosure.

The structure is also vulnerable to small external fires which may start adjacent to the membrane. For assembly buildings, The Building Regulations require that up to 7.5m above the ground, the external enclosure must either be fire-resistant or there must be a clear view to the outside[9]. (This requirement followed the Summerland fire which started in a small outside kiosk). Any risk of unseen fire spread in voids or cavities should be avoided by the use of baffles.

### Means of escape

Once people are alerted to a fire they must have sufficient time available to reach a safe place (usually the open air at ground level) either directly or through an exit to a protected route, without being exposed to undue hazard by structural collapse or heat and smoke. It is of course necessary to design for escape during deflation even without a fire. The *DD50* gives guidance on exit widths and travel distances but these are not related to the deflation time and appear to be derived from rules for escape in the case of fire. It is useful therefore to consider these rules as applied in conventional, i.e. rigid buildings:

It is generally required either explicitly, or implicitly, that an enclosed area which may contain a fire can be totally evacuated within 2½ minutes. The aggregate width of all exits less one (disposed to give people alternative direction of travel), is provided at the rate of 530mm per 100 occupants. It is assumed that a crowd will travel at a speed of 18m/minute, the maximum travel distance to an exit thus being 45m. Where the floor layout cannot be determined beforehand, a maximum direct distance of 30m is required. Where there is no alternative exit a maximum travel distance of 12m is usually specified.

The evacuation time of 2½ minutes was originally adopted because it was thought that people would panic if they were at risk for longer than this[10]; it was not apparently based on the likely pattern of fire spread and smoke generation. In fact there is reason to believe that, at least when people are in groups, they do not tend to panic, provided they can see there is a way for them to escape, but irrational behaviour may well be caused by poor visibility or inhalation of carbon monoxide. It would seem logical therefore to take into account the patterns of smoke generation and accumulation from a fire and the toxic content of the gases. This type of approach has already been adopted in covered shopping centres, where exit times of considerably longer than 2½ minutes are accepted because smoke control measures are installed, specifically designed for the circumstances of each centre.[11]

In what way can escape from fire be affected by the fact that the structure is air-supported?

First, it must be assumed that deflation can occur. It is reasonable to assume that the fans will continue to operate during the early stages of the fire but, since revolving doors cannot be used for escape, there will be loss of air through the emergency exits and through any hole burnt in the membrane by the fire. If there is no supplementary support structure then an estimate must be made of the time available before the membrane could approach head level – about 2.5m above the ground – and start to obscure exits and emergency signs.

Second, there should be independent supports for emergency exits, emergency lighting and emergency signs, sufficiently stiff to operate until escape is complete.

Third, smoke may be drawn towards the exits, particularly when there is no venting through a hole in the membrane, and it may be necessary to provide extra mechanical ventilation in these areas to dilute or extract the smoke.

Fourth, deflation accompanied by a wind which causes flapping of the membrane may create turbulence in the smoke layers, bringing the smoke down to head level more quickly than in a rigid building.

Fifth, the deflation, particularly if the membrane flaps in the wind, may cause some alarm to the people escaping.

The importance of these effects must be assessed for the particular structure under consideration. Some methods of assessing smoke and heat production from fires are in the Appendix. Where very large enclosures are concerned, it may well be that the deflation time is so long, and the smoke production in relation to the volume so small that an evacuation time exceeding 2½ minutes would be reasonable. This would avoid the provision of evacuation tunnels (which otherwise might be needed to meet the 45m travel distance) and very large exit widths (which otherwise might be needed to evacuate a large population).

### Other fire protection measures

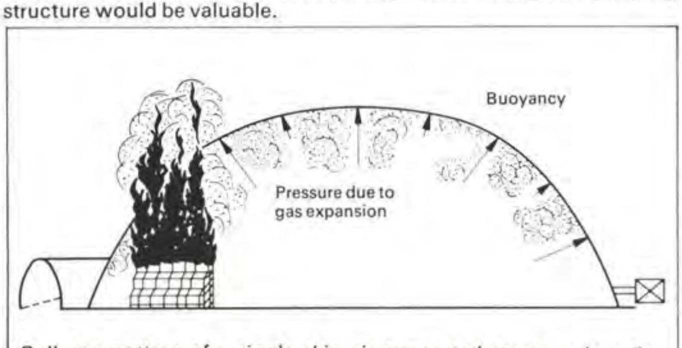
The usual manual alarms and hand-held extinguishers or hose reels for use by the occupants should be provided as appropriate. Automatic detection and alarm systems may also be needed. Automatic sprinklers may be installed but it should be borne in mind that where there is a sloping or descending roof the plume of hot gases from a fire may be deflected away from the sprinkler head directly above, which thus may not operate until the fire is too big to be controlled by the sprinklers. With high-racked storage, however, the sprinklers can be built into the racks, thus avoiding this problem.

### Fire brigade facilities

Where there is a supplementary support structure the fire brigade may be able to enter to fight the fire. Smoke removal could be achieved by opening the doors and venting the fire through a hole in the membrane; this hole may have been burnt through the fabric by the fire or a flap may have been opened by the brigade. However, it may well be dangerous for the brigade to enter if collapse is likely and fire fighting can then only take place from outside. The appropriate hydrants and hardstanding for vehicles must be provided, bearing this in mind.

### Concluding remarks

Where a coated fabric is used as the membrane for an air-supported structure it is inevitably vulnerable to any fire other than a very small one. However, where safety of the occupants is concerned it should be possible to provide a reasonable level of safety. A more clearly stated performance requirement for escape design taking into account smoke generation and movement is needed and an assessment of the reaction of people to the sight (and sound) of a deflating structure would be valuable.



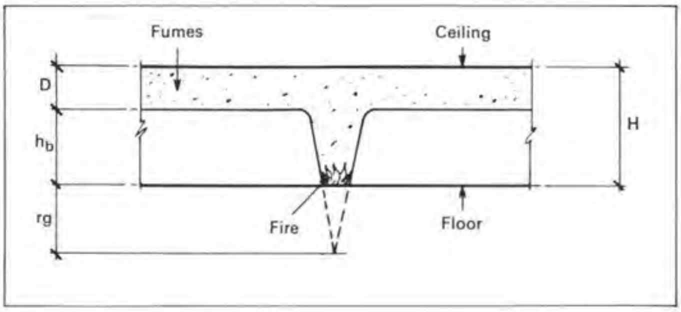
Collapse pattern of a single skin air-supported structure in a fire with holes in side walls – stability may be maintained for a considerable period due to buoyancy effects.

## APPENDIX

### 1. Smoke generation

1.1 A fire produces a plume of smoke and hot gases which entrains air as it rises, thus increasing the volume of smoke. When the smoke plume reaches ceiling level it spreads sideways and downwards.

1.2



Assume a fire occupying a floor area $A_f$ and a smoke layer at a height $h_b$ above the floor. Provided $h_b$ is several times greater than $\sqrt{A_f}$, the fire may be considered to originate at a point $r_g$ below the floor where $r_g \triangleq 1.5\sqrt{A_f}$.

The mass flow of hot gases into the layer[1,2] is given by:

$$M = 0.043\rho\, r_b^{5/2}\,(2g\theta/T_o)^{1/2} \qquad \text{kg/s}$$

where $\rho$ = density of hot gases kg/m³

$r_b = r_g + h_b = H + 1.5\sqrt{A_f} - D$ m

$g$ = 9.81 m/s²

$\theta$ = temperature rise of hot gases °C

$T_o$ = ambient temperature = 290 °K

$D$ = depth of smoke layer m

i.e.

$$M = 0.0112\rho\,(H + 1.5\sqrt{A_f} - D)^{5/2}\sqrt{\theta} \qquad \text{kg/s} \qquad (1)$$

$$\text{Volume flow} = \frac{M}{\rho} = A\frac{dD}{dt} \qquad \text{m}^3/\text{s}$$

where floor area = A m²

$$\frac{dD}{dt} = \frac{M}{A\rho} = \frac{0.0112}{A}(H + 1.5\sqrt{A_f} - D)^{5/2}\sqrt{\theta} \qquad \text{m/s}$$

$$t = \frac{A}{0.0112\sqrt{\theta}}\int_0^D \frac{dD}{(H + 1.5\sqrt{A_f} - D)^{5/2}}$$

ie

$$t = \frac{A}{0.0112\sqrt{\theta}}\left[\frac{1}{(H + 1.5\sqrt{A_f} - D)^{3/2}} - \frac{1}{(H + 1.5\sqrt{A_f})^{3/2}}\right] \qquad (2)$$

By conservation of heat

$$DA\rho c\theta = Qt \qquad (3)$$

where $c$ = specific heat of gases = 1KJ/kg°C

$Q$ = heat output of fire kW

and $\rho = \rho_o T_o/(\theta + T_o)$ kg/m³

$\rho_o = 1.22$ kg/m³

By using trial figures in equation (2) and (3) the values of $t$ and $\theta$ may be found. Typical values of Q are given in paragraph 6 below.

1.3 When the flames from the fire are close to the smoke layer, the mass flow of hot gases into the layer is given by:

$$M = 0.188\,P\,h_b^{3/2} \qquad \text{kg/s}$$

where $P$ = perimeter of fire $\triangleq 4\sqrt{A_f}$ m

thus

$$\frac{dD}{dt} = \frac{0.752\sqrt{A_f}\,h_b^{3/2}}{A\rho} \qquad \text{m/s}$$

and

$$t = \frac{A}{0.376\sqrt{A_f}}\left[\frac{1}{\sqrt{H-D}} - \frac{1}{\sqrt{H}}\right]\text{s} \qquad (4)$$

## 2. Flame height

2.1 The flame height $h_f$ above a wood fire [13] is given by:

$$h_f = 40 \left[\frac{R}{A_f \rho_o \sqrt{gD}}\right]^{2/3}$$

where $D$ = diameter of fire $\simeq \sqrt{A_f}$ m

$R$ = rate of burning kg/s

Putting $Q$ = C X R kW

where $C$ = net calorific value of wood kJ/kg
= $13 \times 10^3$

gives $h_f = 0.030\, A_f^{1/3} \left[\frac{Q}{A_f}\right]^{2/3}$ m (5)

## 3. Fire area

A fire is likely to grow exponentially during its initial stages, and if we make the assumption that it doubles in size every 4 minutes [15] then:

$$A_f = Ao\ e^{0.173\,T} \quad m^2 \qquad (6)$$

where $T$ = time min

$Ao$ = fire area when T = O m$^2$

The average area of fire over time T is given by:

$$A_{fav} = \frac{Ao}{0.173\,T}\left(e^{0.173\,T}-1\right) \quad m^2 \qquad (7)$$

If escape begins when T = O then Ao is the area when the fire is detected and if people are present Ao is probably greater than 1m$^2$ but less than 10m$^2$.

## 4. Smoke and visibility

The total mass of material burnt is given by R× t and the concentration in the smoke layer is $\dfrac{R\times t}{D\times A}$ kg/m$^3$

The following table shows the mass of various materials burnt to give 4.5m visibility when mixed with air in a volume of 540m$^3$. Visibility is taken as inversely proportional to smoke concentration i.e. half the concentration gives double the visibility. These values are based on measurements of light attenuation and take no account of irritation of the eyes.

| Material | Mass burnt to give 4.5m visibility in 540m$^3$ kg |
|---|---|
| Wood | 1.2 |
| Polyurethane foam | 0.91 |
| Kerosene | p.24 |
| Foam rubber | 0.22 |
| Expanded polystyrene | 0.16 |

## 5. Toxic products

The amount and type of toxic products generated depends on the material and the ventilation conditions. An indication is given below for two common toxic products, carbon monoxide (CO) and hydrogen cyanide (HCN), showing the mass generated by combustion of 1kg of various materials[16]. Because of its greater bulk density, the products from wood furniture may predominate.

| Material | CO produced kg/kg | HCN produced kg/kg |
|---|---|---|
| Cotton and wood | 0.50 | — |
| Wool | 0.23 | 0.12 |
| Nylon | 0.44 | 0.11 |
| Acrylic fibres | 0.30 | 0.26 |
| Polyurethane foam | 0.55 | 0.35 |

The maximum allowable concentration of CO for short period exposure is 4,000 ppm and for HCN 300 ppm[16].

## 6. Burning rate and heat generation

Values of $\frac{R}{A_f}$ and $\frac{Q}{A_f}$ have been estimated from fire incidents in industrial premises[17] and are given below:

| Building contents | Height of contents m | $\frac{R}{A_f}$ kg/m$^2$.s | $\frac{Q}{A_f}$ kW/m$^2$ |
|---|---|---|---|
| Crated furniture | 3.3 | 0.008 | 100 |
| Vehicles, petrol, paint | 0.8 | 0.020 | 260 |
| Stacked, sawn, timber | 1.5 | 0.030 | 390 |
| Books, furniture | 3.0 | 0.007 | 93 |

| Building contents | Height of of contents m | $\frac{R}{A_f}$ kg/m$^2$.s | $\frac{Q}{A_f}$ kW/m$^2$ |
|---|---|---|---|
| Stacked cardboard | 1.8 | 0.025 | 320 |
| Stacked chipboard | 2.4 | 0.007 | 86 |
| Cartons, electrical goods | 2.0 | 0.024 | 310 |
| Cardboard cartons | 7.0 | 0.048 | 620 |
| Cardboard reels | 7.0 | 0.016 | 210 |
| Packaged goods | 3.6 | 0.041 | 540 |

For furniture in offices and residential accommodation values of 0.020 kg/m$^2$.s for R/$A_f$ and 290 kW/m$^2$ for Q/$A_f$ may be adopted.

