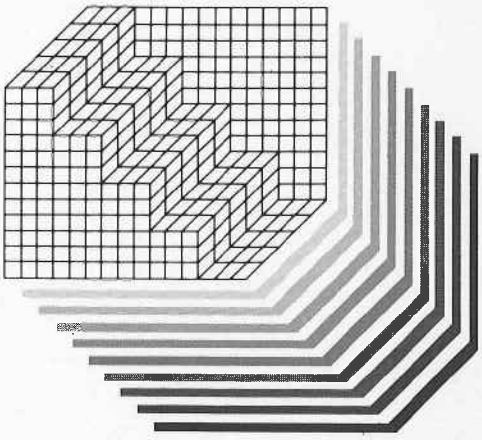
Patterns 5



Patterns 5

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May 1989
Published by Buro Happold Consulting Engineers

Editor Robbie McElhinney
Technical Editor Michael Dickson

Design Christian Hills Design
Filmsetting Sulis Typesetting
Print The Midway Press

Chariots of Fire

The two reasons for this article are closely related. This practice is devoted to advancing engineering – which is about value – achieving the most appropriate solution which is cheapest to construct and to maintain. There are many aspects to engineering problems, but an isolation of one objective can result in the generation of a design. Achieving structures of least weight is such an approach – development of tension structures the result.

Though only a small part of the practice's total work load, this field has been a hobby for most of us for very many years. We have not only designed and constructed a large number of tension structures worldwide, but we have taken a major role in studying and explaining their behaviour and in developing much of the current theory used for such structures. And among us, Ian Liddell's contribution to this work has been considerable. How better to celebrate his 50th birthday than by devoting most of an issue of Patterns to something he enjoys so much?

I first met Ian 29 years ago when he came from Cambridge, via Imperial College, to work on Sydney Opera House. The main reason we became friends was because we belonged to that small group owning motorcycles – he had an HRD Black Shadow, the back wheel of which could be taken off without dirtying your hands – very covetable! Ian always had style – such talent needed nurturing. I encouraged his transfer to Holst's extremely effective management training scheme, and seduced him back to join me when Trevor Dannatt won the UIA competition for the Conference Centre and Hotel for Riyadh in Saudi Arabia. We have worked together on an amazing range of structures ever since.

Ian Liddell is, in many ways, the most able engineer I know. While occasionally there are times when we would slow Ian's attack in some situation, there are many more times when we stand in amazement at his ability to conquer almost any engineering problem. More than that, it is his honesty of character which one admires him for, his loyalty and generosity. It was his house we all lived in when we first set up this practice. It is his ability which has so often carried us on. Certainly the occasion of Ian's half-century is a good moment to review a field of work to which he and all of us have devoted so much time in the last quarter of a century.

Tension structures – a brief history

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

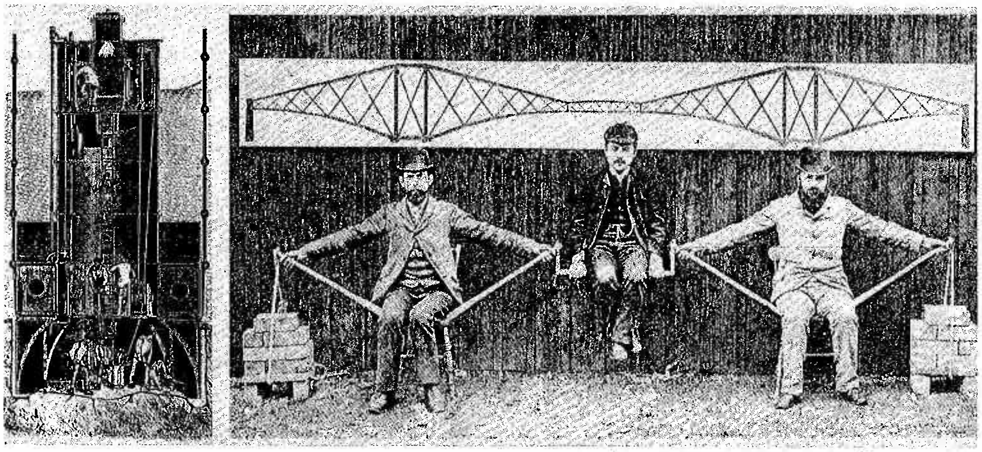


Fig 1.1 *Fowler and Baker's design for Forth Bridge*

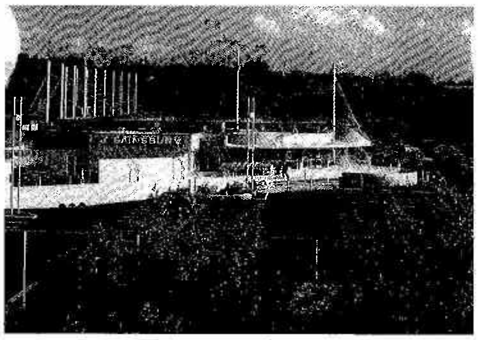


Fig 1.2 *Roof at Sainsbury's store, Canterbury*

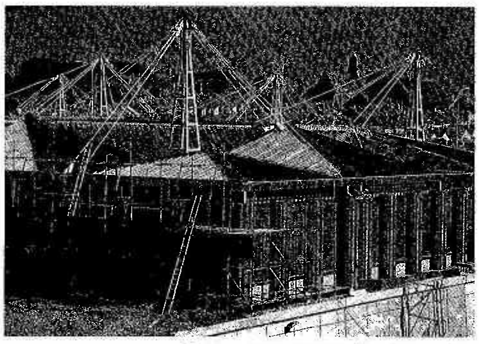


Fig 1.3 *Tesco supermarket roof, Bristol*

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

It is the membrane action roofs, surface stressed structures, which have represented a new approach to design. The traditional approach in buildings has been to reduce deflections and deformations to preserve the integrity of the claddings and partitions, and so loadings have been resisted by increases in forces within the structure. Conversely, a surface stressed structure aims to achieve a minimum increase in force level, and thus a minimum need for expensive material, by distributing loading by an acceptable change of shape. The challenge of this possibility has fascinated many able engineers, all my partners among them. It has provided a new frontier of design consistent with the drive for economy which our education has brought us up to strive for. But the shapes evolved are geometrically very sensitive and not within the public's visual experience. It is architects who have tackled and are tackling this latter problem. We provide the engineering possibilities which, in working together with the architects, advances building.

Though the tent is a very old building type and many schemes in the past have been proposed to develop

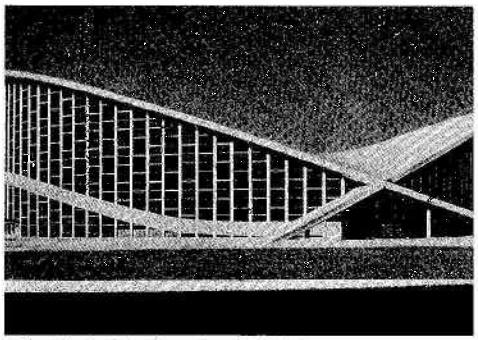


Fig 1.4 Saddle shaped roof of Raleigh Arena, N. Carolina

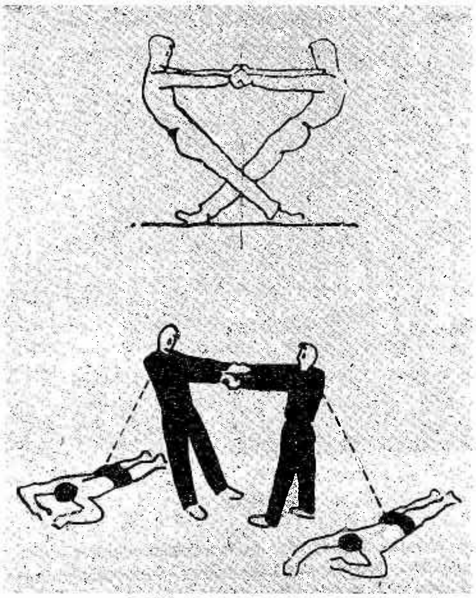


Fig 1.5 Severud's sketches for Raleigh Arena

it on a grand scale, it was not until Mathew Nowicki, with the help of the engineer Fred Severud, designed a saddle shaped roof for the Raleigh Arena in North Carolina in 1952 (Fig 1.4), that a doubly curved suspension form was first used in architecture. The relationship of the raking seats to the roof is best expressed in the drawing Fred Severud made to explain it (Fig 1.5). The building details gave some minor problems after erection. The roof had relatively light cladding (30kg/m²) and a flat cable net, so flutter could develop. This was subsequently corrected by providing damping springs at the cable connections and by adding guy wires to the underside of the roof. The potentially unstable arch cracked at the foundations and the instability had to be eliminated by the insertion of perimeter columns. However, overall, it was a simple idea clearly carried out. It was immensely innovative and its impact was enormous.

Of the architects in this century who have struggled to explore new methods of building, Eero Saarinen must rank high. In 1956, again working with Severud's engineering firm in New York, he designed the Ingall's Ice Hockey Rink for Yale University (Fig 1.6), which uses a sprung bow arch to support cables draped to curved edge beams. I had just joined Severud, Elstad and Kruegur and was alllocated to this project. The arch was cast and stabilised by straight cables to the edge beams, the support cables which hung below being designed as pure suspension cables. Internal guy ropes were also provided.

The two firms followed this in 1958 with a single curvature cable roof for Dulles airport, Washington DC, treated architecturally in a quite classical manner. I worked on this too but not on the roof. Surprisingly in the USA, dominated at that time by steel structures, both these buildings used reinforced concrete for their support systems and achieved a sculptured elegance and sense of performance which, though probably not fashionable today, still seems totally appropriate to their context.

The earlier 1956 concrete arch design for Yale was a forerunner to the design by Kenzo Tangye and Frei Otto as architects (and which I was in charge of and on which several of us worked when with Ove Arup and Partners) which won the Kuwait Sports Centre competition in 1969 (Fig 1.7). This used a steel arch, stabilised by flexible cable nets and a variety of claddings – from solid through translucent to shade netting. Both are fascinating exercises in the use of different materials and represent a developing public acceptability of the building type. Yet all the 'Severud engineered' buildings, unlike the Kuwait sports centre, are basically quite stiff, and developed from the theme of suspension bridge design.

Evolution of lightweight structures

In Europe however, the German architect Frei Otto who had studied in the USA, was fascinated by light weight structures, especially traditional tents. He was supported by Peter Stromeyer, a member of a family of tent makers, and together they produced a whole series of very beautiful fabric tents from 1955 onwards. At first the fabrics available had relatively weak base cloths and the coatings, in order to provide waterproofing, fire retarding and appropriate life extension, were of limited effectiveness. With time however, the technology of fabrics has developed enormously and, since buildings primarily exist to amend the climate, further advances have provided and are still providing a whole range of design possibilities. But in the early days fabrics could only span short distances.