### References

(1) FIRE RESEARCH STATION. *Fire Research Note No. 955.* Fire tests on an air-supported structure. Fire Research Station, 1972.

(2) BUILDING RESEARCH ESTABLISHMENT. *Information Sheet No. 16/73.* Air-supported structures. September 1973. BRE, 1973.

(3) BRITISH STANDARDS INSTITUTION. *DD 50: 1976.* Draft for development. Air-supported structures. BSI, 1976.

(4) DEPARTMENT OF THE ENVIRONMENT. *Circular 96/71.* The building regulations, 1965. Air-supported structures. HMSO, 1972.

(5) HERZOG, T. Pneumatic structures: a handbook of inflatable architecture. New York: Oxford University Press, 1976. pp. 142-144.

(6) DEPARTMENT OF THE ENVIRONMENT. Air-structures. A survey. HMSO, 1971.

(7) ENGINEERING NEWS RECORD. Steel bubble roof is light, low cost and durable. *Engineering News Record, 203* (1), pp. 28-29, 1979.

(8) FIRE RESEARCH STATION. *Technical paper no. 5.* Heat radiation from fires and building separation, by M. Law. HMSO, 1963.

(9) STATUTORY INSTRUMENTS. 1976, No. 1676. Building and buildings. The building regulations, 1976. HMSO, 1976.

(10) MINISTRY OF WORKS. Post-war building studies no. 29. Fire grading of buildings. HMSO, 1952.

(11) HOME OFFICE. Fire prevention guide no. 1. Fire precautions in town centre redevelopment. HMSO, 1973.

(12) FIRE RESEARCH STATION. *Technical Paper no. 7.* Investigations into the flow of hot gases in roof venting, by P. H. Thomas, et al. HMSO, 1963.

(13) THOMAS, P. H. Buoyant diffusion flames. *Combustion and Flame, 4* (Dec), 1960.

(14) FIRE RESEARCH STATION. *Fire Research Note No. 856.* Fire problems of pedestrian precincts. Part I. The smoke production of various materials, by A. J. M. Heselden. Fire Research Station, 1971.

(15) FIRE RESEARCH STATION. *Fire Research Note No. 886.* The number of sprinkler heads opening in fires, by R. Baldwin and M. A. North. Fire Research Station, 1971.

(16) BUTCHER, E. G. *and* PARNELL, A. C. Smoke control in fire safety design. Spon, 1979.

(17) FIRE PROTECTION ASSOCIATION. *Fire Prevention Science and Technology No. 17.* Studies of fires in industrial buildings. Part 1: The growth and development of fire, by C. R. Theobald. FPA, 1977.

### Editor's note

This article is based on a paper given at the Institution of Structural Engineers Symposium on 'Air-supported structures: the state of the art', at the Café Royal, London, 4 June 1980.

# Coated fabrics for lightweight structures

## Tony Read
## Turlogh O'Brien

### Introduction

This article provides an introduction to the construction and characteristics of coated fabrics used for lightweight structures.

In order to provide an appreciation of the significant features of coated fabrics, the characteristics of three 'standard' materials are discussed and contrasted. These are rubber-coated nylon, PVC-coated polyester, and PTFE-coated glass.

### Classification of lightweight covering materials

It is possible to classify lightweight coverings in a number of ways. Fig. 1 provides a useful method for a materials study.

**Films** are thin flexible sheet materials of isotropic properties in one plane. They may be made of plastics, rubbers or metals and usually have low air permeability.

In general, unreinforced films are not used very much as architectural coverings but the cheaper materials are sometimes used as temporary membranes in 'fun' architecture. The use of thin metal foils laminated with high performance plastic films is being studied for high altitude balloons and airships.

**Fabrics** are woven yarns which have the two directions of weave at right angles. Various types of weave are available and yarn size and spacing can be varied. Materials for making fabrics are natural organic fibres, mineral fibres, metal fibres and synthetic (plastic) fibres. Combinations of organic and synthetic fibres are also commonly used (e.g. cotton spun onto a polyester core). In general these materials can be considered as being anisotropic (although it is possible to arrange for the mechanical properties to be approximately equal in two directions at right angles to each other in one plane) and they will also have higher degrees of air permeability than films. The weave of the fabric is usually constructed such that some angular displacement is possible between the threads.

For the great majority of applications it is not possible to use a film or a fabric on its own because the films are not strong enough and because the fabrics are not sufficiently durable and impermeable. It then becomes necessary to use a *coated fabric* or a *reinforced film*.

**Coated fabrics** are formed by taking a conventional fabric and coating it with one of the following materials:

polyvinyl chloride (PVC),

polyurethane (PU),

silicone

polytetrafluorethylene (PTFE),

polychloroprene (*Neoprene*),

chlorosulphonated polyethylene (*Hypalon*),

Not all coatings are used with all fabrics and factors such as adhesion, chemical compatibility, stress/strain compatibility, and coating temperatures need to be taken into consideration. The combinations which are commonly used in Europe, USA and Japan are:

*Neoprene* or *Hypalon*-coated nylon fabric

PVC-coated polyester fabric

PTFE-coated glass fabric

In Japan other combinations have also been used such as:

PVC-coated vinyl fabrics

PVC-coated glass

*Hypalon*-coated glass fabric

**Reinforced films** are formed by taking a conventional film material and reinforcing it with an open weave fabric. This is usually achieved by laminating the fabric between two thin layers of film. A method of holding the three layers together is required (adhesive or heat welding) and a method of excluding air. Membranes of this sort are not often used for lightweight structures but may be necessary where high light translucence is required. Combinations which have been considered are:

polyester-reinforced polyethylene film

polyester-reinforced PVC

stainless steel-reinforced FEP film

glass-reinforced FEP film

*Kevlar*-reinforced FEP film

### Construction of coated fabrics

The production of a coated fabric involves a number of different processes and suppliers in the textile industry.
These processes are:

(1) Production of yarn by spinning, drawing and twisting together of fibres
(2) Weaving of yarn into fabrics
(3) Coating of fabrics.

### Yarns

A yarn refers to the basic component which is used in the weaving process. In some cases yarns may be twisted together into threads which are then used for weaving. The yarn is usually composed of a number of other elements called fibres or filaments.

These are characterized by being very long (up to 100mm) and very thin (about 10μm).

In high strength fabrics the fibres are produced as continuous filaments (nylon, polyester and glass) which are twisted or cabled together to a greater or lesser degree to form the yarn.

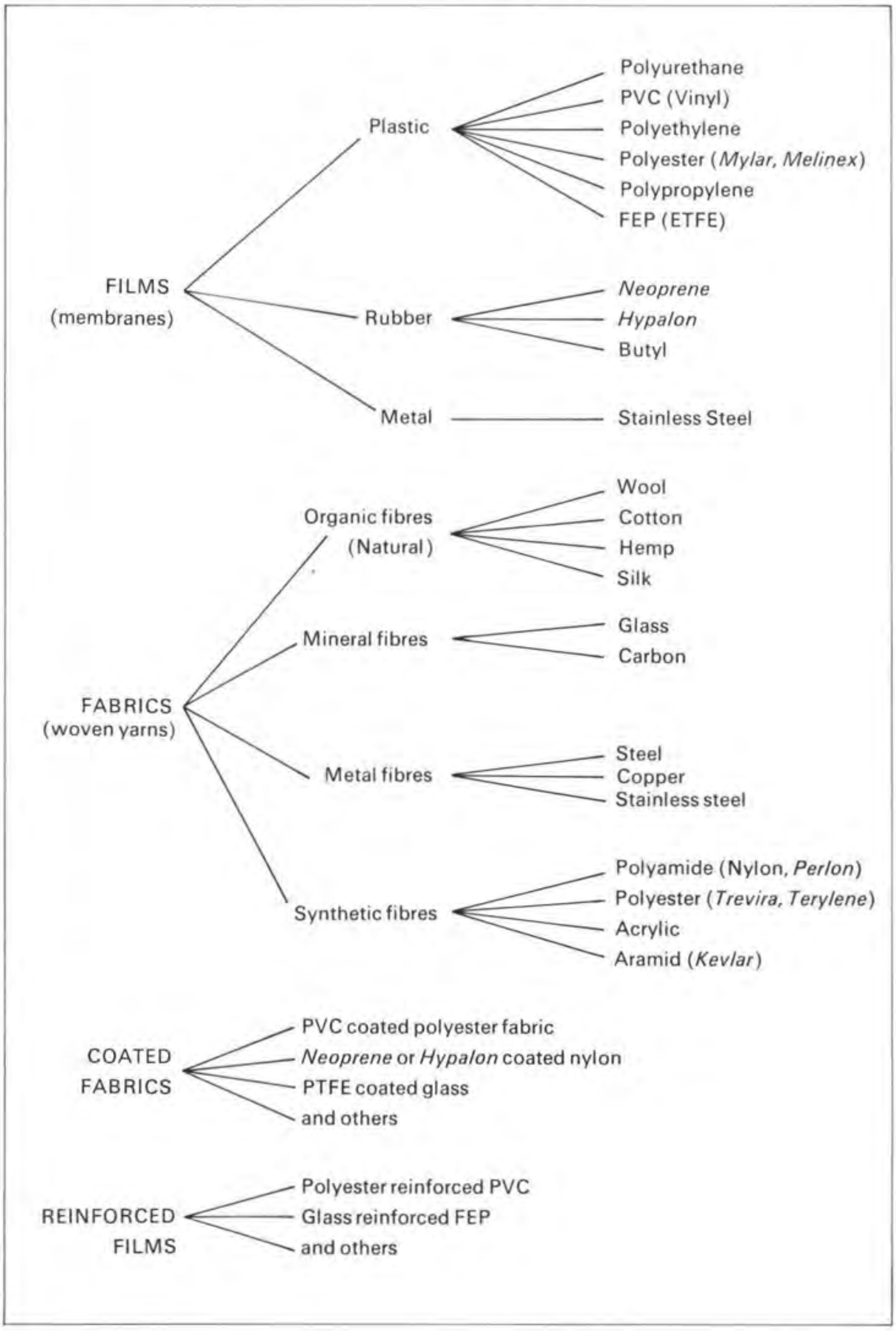


**Fig. 1**
Classification of covering materials of lightweight structures

The textile industry uses a special term known as *tex* to describe the 'thickness' of material in a yarn. The yarn tex is the weight in grams of one km of yarn and yarn strength is then measured in Newtons per tex.

### Fabrics

During the weaving process two sets of yarns at right angles are threaded in and out of each other. This is achieved in practice by having one set of parallel continuous yarns (known as the warp) stretched along the length of the cloth, and passing another continuous yarn (known as the weft or fill) backwards and forwards through the warp yarns by means of a shuttle.

The warp is usually kept under tension while weaving which results in it achieving a straighter profile, in the fabric than the weft. This leads to different mechanical properties in the warp and weft directions.

The warp and weft can be woven together in a variety of different patterns, many of which are for visual purposes but some achieve different mechanical and physical properties.

For coated fabrics the main weaves of interest are as follows:

Plain weave (1 × 1) – Each weft thread passes over and under each warp thread alternately and vice versa.

It is also known as taffeta, linen weave and cotton weave.

Plain weave (2 × 2) – Two weft threads together pass over and under two warp threads together alternately and vice versa.

This may also be known as basket weave, panama weave, canvas weave, matt weave, and hopsack.

It is also possible to construct unbalanced plain weaves (2 × 1, 3 × 1) in which the thread count in each direction will be very different.

### Coatings

The coating process has to be designed to achieve good penetration of the fabric, good adhesion and an adequate thickness over all parts. It is usually carried out in several stages in which the fabric is prepared for chemical compatibility with the coating; primers or lubricants are applied; the main bulk coats are applied; and surface finishes are added. The two main methods of application are by spread coating in which the hot fluid material is applied by a spreading blade to the fabric as it passes underneath it; and by calender coating in which a thin film of coating is first deposited onto a calender roll and then transferred onto fabric as it passes between the rolls. These two systems apply to PVC and rubber coatings but for PTFE the glass fabric passes through a dip coating of resin emulsion and is subsequently dried and sintered onto the fabric by passing it through various ovens.

The composition of the coatings will vary considerably according to the application. A typical PVC coating for instance may have 10 or more ingredients, while a PTFE coating will have less ingredients due to its inherently better durability under weathering (and thus not requiring components such as u.v. absorbers and plasticizers).

A minimum thickness of 250 µm of PVC coating is usually recommended for adequate durability. This is reduced to 100 µm for PTFE coatings over glass.

Some coatings are given extra finishes for various reasons. For instance, a PVC coating may be given an acrylic finish to improve dirt shedding – a *Neoprene* coating may be finished with a *Hypalon* paint to achieve colour requirements; and a PTFE coating is usually given an FEP top finish to finally seal any pinholes or imperfections, and make it heat-sealable.