In 1966 Otto teamed up with another architect, Rolf Gutbrod, to win two major competitions using long span tensile roofs. One was for the German Federal

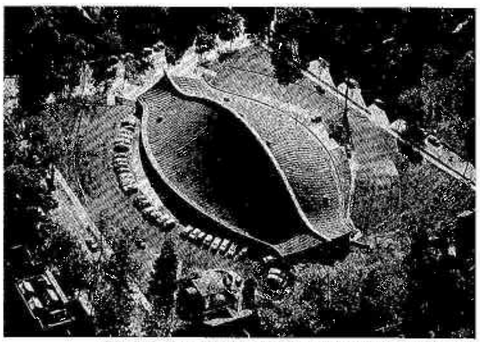


Fig 1.6 Ingall's Ice Hockey Rink, Yale University

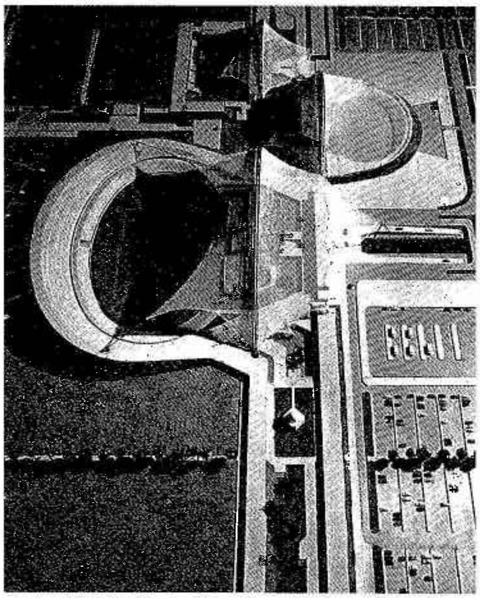


Fig 1.7 Competition winner for Kuwait Sports Centre

Pavilion for Expo '68 in Montreal (Fig 1.8) using a free form cable net supported by masts, the concentration of forces at mast tops being accommodated by the use of main cables with stress relieving loops, and clad with translucent PVC coated terylene. National pride ensured that many engineers worked on the design of this building, the principal being the firm of Leonhardt and Andra, and a major part of the design was carried out by physical model testing and simple hand calculations.

The second building was the Conference Centre for Mecca in Saudi Arabia (Fig 1.9) where a much more tailored system of cable structures was developed, with either highly insulated lightweight cladding covering the air conditioned spaces, or shade protecting structures covering the open spaces. Engineering design was extremely conscientiously carried out by a group I headed in Arups, including several of those now in our current practice.

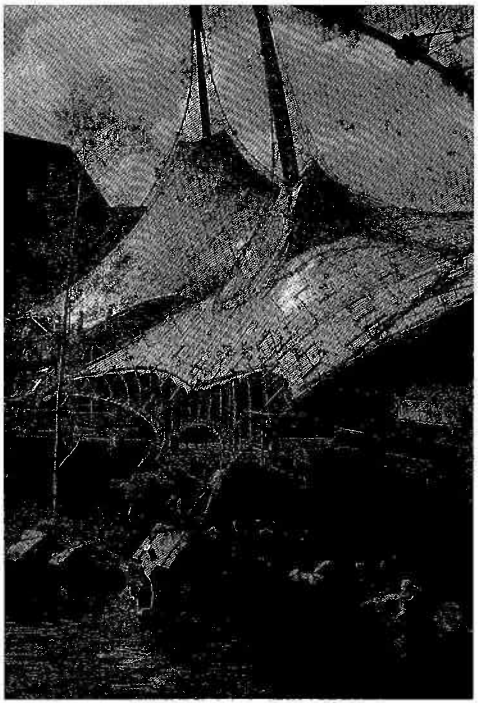


Fig 1.8 German Federal Pavilion at Expo '68 Montreal

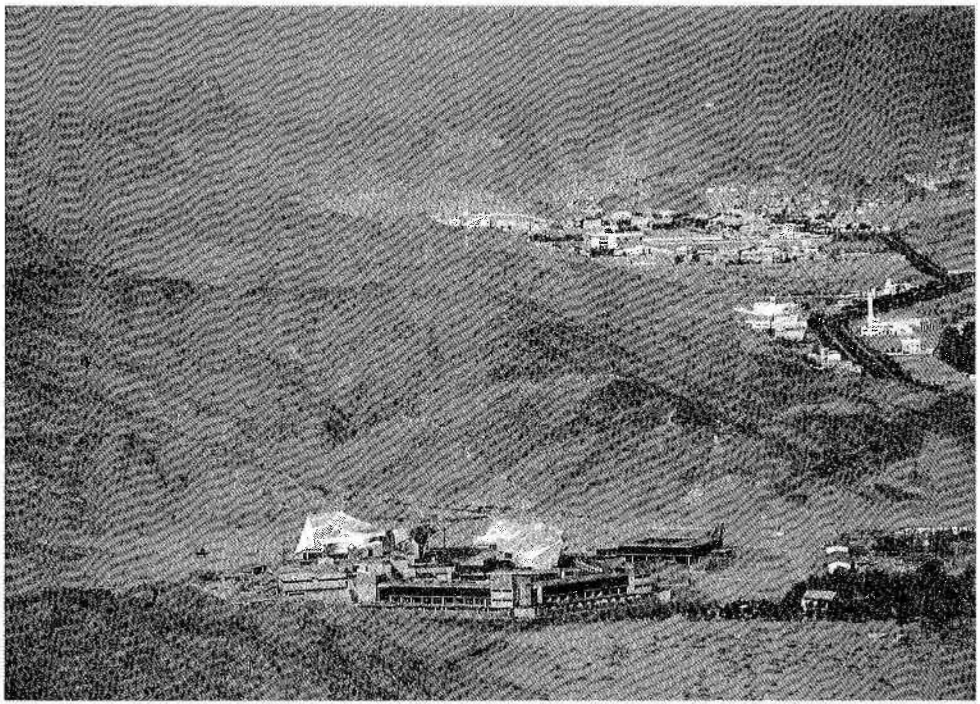


Fig 1.9 Aga Khan award winning Conference Centre, Mecca

These two buildings were very different in character but visually extremely original – Montreal acceptable because it was an exhibition building, Mecca because it was seen as continuing the traditions of the Arabic tent and the shade kaffess. Both buildings achieved considerable recognition. Gutbrod and Otto received the Perret award of the UIA for Montreal, and the Aga Khan Award for 'the most technically innovative building of a decade in the Muslim world' for Mecca. However, the demolition of the Montreal Pavilion after the exposition, and the inability for non-Moslems to visit Mecca probably reduced the impact of each respectively.