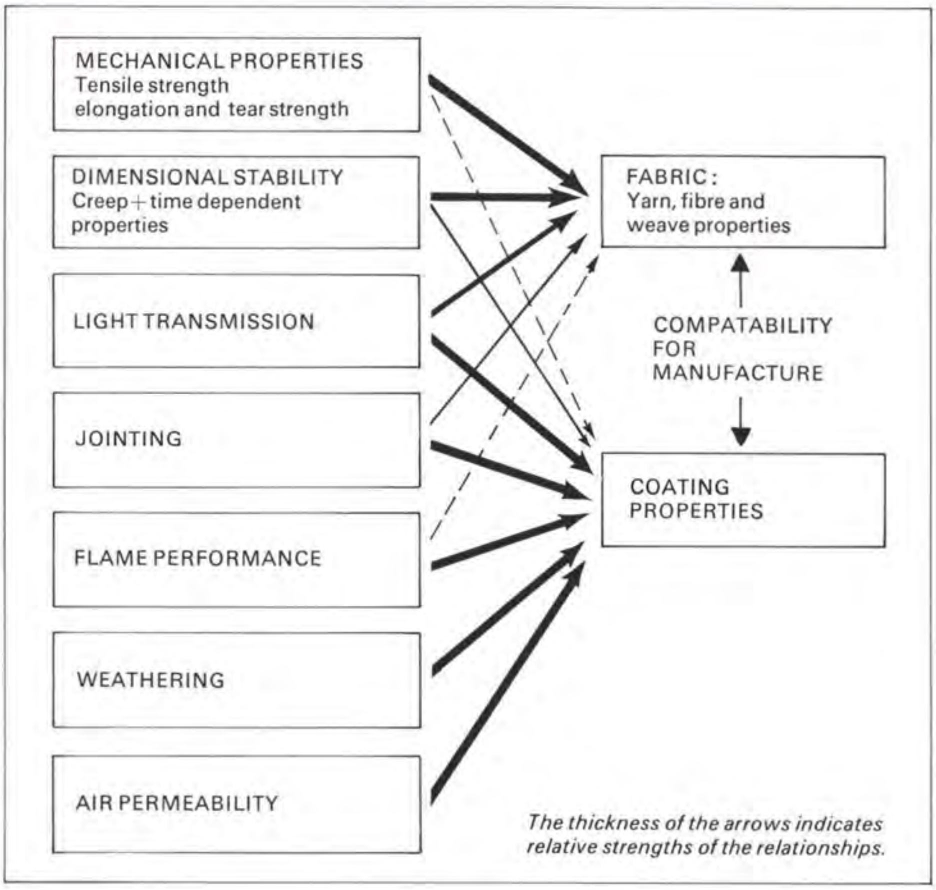


**Fig. 2**
Composite properties of coated fabrics and their relationship to the fabric and coating

### Characteristics of coated fabrics

The envelope materials for lightweight structures may be required to have a wide range of properties and these can contain several incompatabilities (e.g. translucence and u.v. resistance, lightweight and adequate tensile strength). It is not often possible to completely satisfy all these requirements in one material so that a compromise is generally necessary. It is however, possible to select coatings and fabrics to meet different aspects of the requirements.

The relationship between the composite properties of a coated fabric and the separate properties of the fabric and the coating is set out in Fig. 2.

### Mechanical properties

The short-term properties of the coated fabric are primarily determined by the fabric although the coating will undoubtedly have some influence as well. For instance, a basic glass fabric having a tensile strength of 6500 N/50mm can, when coated with PTFE, have a tensile strength of 9000 N/50mm.

The short-term mechanical properties which are of primary interest in lightweight structures are: tensile strength, modulus, and elongation, and tear strength and propagation, but even more important is the way these properties are maintained with age and when permanently stressed or under cyclic loading.

The *tensile strength* is obviously an important feature since these membranes are primary structural components of the building.

The *tensile modulus* is of particular importance to the accuracy of the cutting pattern and erection tolerances. A material with a high modulus is far more critical in these respects and the likelihood of wrinkles, creases and sags is greater.

It is also important that the *elongation* of the material under working load is not too great, otherwise the membrane will lose its shape.

Damage to membrane structures usually takes the form of tearing of the fabric rather than direct tensile failure. The *tear strength* and *resistance to tear propagation* are a measure of a fabric's ability to stand up to damage of this sort.

The parameters of the fabric construction which affect the mechanical properties are:

fibre material
yarn construction + weight
fabric construction + weight

The broad mechanical characteristics of nylon, polyester and glass fabrics are as follows:

| | |
|---|---|
| nylon: | high strength, low modulus, high extension |
| polyester: | high strength, medium modulus, medium extension |
| glass: | very high strength, high modulus, low extension. |

In combining the filaments into a yarn there is an opportunity to modify the elastic modulus by using a twisted or cable construction (which provides greater extensibility than straight filaments) and to increase the tear resistance by using heavier yarn constructions. During tearing of the fabric each yarn is broken separately so that yarn strength is the determining factor, not the number of yarns per centimetre.

In weaving the yarns into a cloth there are a number of factors which have to be considered. For a given tensile strength of fabric it is possible to use a lesser number of large tex yarns or a greater number of small tex yarns. There is also the opportunity to select different strengths in the warp and weft directions by selection of yarn size and spacing.

For air-supported structures it is usually recommended that the tensile strengths of the coated fabric in the warp and weft directions are within 10% of each other.

The extension under load of the fabric at the beginning of the stress-strain curve is strongly influenced by the fabric construction. For equal weights of cloth, a fabric having a large number of small yarns will have a smaller extensibility in this region than a fabric having a lesser number of large yarns. This de-crimp zone is an important feature in glass fabrics since it provides some opportunity to stretch the fabric at low loads during fitting and erection. During weaving, the warp yarns are usually held straighter than the weft yarns and thus the shape of the stress-strain curve is different for each. Typical stress-strain curves in the warp and weft directions for PTFE-coated glass fabric are shown in Fig. 3 and for *Neoprene*-coated nylon in Fig. 4.

The stress-strain characteristics may be modified in practice when the material is stressed in biaxial tension. Skelton has shown that a fabric that is heat set and coated under warp tension shows large differences in stress-strain behaviour both in warp and weft direction and in uniaxial and biaxial tension. When the same fabric is heat set and coated under weft tension the performances become more balanced (see Fig. 5).

The tear strength of a fabric can be improved by using 'rip-stop' techniques. This involves either weaving two warp or weft threads together at regular intervals throughout the construction to provide a double yarn strength to prevent the tear passing, or incorporating an extra yarn of heavier tex at intervals throughout the weave. For a given weight of fabric construction a basket weave (2×2) will have a greater tear strength than a plain (1×1) weave, and a tightly packed construction will have a lower tear strength than a looser open weave. The latter allows the yarns to bunch up together under tearing action to provide a rip stop effect.

Research has been carried out into ways of improving the tear resistance for a given tensile strength by using stitched yarn constructions and soft rubber coatings on the yarn[1, 3, 4].

Skelton[1] has studied the resistance to *tear propagation* of various fabric constructions as a percentage of the pre-stressing load necessary to propagate the tear. In general all of the techniques used to increase the tear resistance also increase the resistance to tear propagation.

### Dimensional stability

The dimensional stability of a coated fabric, when stressed for a period of time, is mainly dependent on the basic fibre material of the fabric and not on yarn or weave construction. It is also to some extent influenced by the coating, since many of the fibre materials will lose strength on weathering and the coating is necessary for protection. In addition the mechanical properties of plastic materials (i.e. synthetic fibres) are usually sensitive to temperature and sometimes to relative humidity as well.

The long-term tensile strength of coated fabrics is lower than the short-term strength. Herzog[2] reports on tests with PVC coated polyester fabrics which showed that under permanent loads of 80% of the short-term tensile strength, failure occurred in some samples after a matter of hours and, in many, after several days. However, at 50% of the short-term value, the samples lasted for 10,000 hours without failure and when subsequently short-term tested to failure, showed no significant decrease in strength. Similarly, under the same percentage loading, the warp extension increased from about 7.5% to about 8.5% and the weft extension increased from about 13% to about 15% after 10,000 hours.

Seaman and Venkataraman[3] compared qualitatively the performance of nylon and polyester base fabrics. Nylon absorbs moisture from the atmosphere and in so doing expands. Both polyesters and nylons are affected by u.v. light to some extent when unprotected. The American Enka Company[3] record 90% loss of strength for continuously loaded nylon after 110 weeks under u.v. exposure. Polyester fabric loses 20% of its strength under similar conditions. Hajek and Holub[7] showed the important effect the coating has in limiting loss of strength in nylon fabrics by exposing fabrics with different weights of rubber coating for 25 months under natural conditions. The 90% loss in strength of an uncoated fabric was reduced to 5% loss in strength with the maximum coating weight of 160g/m$^2$.

**Table 1:**
Construction and properties of some typical coated fabrics

| | PVC coated polyester fabric | PTFE coated glass fabric | *Neoprene* coated nylon fabric |
|---|---|---|---|
| Thickness (mm) | 0.67 | 0.8 | 0.8 |
| Weight (g/m$^2$) | 800 | 1352 | 750 |
| Fabric weight (g/m$^2$) | — | 476 | — |
| Yarn construction | d tex 1100 f 200 | 34×4×2 tex | d tex 840 |
| Weave | plain 1/1 | plain 1/1 | — |
| Thread count (threads/cm) (warp/weft) | 4.9/4.7 | 9.5/7.5 | 5/5 |
| Tensile strength (N/50mm) (warp/weft) | 1760/1660 | 7300/6100 | 2000/1660 |
| Elongation (%) (warp/weft) | 14/19 | 6/7 | 25/30 |
| Tear strength (N) (warp/weft) | 310/350 | 425/308 | 550/735 |

Both nylon and polyester are temperature-sensitive materials. With increase in temperature the strength decreases and the elongation increases.

At low temperatures (—20°C) strength and modulus will increase but vinyl coated fabrics become increasingly brittle and there is some danger of cracks developing in the coating. Herzog[2] and Krummheuer[9] have both shown reductions in strength of 10-20% for high strength polyester fabrics tested at 70°C compared to those tested at 20°C. Krummheuer also showed that the creep rupture strength (at 105 hours) for polyester materials decreased from about 70% of the short-term strength when kept at room temperature to about 60% when kept at 70°C.

Glass fabrics are expected to provide good dimensional stability although very little published information is yet available. Accelerated weathering tests, however, have shown no loss in tensile strength after 8,000 hours exposure. Glass fibres are degraded under moist conditions and the exclusion of water from the fabric by the coating is a critical factor, but the material is known to be dimensionally stable over conditions of varying temperatures and humidity. Bird[8] has reported no 'significant' loss in physical properties from samples taken from a building six years old.

For an estimation of long-term strengths of coated fabrics based on short-term results Hearle has suggested a general rule-of-thumb that the short-term strength should be reduced by 10% for each factor of 10 that the service life exceeds the testing time.

### Light transmission

In many cases with lightweight coverings some degree of light transmission is required. This may be to provide suitable conditions for plant growth or merely to provide a reasonable level of natural lighting for sports or concerts. On other occasions, e.g. for a travelling cinema or theatre, zero light transmission is preferable. For coated fabrics the level of light transmission will be determined by the translucence of the basic yarn, and that of the coating, and by the yarn spacing in the weave. Where opaque materials (e.g. metals) are used for the fabric it can be shown that the light transmission is dependent on the ratio of the yarn diameter to the yarn spacing of the weave. Polyester, nylon, and glass yarns are not opaque and some degree of translucence can be achieved. Indeed where 'black out, conditions are required the coating will need to be designed specifically for this requirement since PTFE and vinyl both have some translucence unless heavily pigmented. Rubber coatings can generally achieve opacity without great difficulty because of the carbon used in their compounding. Where high levels of light transmission are required for plant growth (typically greater than 80% transmission in the 400-700nm visible frequency) it is necessary to use a grid weave construction and an unpigmented coating. It is often more practical in these circumstances to use a reinforced clear plastic film.

Even though the light transmission values for these materials is low compared with typical glazing materials, the total light levels in air-supported buildings can be perfectly acceptable for some uses by virtue of the large area of material admitting light. In other cases it may be necessary to incorporate windows made from a transparent film such as PVC.

### Joining

Methods of joining coated fabrics are related both to the fabric and the coating. The three most commonly used methods are heat sealing, cementing and sewing. Heat sealed and cemented joints rely on the shear strength of the elastomer or the cement and the adhesive bond between the coating and the fabric. This last aspect is very important and in many cases it is the adhesive strength of the coating to the fabric which is the limiting factor determining the strength of welded or cemented seams. Sewn joints rely on the tensile strength of the sewing thread and on the type of lapping system used. Highest strengths can be obtained from sewn joints but these cannot be used for glass fabric because of the brittleness of the yarn and the likelihood of inducing tears. PVC-coated polyester is usually heat-sealed and sewn for maximum strength. Rubber-coated nylon is cemented with rubber solution because this coated fabric is often used in high pressure structures where sewn joints would leak. The jointing of PTFE-coated glass is a highly specialized process requiring special equipment and techniques. It is basically a welding method which uses a thermo-plastic FEP interlayer to obtain good bond to the PTFE.

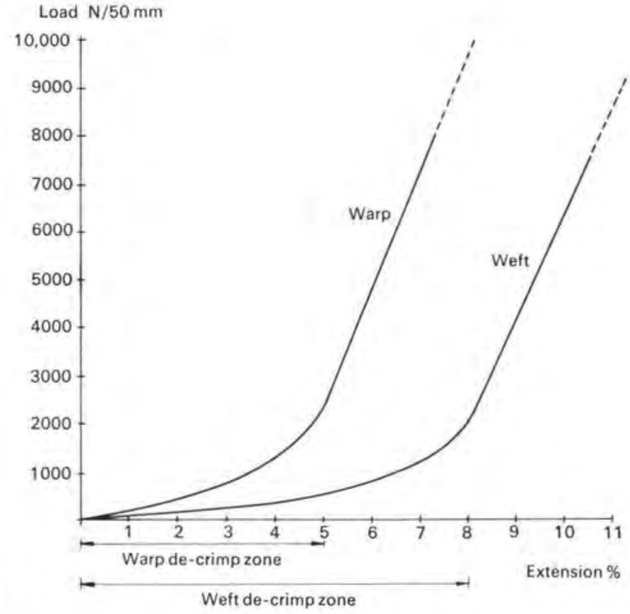


**Fig. 3**
Typical load-extension curve for PTFE coated glass fabric
Glass weight: 615 g/m$^2$; Weave: plain
Coated fabric weight: 1657 g/m$^2$; Thickness: 0.99 mm

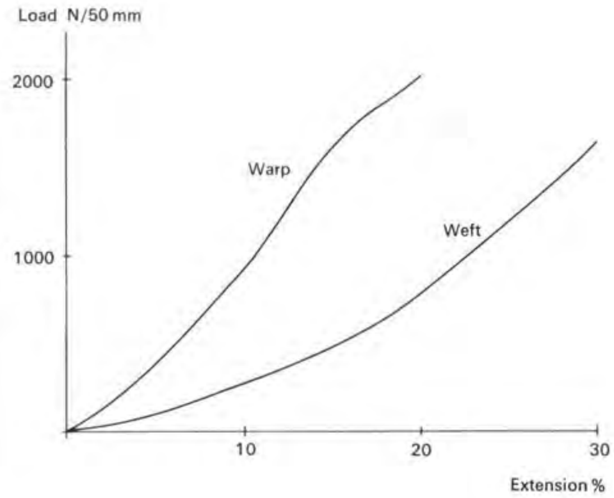


**Fig. 4**
Typical load-extension curve for *Neoprene* coated nylon
(Coated fabric weight: 1000 g/m$^2$)

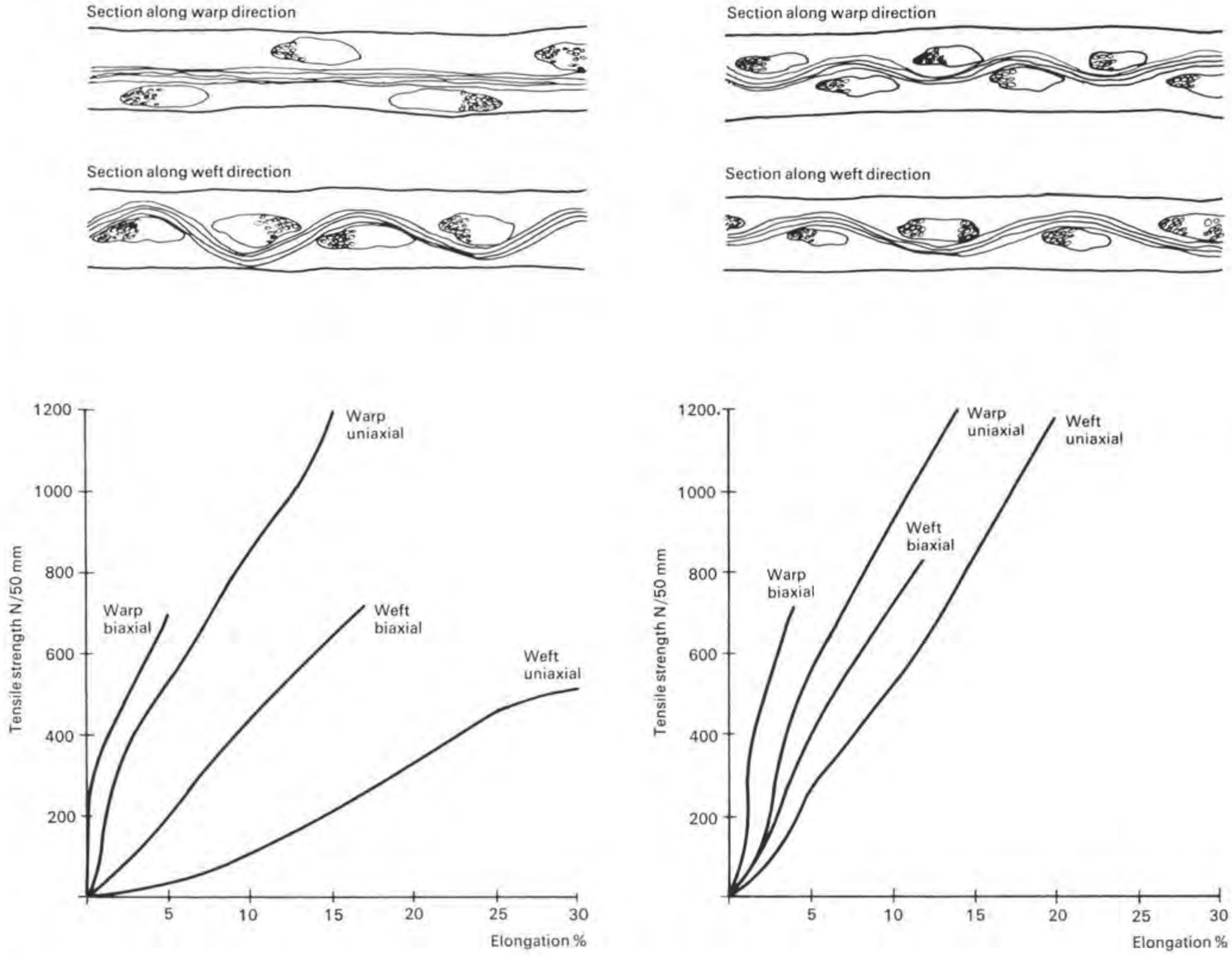


**Fig. 5**
Structure and behaviour of similar fabrics heat set and coated under warp tension (left hand side) and under weft tension (right hand side). (Taken from Reference 1)

The strength of fabric seams in lightweight membranes is an important area of concern for designers. Considerable work has been done on joints in PVC-coated polyester fabric[6,9] both under continuous and intermittent stress and also at high temperatures. Welded joints showed considerable reduction in strength at high temperatures (70°C) and only when placed under a prolonged load of 15% of the short-term tensile strength of the fabric did they remain intact for more than 10,000 hours.

### Flame performance

The flame performance of a coated fabric is governed almost entirely by the characteristics of the coating but the nature of the fabric does also have some influence. The performance can be judged by a number of different small-scale tests which usually involve measuring the length of charring and burning and the time taken for the flame to extinguish. The test normally carried out is *BS 3119* 'Method of test for flameproof materials, and the performance is judged by *BS 3120* 'Performance requirements of flameproof materials for clothing and other purposes'. This test is quite a severe one and in many cases some sort of relaxation is given.

Both PVC coatings and rubber coatings are flammable and require the addition of large amounts of flame-retardant materials to achieve the highest flame performance. With *Neoprene* coatings on nylon the fabric and the coating adhesive make a significant contribution to the overall performance. Thick coatings of rubber with high levels of fire retardants are required to smother this effect in order to achieve high performance. PTFE-coated glass fabrics have a significant advantage over other coated fabrics because the combustible content is significantly reduced. The fabric remains intact after flaming so that the normal British Standard tests for building materials can be applied to it. When tested to *BS 476 Part 7* it achieves a Class 1 surface spread of flame and it is also classified Class 0 to *BS 476 Part 6* 'Fire propagation test of materials' as well as being flameproof to *BS 3119* and *3120*. No special flame-retardant materials are added to the coating.

In assessing flame performance it must be remembered that under real fire conditions other factors may be as important as this, such as smoke generation, toxic fumes and integrity of seams.

### Weathering

The choice of the coating material is largely responsible for the durability and weathering characteristics of coated fabrics. Temperature, u.v. light, oxidation, moisture, agressive chemicals and organic growth can all play their part in degrading the properties of the coated fabric until it is unable to fulfill its performance requirements.

In the majority of cases some sort of coating is very much needed to provide protection to the fabric. Nylon is degraded by the action of sunlight and oxidation, and can lose strength quite rapidly unless protected. The same is true also of *Kevlar* fibres. Glass fabric is affected by moisture which causes loss of strength. Polyester fabrics are the most resistant to degradation by sunlight and oxidation.

Vinyl coatings are compounded from a number of chemicals to achieve different purposes. Adhesion, flexibility, u.v. absorption, flame resistance and abrasion resistance can all be important in determining the overall durability. The use of transparent or translucent coatings will increase the rate of u.v. attack as will also the use of flame retardant compounds, especially in combination with the former. Nearly always when compounding these coatings there is a continual compromise being made to balance one set of requirements against another. Hilscher[6] has shown that problems can exist with PVC coatings due to fungal growth as a result of water wicking up between the fabric coating, and due to dirt sticking on the surface of the coating making it difficult to clean. PVC coatings are now commonly formulated to contain a fungicide and coating techniques are designed to prevent water wicking. Developments have continued with improved PVC polymer formulations having inherently better flexibility and u.v. resistance, and also with producing thin over coatings based on acrylic, urethane or PVF (polyvinyl fluoride) materials to improve the surface soiling characteristics. Mewes[11] confidently assigns a service life of 12 years to translucent PVC-coated polyester fabrics and 18 years to opaque materials, but this does not seem to be generally supported. A figure of 10-15 years would seem to be more realistic.

Synthetic rubber coatings such as polychloroprene (trade name *Neoprene*) and chlorosulphonated polyethylene (*Hypalon*) are the materials originally used for air houses for military applications. These coatings have greater extensibility than PVC and so tend to be used with the more extensible fabrics such as nylon. *Neoprene* is graded on exposure to oxidation and sunlight. The durability is influenced greatly by the amount and type of pigment available to counteract u.v. light. Carbon fillers tend to give better durability although other colours are also quite feasible. *Hypalon* has much better resistance to sunlight and oxidation and can be produced in a variety of light colours, including white, which have good durability. *Neoprene* has better adhesion and mechanical properties than *Hypalon* so that it is feasible to apply a *Neoprene* coating to the base fabric and then use a finishing coat of *Hypalon* for good durability and appearance. A life of 8-12 years seems to be reasonably obtainable with these coatings.

PTFE is the newest coating material to be used in the lightweight coverings field. The basic raw material has a proven durability of at least 20 years in u.v. exposure tests in Arizona, and the indications are that the material has extremely good all round durability. Some early concern about microcracking of the coating due to shrinkage and fabric flexing has been overcome by the incorporation of glass microspheres into the coating to act as a lightweight filler. PTFE is probably the most inert plastics material available and does not need to rely on u.v. absorbers, pigments and flame-retardant materials being added to it to improve its performance. For this reason the accelerated weather test predictions of a real life of at least 20-25 years[8] are likely to be fulfilled, provided physical factors such as adhesion to the fabric and integrity of the coating can be maintained.

### Air permeability

For air-supported structures the coated fabric is required to have a low permeability to air. It is not generally possible to achieve low enough values with uncoated fabrics even with a very tight weave. For high pressure air structures a fairly heavy coating is required to prevent air loss over a period of time and the extension of the coated fabric under load and the performance of the seams can be significant factors. Synthetic rubbers have the greatest resistance to air permeability and are the coating materials generally chosen for these applications.

### Conclusions

In general it can be seen that there is a very close relationship between the design aspects of lightweight structures and the materials properties of the coated fabrics.

The three materials discussed in this article have different areas of use because of their different characteristics. PVC-coated polyester is an economic material and can be readily stressed out without sophisticated techniques. It has reasonable durability and is quite appropriately used for the majority of 'temporary' structures of this sort. Where more permanent structures with good durability and fairly predictable long-term performance are required then PTFE-coated glass fabric is most appropriate. Rubber-coated nylon is more appropriate for high pressure air structures and for demountable structures where the material is likely to receive a great deal of flexing.

An adequate range of materials exists for the majority of applications but future developments are expected to concentrate on lighter weight materials with enhanced durability and on high strength materials with increased light transmission.

### References

(1) SKELTON, J. Comparison and selection of materials for air-supported structures. *Journal of coated fibrous materials, 1* (April), pp. 208-221, 1972.

(2) HERZOG, T. Pneumatic structures: a handbook of inflatable architecture. New York, Oxford University Press, 1976.

(3) SEAMAN, R. N. *and* VENKATARAMAN, B. Utilization of vinyl coated synthetic fabrics in industrial applications. *Journal of coated fabrics, 5* (April), pp. 225-247, 1976.

(4) FRITZSCHE, E. Strain measurements on industrial fabrics for pneumatic structures. 1st International Colloquium on Pneumatic Structures, Stuttgart, 1967, pp. 137-141.

(5) SHIMAMURA, S. *and* TAKEUCHI, O. Mechanical behaviour of selected coated fabrics used in membrane structures in Japan. Proceedings of the 1971 IASS Pacific Symposium, Part II, on Tension Structures and Space Frames, Tokyo and Kyoto, Paper No. 6-1, pp. 493-502. Architectural Institute of Japan, 1972.