As a consequence, 1966 was the year I started working with Frei Otto on the second of these buildings, and our practice continues to work with him on this type of solution. Indeed we, and in particular our Special Structures Group under Ian's direction, now design a very large number of this type of structure, ranging from Baltimore Harbour Lights (Fig 1.10) to the new Imagination headquarters in London.

When Behnisch and Partners produced a very elegant development of the Montreal design for the Munich Olympic Stadium in 1972, again with Leonhardt and Andra as principal engineers, it achieved worldwide television coverage. In 1976, again with Gutrod and Otto and in collaboration with

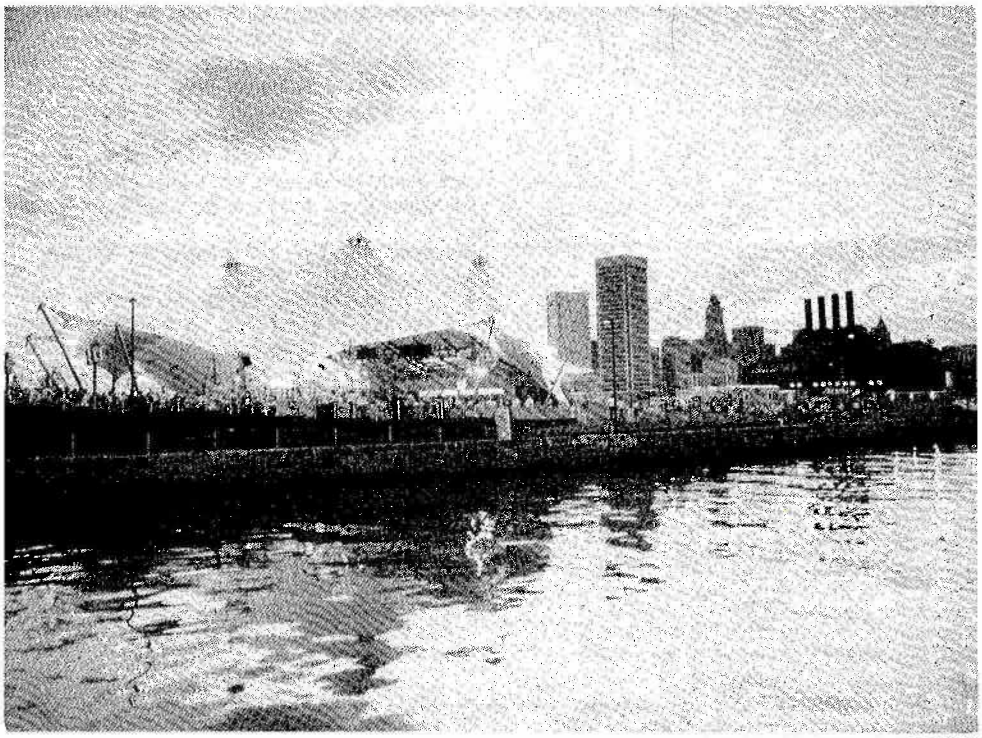


Fig 1.10 Baltimore Harbour Ligh

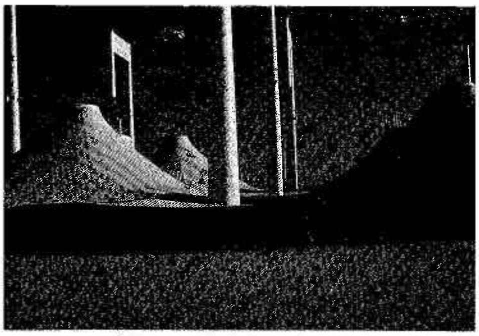


Fig 1.11 Hajj Pilgrims Terminal, Jeddah, S. Arabia

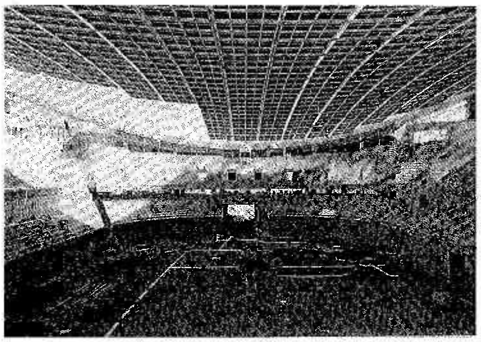


Fig 1.12 Calgary Saddledome under erection

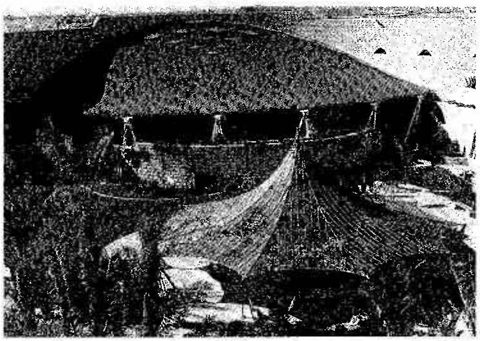


Fig 1.14a Dining 'rose' and Heart Tent, Diplomatic Club, Riyadh

Arups, we designed the 2½ acre stadium of this type for the University of Jeddah which is described later in this issue.

Germany, like Japan, encourages both architect and engineer designer/academics, and the research environment has been greatly stimulated by these projects in Montreal and Munich. The amassing of knowledge of new methods of designing around Frei Otto, and subsequent spinning off from SFB 64 has been enormous. We were ourselves corresponding members of this Stuggart-based research group, have gained enormously from it, and have provided to it a considerable engineering input.