(6) HILSCHER, E. Problems with coated polyester fabrics. Annual conference of the Industrial Textiles Group of the Textile Institute in Manchester, June 1975.

(7) HAJEK, M. *and* HOLUB, Z. Some problems concerning the testing of materials for pneumatic structures. 1st International Colloquium on Pneumatic Structures, Stuttgart, 1967.

(8) BIRD, W. W. Teflon coated fibreglass – an outstanding new material for fabric structures. Symposium of the International Association for Shell and Spatial Structures, 1978.

(9) KRUMMHEUER, W. Mechanical properties of PVC-coated polyester fabrics and their joints. Industrial Fibres of Enka, Enka AG, Industrial Yarns Institute, Wuppertal.

(10) FRANCHI, G. *and* OMACINI, A. Polyvinyl chloride compounds in the manufacture of air supported structures. Conseil International du Bâtiment pour la recherche, l'étude et la documentation and the International Association for Shell Structures, International Symposium on Air-supported Structures, Venice, 1977.

(11) MEWES, H. Coated fabrics made from high-strength polyester filaments for air-supported structures and lightweight surface-supported structures. Heidelberg: Stassenbau, Chemie und Technik Verlagsgellschaft m.6.H, 1969.

(12) MORTON, W. E. *and* HEARLE, J. W. S. Physical properties of textile fibres. Heinemann, 1975.

(13) HEARLE, J. W. S., GROSBERG, P. *and* BACKER, S. Structural mechanics of fibres, yarns and fabrics. Vol. 1. New York: Wiley Interscience, 1969.

# Form finding, control and modification for tension structures

## Alistair Day

The shape of tension structures is often established by using soap bubbles to generate the form of the structure. Bubbles are used as they provide a pleasing form and also give a structure which has curvatures appropriate to a uniformly tensioned membrane. With the advent of finite element it is now possible to simulate the form-finding of the structure by calculation and, using a program based on the outline given in Ref. 1, the calculations which can be made are an exact parallel of blowing or stretching of soap bubbles. An example of a form found in this way is shown on Fig. 1. The main problem now is not the finding of the form but the realization of the uniform tension.

The structure is formed from panels of fabric which are welded together. These panels are cut from rolls and to do this, cutting patterns are required. One possible way is to form the surface and then derive a geometric expression for the surface or a set of co-ordinates for a grid on the surface which is the general approach used if the form has been found from an actual soap bubble. However, with finite element representation of the structure, it is obviously possible to try to form the cutting pattern from the finite elements. The finite element representation shown in Fig. 1 cannot be used in this way because the plan projection of the elements is very irregular and it is not possible to develop strips of fabric to correspond to groups of elements. The arrangement of finite element in this figure arose from an initial regular grid which distorted to that shown in the figure in the course of calculation. This is because the calculations are simulating a soap bubble by flat facets which have to fit a surface which in nature would be continuously curved. To fit this curved surface the elements tend to become distorted as any sharp curves in the natural shape tend to be cut off by the flat elements taking up the position of the chord across the curve. For this reason the development of the surface must be controlled.

### Design of the Papal canopy

To demonstrate how this control is obtained, the design of the canopy for the Papal Mass in Phoenix Park in Dublin will be used. After discussions with the architects, Scott Tallon and Walker, it was decided that the canopy would be rectangular in plan with a central raised point. Views of the finished structure are shown on Figs. 2 and 3. The form-finding calculations for this assume a soap film supported by a rigid boundary, representing the steel perimeter of the structure. The film is then lifted to a central point which in the real structure is provided by a tie to the steel portal which can just be seen in Fig. 2. The design of the canopy now consists of developing a set of cutting patterns from which fabric can be cut which, when welded together, form this shape. A plan view of the elements which were used in this design is shown in Fig. 4. This plan reflects the first constraint which must be considered when deriving a set of finite elements. Because the fabric must be made in long strips whose width must not exceed the width of the fabric rolls, the elements must be arranged in strips which will eventually develop patterns of less than this width. As a soap bubble is being used for this form-finding, a number of different element layouts are feasible. However, with the constraint of the final cutting pattern borne in mind, it is seen that the

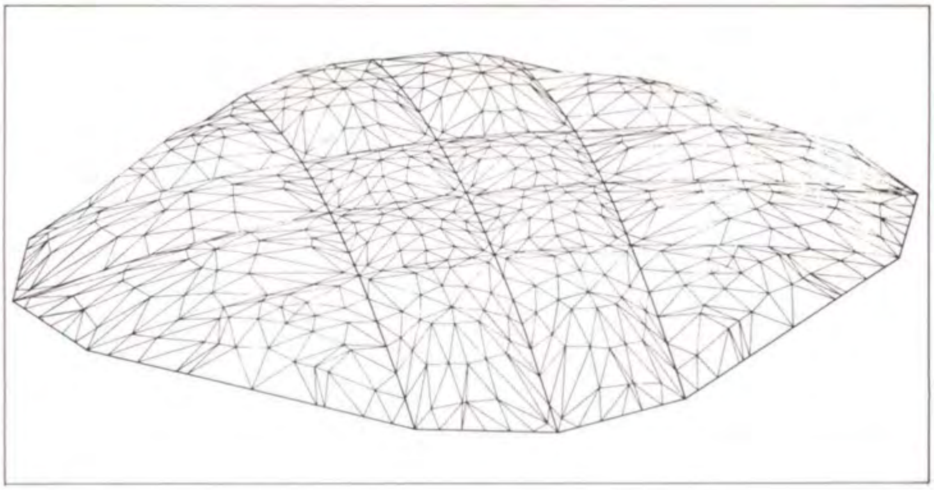


**Fig. 1**
60m square cable/membrane roof in Corsica

**Fig. 2**
Papal canopy, Phoenix Park, Dublin
(Photo: Harry Sowden)

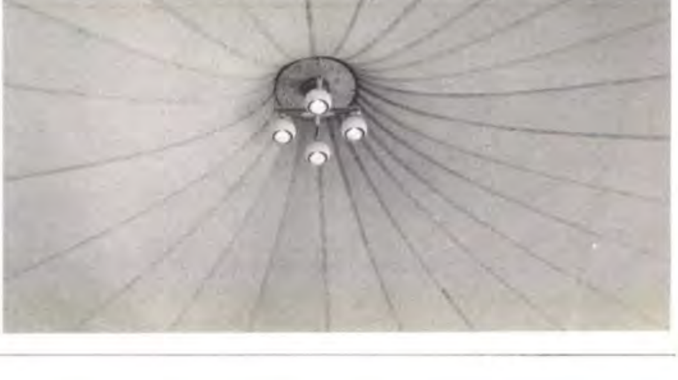


**Fig. 3**
Papal canopy, detail
(Photo: Harry Sowden)

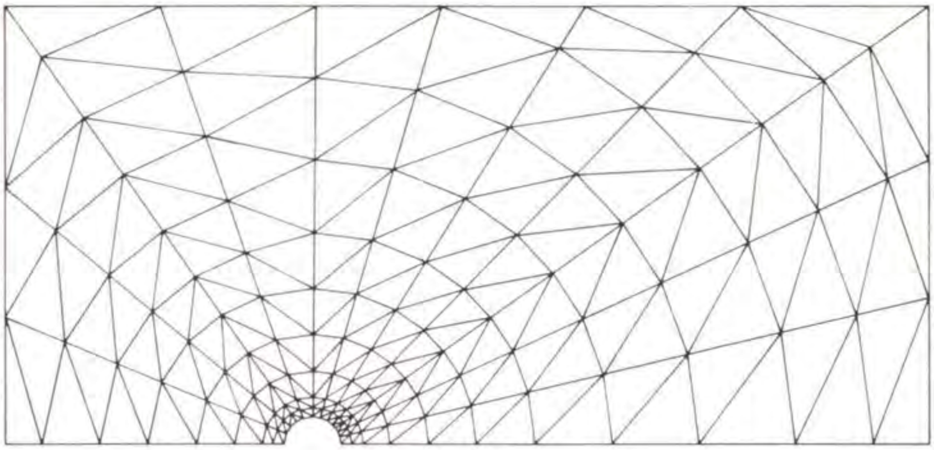


**Fig. 4**
Papal canopy, plan view of elements

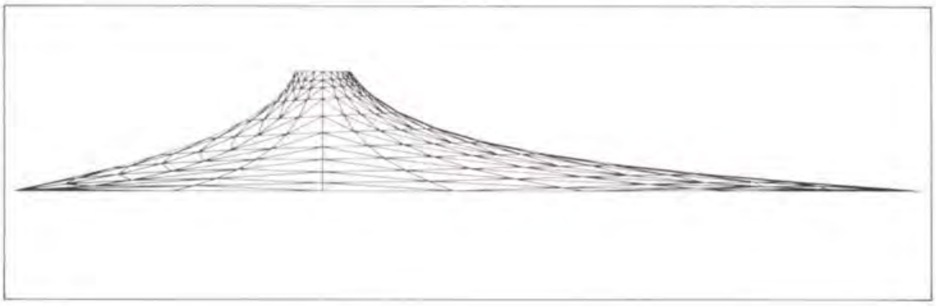


**Fig. 5**
Papal canopy, elevation of elements

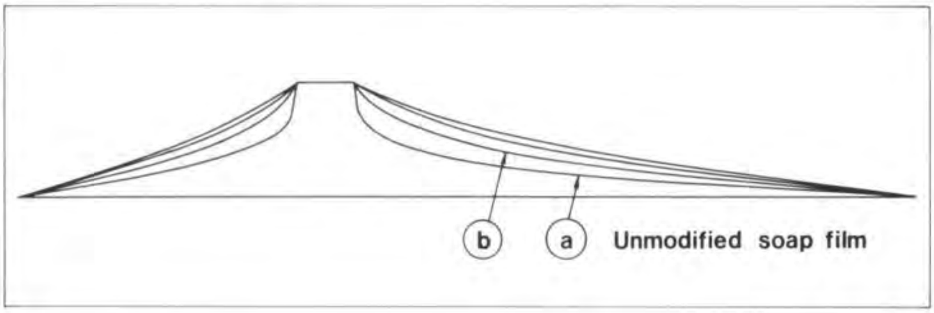


**Fig. 6**
Papal canopy, various profiles

elements are arranged in triangular sets with straight edges, the intention being that the straight edges become the edges of the individual pieces of fabric which are welded at these edges to form the complete structure. If this plan of elements is now considered as a soap bubble and the central ring lifted from the plain of the rectangular boundary the elevation (a) shown in Fig. 6 will be obtained. If the elements are lifted without any constraint it is found that the initial straight lines between what will be the panels do not necessarily remain straight and can become irregular. This is quite unsatisfactory if the triangular groups of elements are used to derive a cutting pattern, because a smooth curve is essential along the edge of the fabric pieces. To overcome this, the position of the radial lines must be controlled during the development of the soap bubble so that the projection of these lines remains straight. This is done by suppressing any lateral deflections of all the nodes. This means that when the cutting pattern is developed from these strips a smooth curve will be obtained along the edge. It should be noted that, although the projection of the lines is straight, the development of the lines in general will be curved. Only in the special case of a cone will the developed lines be straight. As noted above, the elevation of the resulting soap bubble is shown in Fig. 6. To carry out calculations on this form it is presumed that the geometric form of the soap bubble is 'frozen' and assumed to be the initial position of the structural fabric. Calculations can now be carried out on this model of the fabric to test its ability to withstand the applied loads and also to develop the prestressing of the fabric. It is the latter operation which proved to be the most difficult to realize in practice. In this structure there are two ways in which the fabric can be tensioned – either by a lateral extension of the boundary or by a vertical lifting of the central disc.

### Difficulties in tension

Various combinations of these tension operations were tried but it was found impossible to generate a uniform tension in the structure. The best that could be obtained had the tensions in the radial direction and about $\frac{1}{3}$ of those in the hoop direction. This was due to the very sharp curvature just below the neck of the structure. A prototype of this structure had been fabricated, based on a preliminary form-finding exercise, and when the prototype was stressed similar difficulties in tension of the structure were experienced. Moreover, in the fabrication of the structure the sharp curvatures just below the highest point, i.e. the neck of the structure, caused problems in the welding of the seams in this area, specifically in the short weld lengths which were required to follow the curves in the edge of the fabric pieces.

Examining the elevation of the soap bubble form shown on Fig. 6, the sharp curvature at the neck can be seen and, purely for aesthetic reasons, would seem to be too sharp. Thus, it would appear that for three reasons, namely the appearance, the stressing and the fabrication, it would be desirable to have a less sharp curve in the profile of the structure. The profile (a) in Fig. 6 is that obtained from a uniformly tensioned soap bubble. Thus the modification of the profile would appear to require a non-uniformly tensioned soap bubble. This is impractical in the calculation method at present being used because there is no provision for orthotropic soap bubbles in the triangular elements modelling the surface.

In order to achieve the non-uniform tension for this design, the most practical approach appeared to be the use of imaginary temporary cables lying along the boundary between the intended fabric panels, i.e. the radial line on Fig. 4. These cables would have zero stiffness so that they would behave in a manner similar to the soap bubble elements. These cables are given a prestressing force which effectively produces orthotropic stresses in the surface representing the soap bubble.

Various tensions were assumed in the imaginary cables and calculations were made for each of these tensions which produced the profiles shown on Fig. 6. The lowest of these profiles is the unaltered soap bubble, i.e. effectively no cable force. With progressively increasing forces, the profile becomes flatter as seen on Fig. 6.

The profile marked (b) was chosen as this appeared to be most aesthetically pleasing. The calculation procedure was then carried out whereby this new surface was frozen to represent a fabric surface. The elevation of the element making up the surface is shown in Fig. 5. The temporary cables were taken out so that the surface represented fabric alone and then the varying stressing operations were performed on this new surface. It was found with extensions of the boundary and raising of the disc, that a nearly uniform stress could be generated in the whole surface.

The successful stressing of the modified shape indicates that an unmodified soap bubble is not necessarily the best shape for all structures. The soap bubble surface appears to be quite satisfactory for surfaces such as the hyperbolic paraboloid. The reason for this appears to be the fact that these surfaces are stressed by uniform extensions in two directions, unlike the conical surface which is additionally stressed by a force which is normally to the plane of the boundaries.

The technique of introducing zero stiffness temporary cables has been used to control the mesh pattern and form of a tent surface held between boundary cables, and appears to be a general method which can be used for form modification.

### Reference

(1) DAY, A. A general computer technique for form finding for tension structures. IASS Conference 'Shells and spatial structures, the development of form', Morgantown, West Virginia, USA, August 1978.

# Form definition for the Bridge of Don exhibition and sports centre, Aberdeen

Alistair Day

### Introduction

The oil industry holds an exhibition each year which is devoted to off-shore oil exploration and its venue alternates between Aberdeen and Stavanger. When held in Aberdeen, temporary structures have been erected on each occasion to house it. A permanent multi-purpose hall which could be used for other exhibitions and for sports such as football and athletics is proposed by Grampian Regional Council. The floor area of the hall was determined primarily by its role as an exhibition centre but if used for football and athletics a clear span is necessary. Mr. J. Arnott, Architect to the Grampian Regional Council, determined that an air-supported structure would be the most suitable for the hall and commissioned a design study in September 1979 to establish the structural and programme feasibility of such a hall. This study was followed by detailed design work.

This paper outlines the work which was done to define the two major items in the roof of the hall, namely the geometry of the cables and infill fabric panels.

### Form finding of the cables

The factors or variables which governed the form of the cable layout were:

(1) The option of using a ring beam or ground anchors to restrain the cables

(2) Alternative grid layouts for the cables

(3) Variation of cable spacing in the grids

(4) Clearance required during accidental inversion of the roof.

As it was known that granite occurred close to the surface at the proposed site, the option of carrying the reactions to the cables directly to the ground was available. Scheme designs for this arrangement were made which showed that the viability of these arrangements depended critically on the actual depth of the granite below formation level. In the event, when the site investigation was carried out, it was discovered that the condition and level of the granite was more variable and occurred at greater depths than expected, which meant that the option of directly anchoring to the ground became uneconomic when compared with a ring beam solution, and all further development was based upon an arrangement of cables whose reactions would be resisted by a ring beam on the perimeter of the roof.

Given the constraint of a ring beam, some types of grids are more appropriate than others and certain grid arrangements appear to be more sensitive to imposed loadings. With the development of the internal planning of the structure, an oval plan shape evolved with major and minor axes of 200m and 160m. The plan shape of the ring beam depends on the cable layout, the beam forces arising from the cable forces and rationalization of the planning of the cladding between the ring beam and ground level. Although the beam and cable forms are interdependent it is easier for this discussion to consider them separately. If the cables are arranged parallel to the diagonal of the circumscribing rectangle, a beam with no bending moments can be derived for a uniform internal pressure. From an assumed layout of cables, a ring beam shape was derived and used for calculations of the cable forces; and then from the cable anchorage forces, the bending moment and axial force envelopes for the beam were calculated for various load combinations. The plan shape of the ring beam was then modified to minimize the bending moments and adjusted to give a rational column and cladding layout. The beam shape is shown in Fig. 1.

Within this general form the spacing of the cables can be varied. Essentially, two main variations were considered.

In the first, the cables form a grid of main cables which have been pitched at 12m centres. In the alternative, the main cables are pitched at 24m centres with subsidiary cables reducing the span of the intermediate fabric panels. The latter arrangement has erection advantages as larger pieces can be erected in one operation. However, a significant constraint on using this arrangement is the clearance which is required during accidental inversion of the roof as the sag of the fabric below the level of the main cables is increased. If the specified minimum clearance is to be maintained, this requires the cable anchorages to be raised with the consequence that the columns and cladding on the perimeter are increased in height. It was found that the additional cost of increasing the height was greater than the apparent savings obtained in the fabrication and erection of the roof, so that the decision was made to design the roof as a set of main cables directly supporting the fabric panels.

The above consideration led to a plan configuration of the main cables and perimeter ring beam as shown on Fig. 1. The rise which was available on the main cables had been determined during the preliminary designs for the plan layout and ring beam level so that the next design stage was the form finding of the cables.

Essentially, there are two ways of defining the form of the cables. The first is by arbitrary fixing a geometry which is defined from a set of geometric rules, for example that the cables lie on the intersection of vertical planes and a catenoid. Alternatively, an automatic form-finding process is used for certain prescribed factors. For this design the latter approach was chosen and the form-finding was carried out by determining the shape of a grid of cables in which the force in the cables would remain equal for an internal pressure. This form-finding was carried out using a programme based on the methods described in reference 1 and the results of the form-finding calculations were a set of co-ordinates of the intersections of the nodes of the cables.

Forming the cables in this manner produces a surface in which the central portion, where there is a two-way grid of cables, is essentially the cap of a sphere with the cable lines running on great circles of the sphere. Between the central portion and the boundary the cables lie on a series of circular arcs of varying radii. The difference between the plan projection of the cables and chord, seen on Fig. 1, shows the horizontal curvature developed.

If the cable and panel dimensions are defined by an arbitrary surface then when the roof is inflated, it is likely that the panels will deform when the cables adjust to their equilibrium position. However, with the surface found in the manner outlined above there is no tendency to deform. If the fabric panels are patterned to fit the cable positions, then in the normal inflated position the boundary of the panels will be geometrically similar to the geometry used to develop the patterns, and there will be no shear deformation in the corners tending to produce wrinkling.

### Form-finding for the fabric

In the design of the fabric panels which span between the cables, the general rise required to resist the maximum suction pressures which the panel will experience is related to the fabric strength. However, it was found during the design that the factor which determines the detailed shape of the panels was its

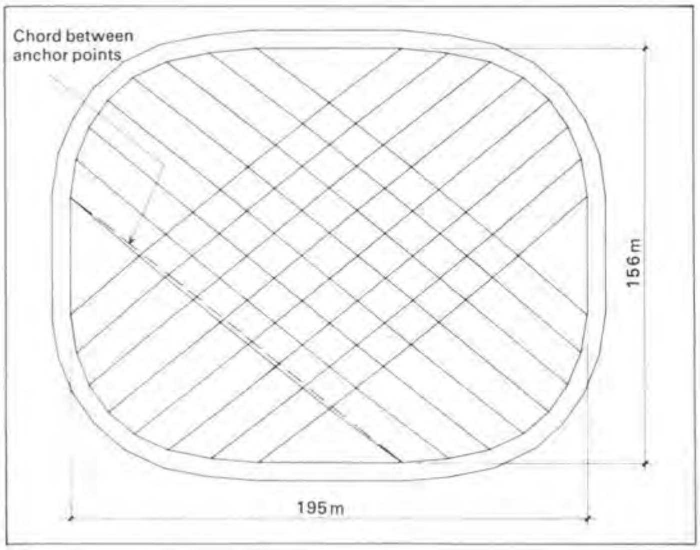


**Fig. 1**
Ring beam shape

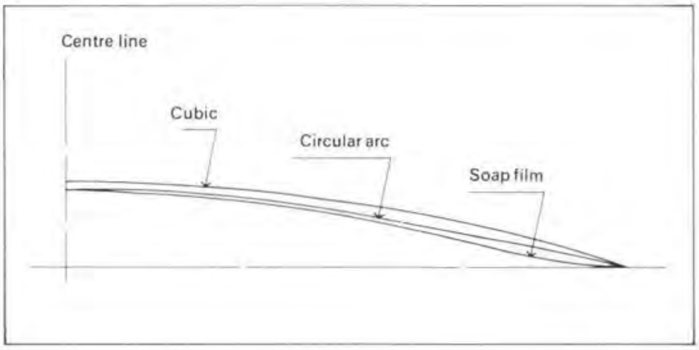


**Fig. 2**
Alternative profiles

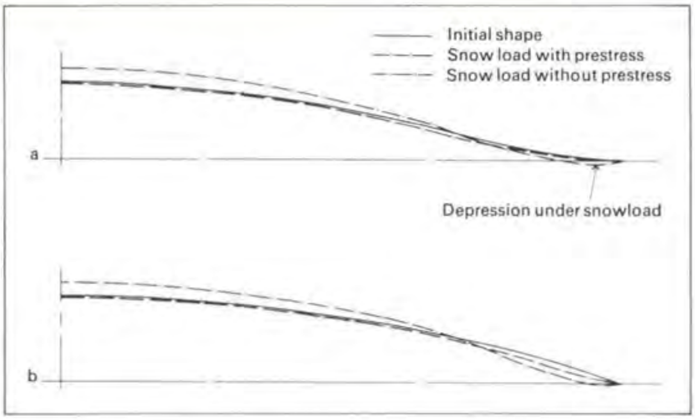


**Fig. 3a-b**
**a)** Soap film profile
**b)** Cubic profile

behaviour for a partial snow load. Problems have been experienced in air-supported structures with ponding occurring at corners of the panels when snow accumulates at these points. As the snow thaws, and if there is any depression in the fabric, the melt water accumulates in the depression and causes it to increase it in depth. A run-away condition can develop in which the increasing depth of the depression attracts additional water and this cycle can continue until locally there is such a large accumulation of water that the panel can fail. Thus one of the design criteria is to prevent this occurrence.

Having established the boundaries of a typical panel from the cable geometry the form of a panel, for example one of the lozenge shape panels in the centre area, can be determined by using a soap bubble analogy for the membrane. In this approach the membrane is replaced by finite elements which are equivalent to a soap film, and the form determined by applying the internal pressure to this film. The profile between the centre and one corner of one of the lozenge panels found by this method is shown in Fig. 2. Taking this surface and considering it as fabric, calculations for various loading conditions can be carried out.

For the interal pressure load case it is found that the stresses in the elements are now no longer biaxially equal as they were when the elements represented a soap film. This is due to the restraint of the clamped boundaries where the elements cannot strain when they represent fabric but can when they represent a soap film. This discrepancy between the idealized film surface and the corresponding fabric has been found on other structures and modifications of the surface have to be made to obtain the uniform prestress desired.

The greatest difference in stresses occurs in the corner of the panels to the extent that the stress in the direction of the diagonal of the panel can become zero, i.e. the fabric will wrinkle in this direction, and this is found to occur in practice.

If this fabric surface has an internal pressure applied together with external loads representing an accumulation of snow in the corner, it is found that a depression will occur in the corner. This is shown on Fig. 3a and appears to be primarily due to the lack of stress in the diagonal direction. To overcome this problem the first approach which was adopted was to consider prestressing the edge of the panels. If calculations are now carried out with edge prestress of the appropriate amount, near uniform biaxial stress can be obtained in the corner for internal pressure and when loaded by the snow load the depression in the corner is markedly reduced as shown on Fig. 3a. Although this approach appeared to considerably improve the behaviour of the panel, the edge of the panel was only marginally above the horizontal position, i.e. it is prone to ponding. The fundamental difficulty of this particular fabric profile is the very flat run out in the corner which is characteristic of a soap film going into a corner. This effect has been noted on a number of structures which have been designed, e.g. a grid shell which was used to form a dome over a rectangular space. A profile which does not have this flat characteristic would be more appropriate to use for these panels. There are two ways to develop such a profile. The first is to use a device of putting imaginary cables in the surface which are given non-uniform properties so that, in combination with the surface tension of the soap bubble, a surface which departs from the soap bubble shape can be formed. This device was used successfully in the design of canopies for the Papal Mass in Phoenix Park, Dublin. This canopy was an anticlastic surface and the use of the imaginary cables in the soap film allowed it to be manipulated quite readily to form a family of surfaces. The corresponding soap film for the panels for the air supported structure are synclastic and use of the imaginary cables is not so readily applicable for this type of surface, so it was decided to use the alternative procedures of prescribing a geometric shape for the fabric surface. Two shapes were tried, diagonal profiles of which are shown on Fig. 2. It is seen that these profiles raise the fabric above the profile developed from the soap film. Calculations using these profiles showed that both were significantly better than the soap film profile, but as the better one is the one marked 'cubic', on Fig. 3, it was adopted for the design of the fabric panels.

The stressed profiles for this shape are shown on Fig. 3b where it is seen that an adequate shape is obtained in the corner.

### Comments and conclusions

The behaviour of the structure under various wind and snow loads coupled with the internal pressure has only been indirectly noted. The behaviour will not be discussed further save to say that structural calculations and wind tunnel modelling have shown that the forms derived result in cable and fabric forces which have satisfactory material factors.