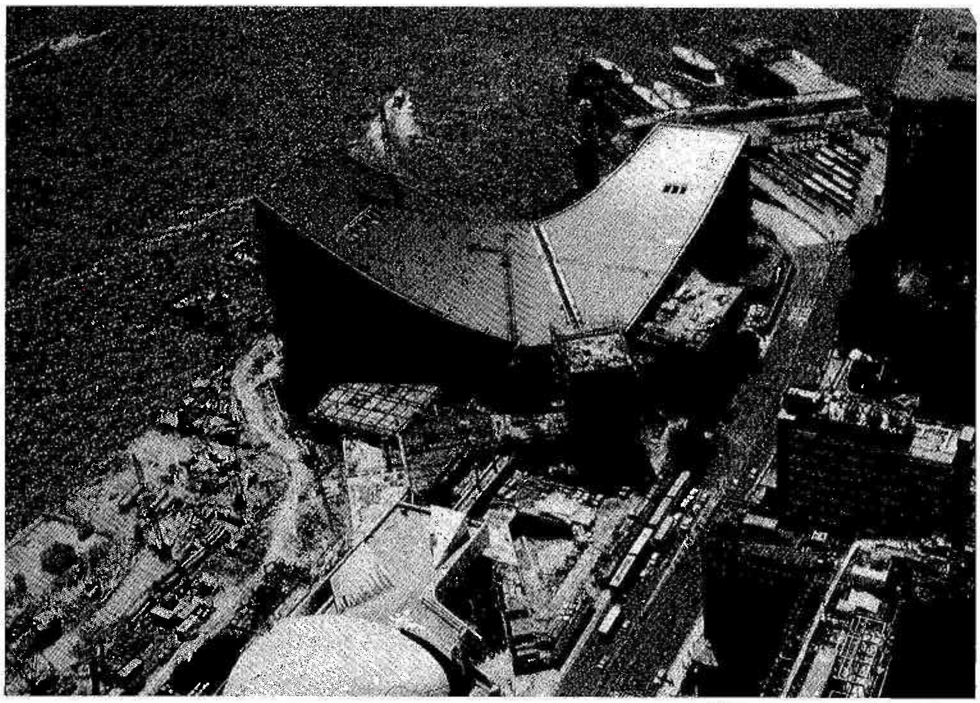


Fig 1.13 Hong Kong Cultural Centre

Further technological advances

Tent design then developed in response to technical advances in several areas. In fabric technology Dupont took the high strength of drawn glass fibre and extended its life by coating it with teflon. Not only did this achieve extremely high strength and long life, though making a rather stiff fabric, but provided interesting translucency and reflectivity characteristics. Furthermore, with teflon being anti-dielectric, the fabric is virtually dirt free. Consequently, its properties as a climatic moderator are very interesting. This was exploited very elegantly in the use of the fabric for a series of 40m × 40m tent covers over the Hajj Pilgrim's terminal at Jeddah in Saudi Arabia (Fig 1.11). The architects and engineers were Skidmore Owings and Merrill, but their partner, Fazlur Khan, cleverly organised the involvement of practically every experienced engineer, fabricator, materials supplier and erector in the world including ourselves in some aspect of the project.

Cable nets are still used for large spans, supporting a variety of materials as cladding. The Saddledome for the Calgary Olympics (Fig 1.12) in which we assisted Jan Bobrowski and Partners, used a concrete cladding, as has the Hong Kong Cultural Centre (Fig 1.13). The roofs for the Diplomatic Club for Riyadh, certainly one of our most innovative projects, used PTFE coated glass fibre, and timber boarding covered with mineral rock wool and clad with ceramic tiles; another used stained glass (Fig 1.14). The design of this project has been described fully in an earlier issue of Patterns.

The commonly used square cable net of some 50cm spacing developed because it is easy to assemble on the ground, is easy to control geometrically and is safe to work on. Radial geodesic cables have become more common as numerical methods of formfinding have been developed, and because use of these allows simpler detailing at mast tops. The cost of PTFE coated glass has stimulated both the development of other materials, such as silicon glass, and improvements to the less expensive PVCs. We used stainless steel crimped wire woven in a grid weave as a fabric for the BDA award-winning aviary for Munich with Jorg Gribl and Frei Otto as architects, but also for aviaries for San Diego in California and Ocean Park, Hong Kong. Furthermore, we have developed tension connection details enabling even unseasoned round wood to be used for a tensile roof for John Makepeace's School for Woodland Studies at Hooke Park in Dorset.

New design possibilities

We have further developed the use of woven and coated fabrics and foils as climatic moderators, in addition to their use as lightweight structural

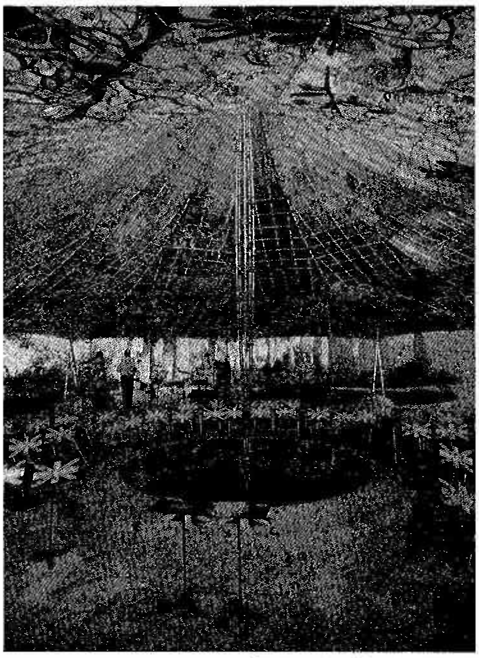


Fig 1.14b Interior of Heart Tent

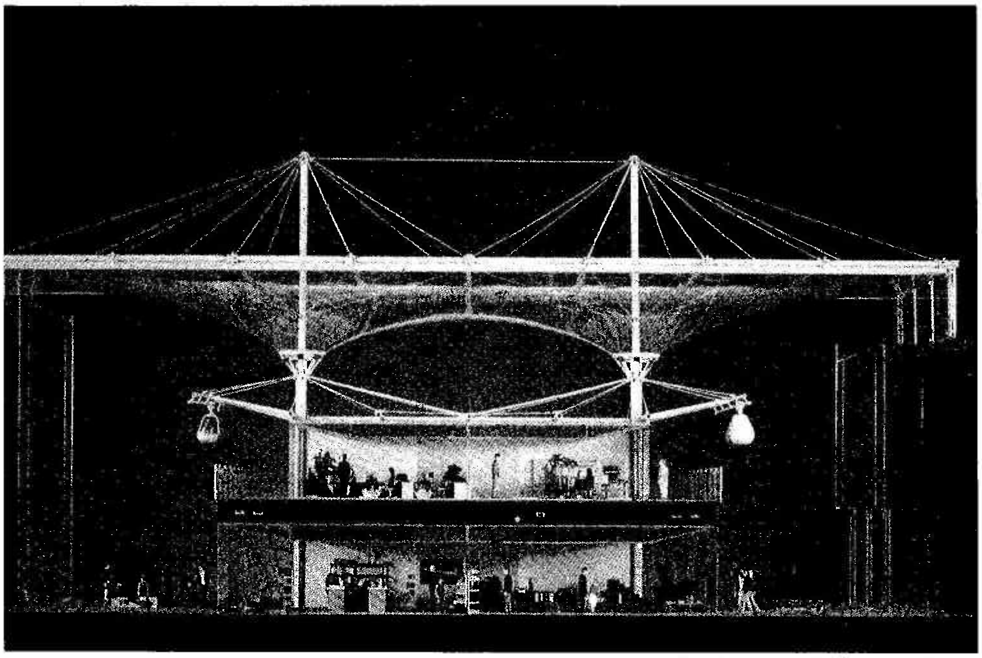


Fig 1.15 Enclosure of Basildon Town Square

materials. This is obviously going to be an important area of development in building in the future – a line of thought Ian is currently exploring in a design with foils with Sheppard Robson. (Fig 4.11)

Over the past decade, growing use has been made of such climate moderators in retail, leisure, sporting and other permanent uses, particularly in the USA, Europe and the Middle East. The awareness that these techniques can and do provide the basis of permanent structures, prompted the Institution of Structural Engineers to award Buro Happold a special award in 1987 "for developing and defining the application of tension structures to permanent constructions".

Nevertheless, apart from a few isolated and notable instances such as the Schlumberger Research Centre, Cambridge, (Arch: Michael Hopkins, Eng.: Hunt/OAP) designs for permanent installations have not been executed. Our own earlier designs for the enclosure of Basildon Town Square with Michael Hopkins as architects is just such a case. (Fig 1.15)

But not all architects are like Frei Otto, whose understanding of how to achieve an optimum form ensures a visual lightness. Many architects – and for that matter engineers – are not much interested in the structural principles which produce these shapes, or have a wish to determine the spaces rather than select from what is easily achieved. This insistence on dictating the shape has turned tent design into clothes design. Structural economy is no longer the objective, nor is internal climate or long life, since fashion change is a perfectly acceptable objective to the architect – and engineering a means of achieving it. I used to belittle this, I no longer do. An emotional impact can serve the client's need and I think engineering can serve sculpture if that is the function of the structure.

Airhouse developments

The extreme form of tensile building is the airhouse in which a thin membrane, with no bending stiffness, is prestressed by an internal pressure so that a tension stress is produced which is high enough not to be reduced to zero by external loads. A fan is needed to maintain the internal pressure, which can be raised for limited periods, and access has to be through some form of air lock to prevent loss of internal pressure. The idea of utilising pneumatic structures is not new. Three thousand years ago rafts were made of goat skins; the sail of a ship is probably the best known example of their use in the past; the car tyre probably the best known example in the present.

F. W. Lanchester, the British car pioneer, in 1918 patented the design of a tent supported by air. It comprised a 'skin' reinforced with cables and anchored round its edges to ensure small air leakage (Fig 1.16). The increased internal air pressure required for support was provided by a centrifugal fan, and entrance to the tent was achieved by small shutters in the door, like paddles in a canal lock. Movement of the flexible air house skin relative to the stiff air lock structure would be allowed for by bellows of fabric around the lock, and additional cable reinforcement would be provided around the opening. This patent describes all that is included today in a single-skin air house, yet Lanchester never made one – a suitable fabric was not available in his day.

It was not until the late 1950s that pressure-supported domes, to cover equipment for the detection of intruder aircraft and missiles in the Arctic, were developed by Walter Bird in the United States. Walter Bird's firm, Birdair, started using isotropic sheet material such as neoprene and hypalon, but subsequently changed to using coated fabrics. The use of woven fabric is important because, although when woven it has the threads at right angles with certain extension qualities, when pulled at 45° to this warp and weft it is much more extensile. In other words, the Poisson's ratio of the material at 45° axes, arising from the lack of in plane shear stiffness in the material, used wisely allows for a change of shape that enables loads to be distributed in a manner suitable for the material. Coating of the fibres then provides both airtightness and protection against deterioration for the base fabric.