This paper has discussed two aspects of the design of the roof of the Bridge of Don Centre, in the case of the cables to illustrate the general approach for automatic form-finding and in the case of the panels to overcome a detail design problem. These discussions illustrate the approach being used in this and other similar roofs being designed.

### Acknowledgements

The author is grateful to Mr. Arnott for permission to draw on the work done on the design of the Bridge of Don Centre and to Terence Haslett, Chris McCarthy and David West who carried out most of the work on the form-finding and patterning.

### Reference

(1) DAY, A. S. *and* BUNCE, J. The analysis of hanging roofs. *The Arup Journal, 4* (3), pp. 31-32, 1969.

### Editor's note

A version of this paper was given at the Institution of Structural Engineers Symposium on air-supported structures, June 1980.

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# Environmental considerations of lightweight structures

## John Campbell

### Introduction

The term lightweight structure is applied in general to buildings which vary a great deal in type and appearance. There are structures which have a tent-like form, inverted hanging chains like the Mannheim Dome, inflatables like the Bubble Theatre and, most recently, the air-supported structure in which the roof is supported by air pressure created by fans.

This last type is affected by the same range of environmental parameters as the other types of lightweight structure but, in addition, has to be designed for low air leakage rates and needs additional fans to provide the air pressure necessary to maintain inflation. This paper, therefore, concentrates on air-supported membrane structures but most of the comments are also applicable to the other structural forms.

An interesting problem which is posed by most examples of this type of building is their sheer size. Large volume, thermally lightweight buildings are not new and have been with us for some time. Typical examples are Jumbo hangars and exhibition centres like the National Exhibition Centre. In these cases, however, the structure is not light-weight and there are no restrictions on the location of plant. With lightweight structures this is not the case and, in most instances, it is necessary for the air distribution equipment to be installed either at low level or at the perimeter.

The structure itself does not directly affect the internal environment in any way. If, however, the structure is lightweight, the implication is that the building envelope too must be of lightweight construction and this in itself starts to narrow down the options open to the building services designer. This does not mean that buildings of this type do not have widely varying thermal characteristics. The envelope can vary between being highly insulated and opaque at one extreme to uninsulated and translucent at the other. It simply means that it is not feasible to use thermal inertia as part of the design insofar as the roof is concerned.

The internal convective flow patterns are in some ways the most difficult thing to predict. The situation with high levels of insulation is fairly straightforward as it is an extension of present knowledge and is directly comparable with large conventional buildings of a thermally lightweight nature.

When dealing with high 'U' values (i.e. high heat loss) surfaces, the situation is not as clear cut as it would at first seem. Most of the work carried out in this field[1] has been aimed at providing comfort in office areas with vertical glazing. Heat is provided under the

**Fig. 1**
BP Dyce Tent
(Photo : Ove Arup & Partners)

**Fig. 2**
Bundesgartenschau Mannheim
(Photo : Robert Häusser)

glazing and, in some cases, double glazing is also used. These measures affect the amount of air movement in the space by counteracting cold down draughts.

With a translucent roof this option is not available to the designer other than by directing jets of hot air along the underside of the roof and increasing the heat loss to an excessive degree. Floor level supply therefore, when feasible, seems to offer the best solution as the hot air introduced at floor level will have to rise past the occupants before it can lose its heat at roof level.

### Design conditions

In the United Kingdom there are basic legislative requirements to be met insofar as the internal temperature of buildings is concerned and these require that a minimum temperature of 16°C be provided. Unless some relaxation can be obtained on this point 16°C will have to be the design condition for these structures.

This point is worth pursuing further. In these energy-conscious times legislation has also been used to define maximum temperatures in spaces that may be achieved legally. These temperatures are seldom achieved in practice. Most buildings are still heated to 22°C when legislation calls for a maximum of 18°C, because most workforces today will not accept that 18°C constitutes a comfort condition for their operation. What is really needed is a method of assessing the comfort range applicable for a given operation so that heating may be applied to maintain the temperature at the bottom of the range and cooling (when required) to maintain the upper limit.

An additional factor which must also be taken into account is the type of clothing worn by the building occupants in question. In an office environment in the UK this varies between 'Jacket on' and 'Jacket off' under normal circumstances with the removal of a tie in addition in extremely hot weather.

In the case of a sporting event, the spectators will be wearing an overcoat in winter and a short sleeved, open necked shirt or blouse in summer. Roofing in a sports stadium will not necessarily alter the way spectators dress and allowance for this can be beneficial insofar as energy consumption is concerned.

An equation which takes into account these different parameters has been developed by Fanger[2] and allows the calculation of comfort conditions to be made.

The equation for thermal comfort is expressed as shown in the panel below :

$$\frac{M}{A_{Du}}(1-\eta)-0.35\,[43-0.061\frac{M}{A_{Du}}(1-\eta)-p_a]-$$

$$0.42\left[\frac{M}{A_{Du}}(1-\eta)-50\right]-0.0023\frac{M}{A_{Du}}(44-p_a)-$$

$$0.0014\frac{M}{A_{Du}}(34-t_a)=$$

$$3.4\,.\,10^{-8}f_{cl}\,[(t_{cl}+273)^4-(t_{mrt}+273)^4]+f_{cl}h_c(t_{cl}-t_a)$$

$$\text{where } t_{cl}=35.7-0.032\frac{M}{A_{Du}}(1-\eta)-0.18\,I_{cl}\left[\frac{M}{A_{Du}}(1-\eta)-\right.$$

$$0.35\left[43-0.061\frac{M}{A_{Du}}(1-\eta)-Pa\right]-0.42\left[\frac{M}{A_{Du}}(1-\eta)-50\right]-$$

$$\left.0.0023\frac{M}{A_{Du}}(44-p_a)-0.0014\frac{M}{A_{Du}}(34-t_a)\right]\qquad(^{\circ}C)\qquad(32)$$

This result gives the desired comfort temperature for a specific set of conditions. It does not, however, allow the designer to swing the temperature either side of the ideal value to minimize energy consumption and obtain an idea of the satisfaction level that will be obtained. These equations have been modified to give an idea of the occupancy reaction in terms of a predicted mean vote on the basis of the ASHRAE scale.

—3 cool
—2 cool
—1 slightly cool
0 neutral
+1 slightly warm
+2 warm
+3 hot

The predicted mean vote can be found from the formula shown on the right.

These formulae are quite complex and lend themselves most readily to solution by computer, but for the purposes of comparison a man standing watching a sporting event in winter wearing a coat or in summer wearing an open neck shirt will ideally want a temperature range from 16°C to 26°C. If, however, a slightly cool condition is allowed in winter and a slightly warm condition in summer this band is now from 8°C to 28°C. These temperatures are typical ones and are intended only as a guide. The equations themselves should be used to determine the correct temperatures for a given application, or, alternatively, the degree of discomfort that will be felt by the users if the building is not conditioned. In addition the equations themselves should only be applied by someone with a reasonable understanding of comfort conditions. It is possible to make the equations balance by using extreme values of the variables and there are limit conditions for each of these which can cause discomfort in their own right if exceeded.

The degree to which discomfort should be accepted also requires discussion. These lightweight structures can be used for two purposes. They may be an enclosure for a type of operation that would normally be carried out in a conventional building, or alternatively and also more probably, they will be enclosing an operation traditionally carried out in the open air.

It is this second approach, that of an 'Enclosed Open Space' activity, that warrants the closest inspection. Here the roof is not intended to provide comfort, but to prevent cancellations in times when the extremes of climate (principally snow and rain) would make it impossible for events to take place. In this case both spectators and participants are normally prepared to be hot in summer and cold in winter and, whilst the enclosure itself will probably create increased expectations on the part of users, a PMV of +1 to —1 would seem to be quite acceptable in this case. There is also a certain amount of precedent for this approach as no one expects a multi-storey car park to be heated to 16°C.

More conventional uses of lightweight structures will result in most cases in the selection of more conventional temperature ranges for two reasons :—

(1) The clothing worn will not vary greatly between summer and winter.

(2) Discomfort even to a small degree will not be acceptable.

In addition it may not even be wise to attempt to change the degree to which temperature swing is acceptable. If increasing the level of discomfort were to increase the number of mistakes made by the building users in their work, it could well be that this would, in the long run, be more expensive than the additional energy, not only to the building owner but also to the community at large.

$$
\begin{aligned}
PMV = (0.352 \exp[-0.042\,(M/A_{Du})] + 0.032)\Big[&\frac{M}{A_{Du}}(1-\eta) - \\
&0.35\,[43 - 0.061\frac{M}{A_{Du}}(1-\eta) - Pa] - \\
&0.42\,[\frac{M}{A_{Du}}(1-\eta) - 50] - \\
&0.0023\frac{M}{A_{Du}}(44\text{-}Pa) - 0.0014\frac{M}{A_{Du}}(34 - ta) - \\
&3.4\times 10^{-8} f_{cl}\,[(t_{cl}+273)^4 - (t_{mrt}+273)^4] - f_{cl}\,hc(t_{cl}-t_a)\Big]
\end{aligned}
$$

where $t_{cl}$ is determined by the equation

$$
\begin{aligned}
t_{cl} = 35.7 - 0.032\frac{M}{A_{Du}}(1-\eta) - \\
0.18\,I_{cl}\,[3.4\times 10^{-8} f_{cl}\,[(t_{cl}+273)^4 - (t_{mrt}+273)^4] + f_{cl}\,h_c\,(t_{cl}-t_a)\,] \quad (^\circ C)
\end{aligned}
$$

and $h_c$ by:

$$
h_c = \begin{cases} 2.05\,(t_{cl} - ta)^{0.25} & \text{for } 2.05\,(t_{cl}-t_a)^{0.25} > 10.4\sqrt{V} \\ 10.4\sqrt{V} & \text{for } 2.05\,(t_{cl}-t_a)^{0.25} < 10.4\sqrt{V} \end{cases}
$$

**Fig. 3**
Bubble Theatre
(Photo : Pentagram)

**Fig. 4**
Bridge of Don
(Photo : Ove Arup & Partners)

## Energy consumption

Most of the Western industrial countries have regulations which govern the energy consumption of buildings. In the United Kingdom, these take the form of Building Regulations governing the maximum 'U' value that can be used. It is possible to deviate from these when desired but only if it can be demonstrated that the energy consumption of the proposed building will not exceed that which would take place if the standard 'U' values are used. This would seem at first thought to be at variance with the lightweight translucent concept now becoming popular. This is not necessarily the case. High levels of insulation presuppose that heat is being introduced in large quantities to warm the space, as insulation can only prevent the loss of energy if there is a noticeable temperature difference between the inside and outside of the building.

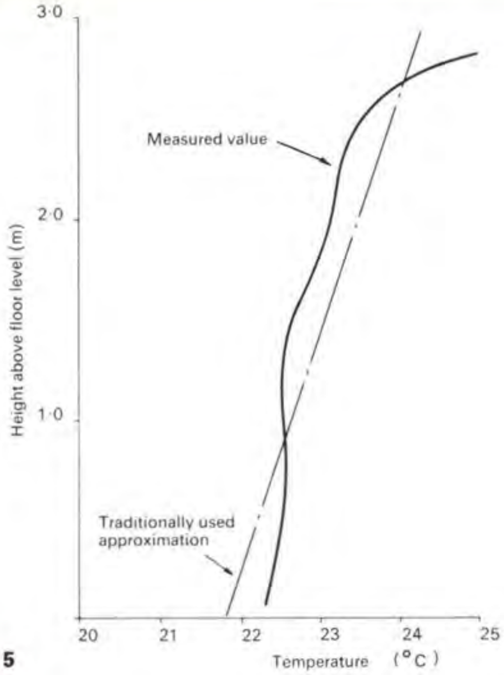

**Fig. 5**

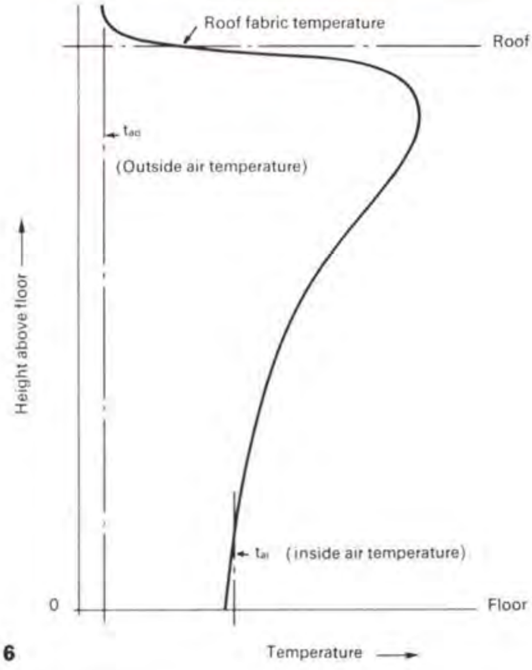

**Fig. 6**

The last item is very important. Given the right conditions it is possible to obtain daylight through a lightweight translucent roof thereby reducing the lighting consumption. In energy terms this can provide a considerable trade off against the heating energy consumption when one considers that the lighting is in use for 52 weeks a year whilst the heating is only necessary in winter.