Like most developments in the building industry, this type of building largely evolved in the craft sense, made by tent or canvas manufacturers looking for new markets. The results may have been useful for

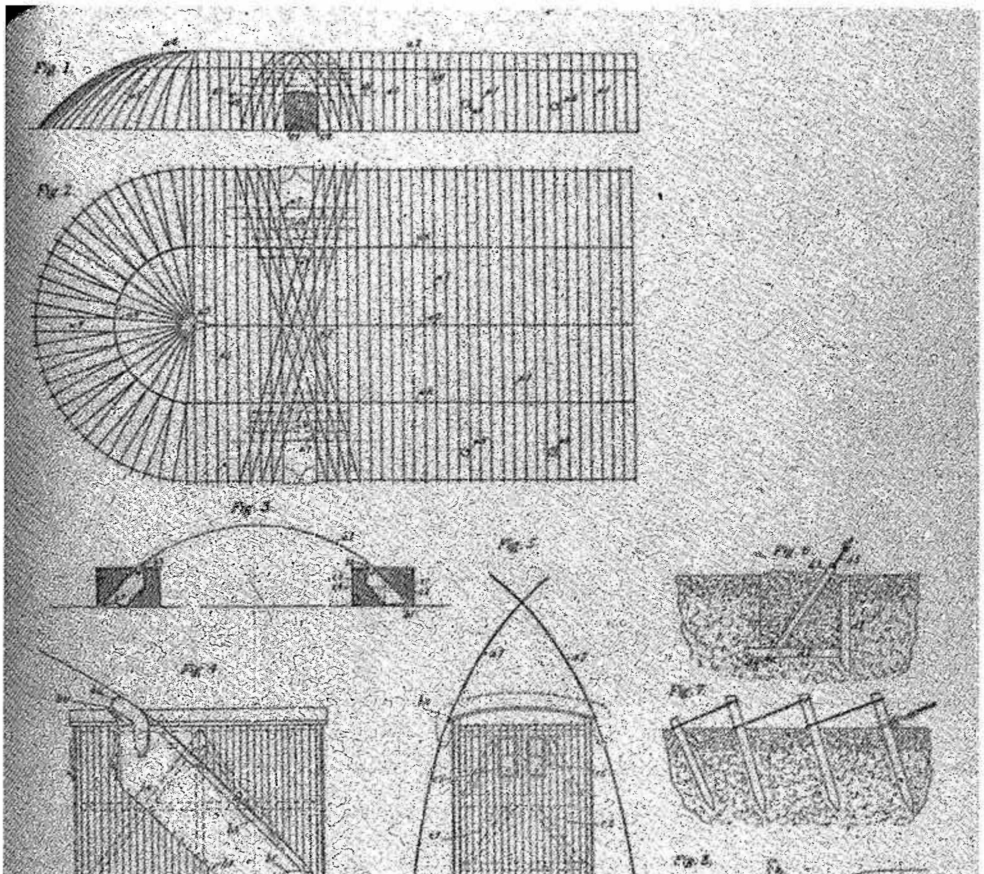


Fig 1.16 Lanchester's patent for air supported tent

Fig 1.17 58°N, Alberta

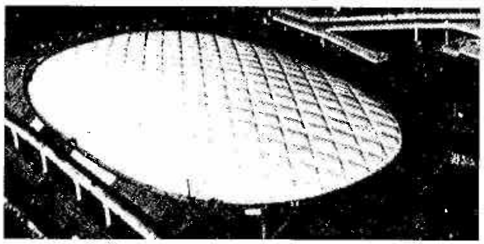


Fig 1.18 US Pavilion at Expo '70, Osaka, Japan

sports halls or swimming pools but have a limited attraction for other uses. Very few architects have been interested in them. In 1971, while with Arups, some of us worked with Frei Otto on a solution for the Hoechst Company, for a one mile diameter airhouse called Arctic City. This was a forerunner to our own 58° North project in Alberta (Fig 1.17), which has been written up in Patterns 1. I think it was the first design to use the uplift which is developed over the top surface from wind pressure. We developed an interest in the type and in 1978 formed a part of a research unit at the University of Bath.

A number of imaginative suggestions originated in the early 1970s, mainly from British artist architects. We worked on some of these. Expo '70 at Osaka in Japan contained a number of such examples but it was difficult to see their use developing. One significant building at that exhibition however, was the US pavilion, by the Cambridge Seven as architects and Walter Bird and Geiger Berger as engineers. It was a low profile 142m × 82m oval shaped (Fig 1.18), roof reinforced by diagonal cables supported on a berm wall so that the wind pressure was largely uplift and, in the event of a collapse, the roof would still be supported over its occupants. This was the first practical example of what designers have been arguing for some time – that the future of the air house lies in its ability to cover large spaces cheaply since the reservoir capacity of air within makes it such an economical space.

Since then a number of stadium roofs have been built in the USA on the same principle, mainly using the more modern fabrics such as teflon coated fibre glass. There have however, been several relatively recent unexpected deflations of such structures, mainly under snow loading, and their popularity has declined. We have been widely consulted on such failures, and Ian Liddell and David Wakefield are currently advising the owners on possible causes and any repairs which are necessary. I rather diffidently suggest that there are higher engineering standards available in Japan, Germany and Britain than in the USA.

Future research

The truth is that the field of airhouse engineering is still a complex and little understood one and many engineers are not willing to work to understand it. Yet it is an exciting field because it is one in which climate, structure and constructability are all utilised. Much recent work has been done and has been published. We have contributed much to the research group centred at the University of Bath. That group has studied interactively most aspects of tensile building design for climate, loadings, materials, structural behaviour, maintenance, constructability and cost, and this work, presented in two conferences and published by the Institution of Structural Engineers, by IL at Stuttgart University, and through many other publications, is core work in this field.

Ian and I were talking the other day about how many other engineers are now working in this field. We can only be pleased at this, but still have concern that not enough examination of work carried out to date is taking place. We do not want the field destroyed by unnecessary failures, so we are organising an international colloquium later this year to discuss case studies.

It will not surprise readers that Ian is the great nephew of the hero of 'Chariots of Fire' – hence the title of this feature. To paraphrase Alan Bennett, our friend and colleague Ian Liddell, with all his energy and his laugh, truly lives to understand the substance of engineering – the pith of reality. We all hope that he may long continue to take the pith out of reality.