One point that must be considered, however, is whether or not this type of structure is a building in terms of any regulations governing the temperature that must be provided internally. This affects the economic comparison considerably. No one is going to pretend that the thermal transmission through a roof with a 'U' value of 5.6 will not be greater than that of a roof with a 'U' value of 0.6. The point is that in reality this type of structure is not applied as an alternative to a highly insulated structure but as an alternative to an open space, to limit the effects of inclement weather. It is, therefore, more accurate to describe such buildings as an enclosed open space. It is energy-wasteful and unnecessary to consider heating this type of structure to normal building temperatures when the alternative can be temperatures below zero.

### 'deemed to satisfy' provisions

It is almost a foregone conclusion that a building with a translucent roof will not comply with the 'deemed to satisfy' provisions of Section FF of the Building Regulations. It is therefore necessary to produce a mathematical model of the proposed design and compare it with the consumption of a hypothetical building which would meet all the parameters of the 'deemed to satisfy' clause.

If the use of the building is fairly standard in terms of operating hours and occupancy, then a simple hand calculation may well suffice for the running costs. If, however, these patterns are unusual it will probably be necessary for a full scale simulation to be carried out.

The THERMAL[3] suite contains suitable programs for this exercise which can simulate component energy consumption and can produce the fuel consumption figures for both building types. It is, therefore, quite feasible to justify the use of a translucent air-supported structure in situations which are ostensibly those of an enclosed open space, or, alternatively, where the climatic moderation required from the enclosure is minimal.

The problems experienced with inflatables can be very similar to those of the air-supported structures but obviously insulated buildings can comply with the 'deemed to satisfy' provisions of Building Regulations without difficulty.

The roof 'U' value affects the building energy consumption indirectly in another way. For obvious reasons the roof has to be both watertight and airtight. This means that the transmission of water vapour through the structure is also limited, with the result that the moisture contained within the air can only be controlled by dilution ventilation. If the moisture level of the air in the space builds up until its dew point temperature is above the internal surface temperature of the roof, condensation will form.

The solution is simple. The dew point temperature of the air in the space must be kept below the surface temperature of the fabric or the surface temperature of the material must be kept above the dew point.

The first of these methods can employ large quantities of fresh air, mechanical refrigeration or adsorption dehumidification. The second will require the use of thermal insulation.

All buildings require some fresh air. This varies from the amount required for breathing to the quantities necessary for the dilution of toxic contaminants. If these volumes reduce the dew point adequately then there is no need for further action. If, however, the process is one which liberates large quantities of water vapour, then mechanical means of control may not prove adequate and thermal insulation will have to be introduced.

The alternatives are, therefore, either a translucent membrane with a high 'U' value which can provide natural light or a highly insulated sandwich and the best solution for a particular application will be that which reduces the condensation risk to acceptable levels and at the same time minimizes the energy consumption.

There are methods available involving differing degrees of complexity which enable the summer-time environmental performance to be evaluated. Most of these methods have been devised to cope with normal height spaces of between 3 and 4m and ignore stack effect. At the heights normally used with air-supported structures, stack effect* will play a substantial part and in fact the controlling force as far as stack effect is concerned is likely to be the heat loss promoted at roof level by the higher internal temperature. There is also another problem which is related to this one. That is the problem of humidity. Moist or humid air is less dense than dry air with the result that warm humid air will rise to high level. When this air cools in contact with the structure, the moist air will condense on adjacent surfaces if these are below the dew point temperature.

If a graph is plotted of temperature against stack height for an office the profiles shown in Fig. 5 are obtained. The relationship between the normally assumed value and typical measured values[2] is shown and it can be seen that the approximation works quite well for spaces of normal floor to ceiling height when the ceilings have a low rate of heat transmission.

Under steady state conditions the heat loss must, by definition, be equal to the heat gain and if the roof is the major area then the principal sources of heat loss will be:

$$Q = Q_{rf} + Q_a$$

where:

$$Q_{rf} = U_o A\,(t_2 - t_o)$$

$$Q_a = m\,C_p\,(t_a - t_o)$$

The stack effect is, therefore, limited to a certain extent by the roof 'U' value, as a rise in temperature will increase the heat transmission reducing the temperature at ceiling level as shown in Fig. 6. So far, the majority of designs have stayed within the limits of extrapolation, but the scope for this type of building is enormous and it is not going to be long before lightweight structures are erected which are far in excess of the size of the units being designed today. This could well exaggerate the situation described earlier and it does not take a great stretch of the imagination to see cold air falling from the roof and mixing with rising warm humid air to form clouds. The answers are straightforward. Industrial dehumidifiers can remove moisture without refrigeration and extract ventilation at high level will discharge humid air rather than drier air at a lower level. Quantification

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*Because of the decrease in density of air as its temperature increases, there is a tendency for warm air to rise creating a temperature gradient between the floor and the ceiling. This motive force is called the stack effect.

of the problem is, however, more difficult and if this expensive equipment is to be sized economically it is necessary to know the way in which absolute humidity varies with height.

This requires the application of the Navier Stokes Equations[4] and computer solution is almost essential.

The design of the ventilation and air-conditioning systems in general terms is much the same as with any other type of building with one notable difference. In the case of an air-supported structure the fans installed have to be suitable for maintaining sufficient pressure to support the roof.

This limits the choice to either aerofoil-bladed axial flow fans or backward curved centrifugal fans. The axial flow fan is relatively noisy but is also easier to silence. Both are equally suitable for this type of use and the ultimate decision will most probably depend on the most suitable plant room arrangement. There is a varying capacity requirement. This requirement could be met by automatic recirculatory dampers, variable pitch fans or using a greater number of smaller fans switched into operation as required. There is a need for pressure flap valves on the outlet from each fan to close when the fan is not in use to avoid leakage through non-operational fans.

One point to watch with axial flow fans is that at low pitch angles their characteristics become of the non-stall type and in addition, the ultimate pressure development at low flow rates can be very high when compared with the normal operating pressure. This point should be checked and, if necessary, high limit warning devices fitted.

The method of controlling the internal pressure is an area in which further development can be made. Most systems for this type of building create a certain differential pressure across the roof membrane. Snow loads can mean that the differential pressure requirement will have to vary and will require manual resetting. It could well be that the use of strain gauges on the cables might be a better method of controlling the internal pressure.

In general terms this type of building does not create any problems that cannot be solved by conventional design techniques. If however, the final design is to be the nost economic in operation, it is necessary that more knowledge is obtained of the convection patterns that occur in large volume spaces. This work is proceeding and will also be valuable for other applications such as atriums.

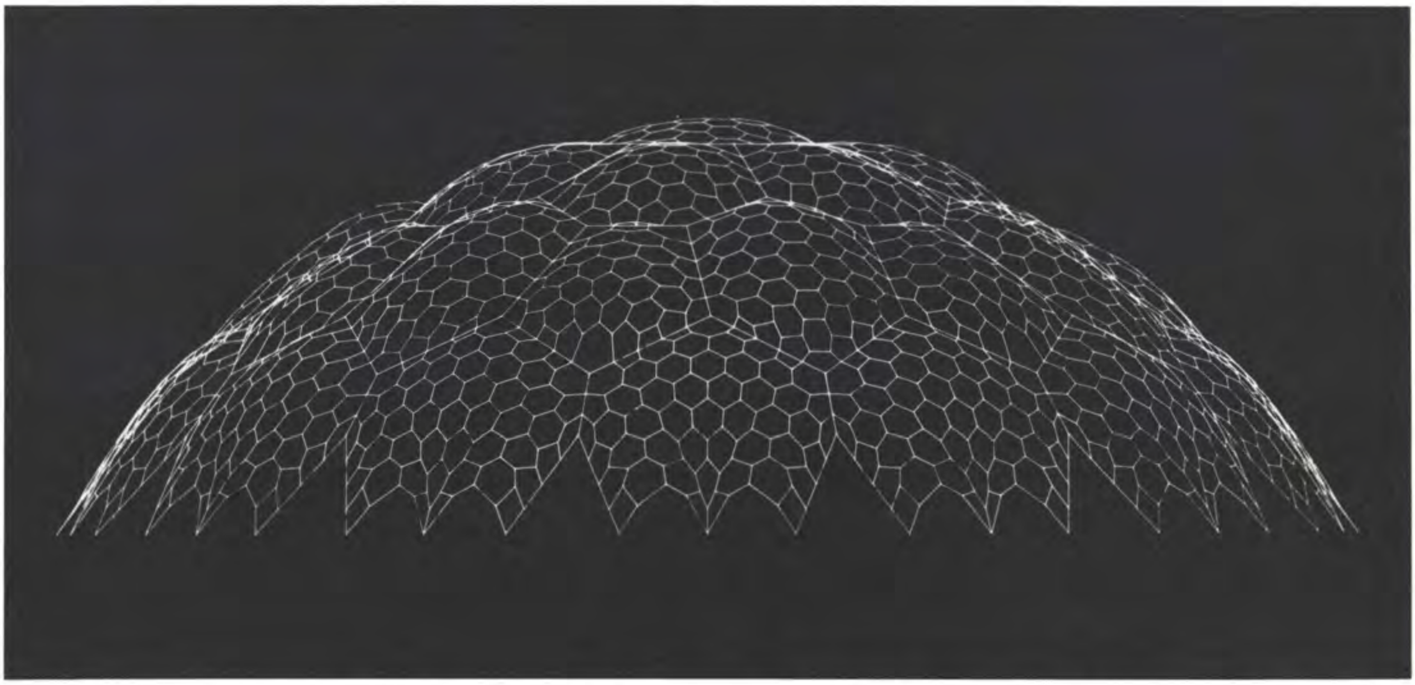
## References

(1) HOLMES, M. J. The effect of cold windows on room air distribution from ceiling diffusers. Project report 15/101. Building Services Research and Information Association, 1975.

(2) FANGER, P. O. Thermal comfort: analysis and applications in environmental engineering. Danish Technical Press, 1970.

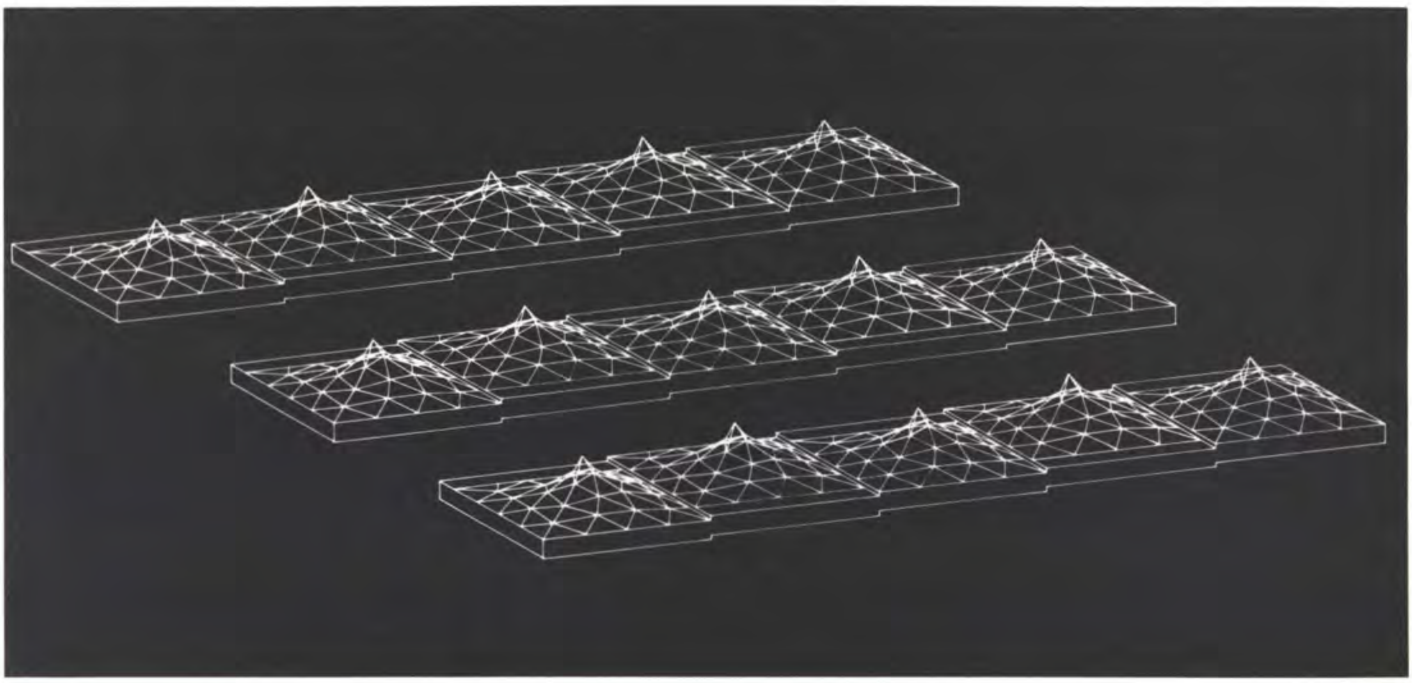
(3) OVE ARUP PARTNERSHIP. OASYS Computer. Thermal Suite.

(4) TRITON, D. J. Physical fluid dynamics. Van Nostrand Reinhold, 1977.



**Above:** A funicular (compression only) dome in tubular steelwork, 90m in diameter, with a 27m rise: computer drawing of half the structural model.

**Below:** Computer drawing of settling tanks, Nchanga Mines, Zambia



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