Ted Happold

The Engineering of Surface Stressed Structures

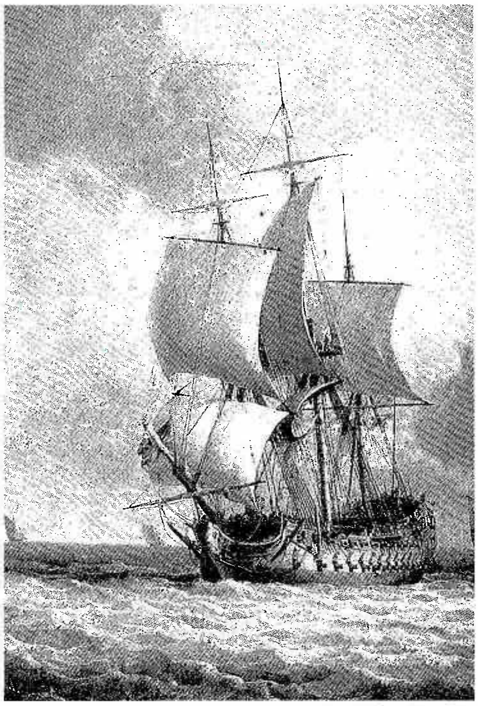


Fig 2.1 An early tension structure

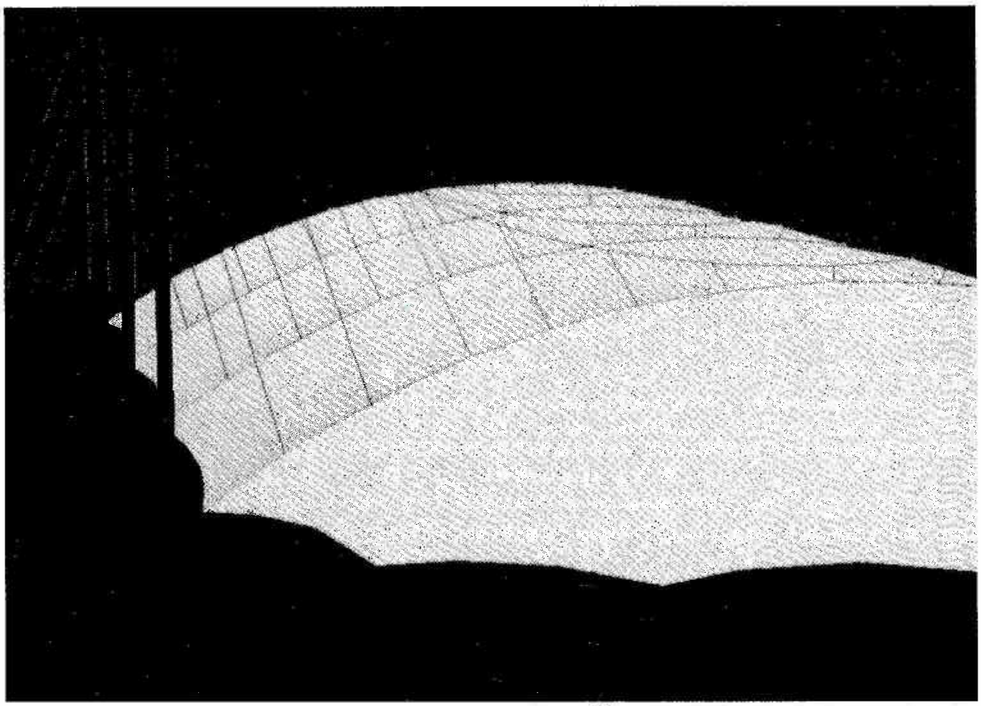


Fig 2.2 CAD representation of a surface stressed structure

In surface stressed structures, the membrane is prestressed to form a load carrying system. This membrane can be either a coated woven fabric, a net of steel cables or an unreinforced structural foil. The prestress can be induced either by tensioning the surface via the boundary and supporting elements, or by pressure acting on one side, in which case it is a pneumatic structure. By using high strength materials in tension, surface stressed structures can provide a structurally efficient solution with a range of interesting architectural possibilities (Ref 2.1).

These structures are geometrically complex and have to be accurately prefabricated in their entirety. (Fig 2.1) Consequently, the bulk of the work in the design office is spent on processing the geometry of all the components. Up to twenty years ago the only way to develop the geometry of a surface stressed structure was by physical modelling. However, to achieve sufficient accuracy this method took time and was expensive in terms of design resources. Improvements in the power of computers and developments in software have resulted in great advances in CAD systems for processing these structures rapidly and in a user friendly way (Fig 2.2).

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

Design Method

For any project involving a surface stressed structure, the process of representative three-dimensional modelling has to start among members of the design team right from the beginning. The design development will commence with either plan and sectional drawings and isometric sketches, but these are difficult to make truly representative. This will be followed by the generation of simple scale models, or computer aided design. Whatever means the design team adopts, it is important that a truly interactive conversation is established so that the design proceeds from the outset on a basis that leads to an effective, economic and elegant result. Much experience of the field is needed during these early stages if the surface stressed structures are to relate properly to all the other elements of the construction.

Within this process, it is still a useful practice for designers to make stretch fabric models of a structure since this helps them understand the forces and forms involved. From these models the surface curvatures can be measured and the principles of the surface patterning established. With this information, approximate engineering calculations based on equilibrium can be made and, with suitably conservative assumptions, used to size components and hence estimate costs. (Ref 2.2, Tables 2.1, 2.2.) The key to this is the understanding of the physical principles which determine the form. Fortunately, these are not difficult to grasp.

The final stage of the process will be computer formfinding and the computer model is then used for exact load analysis and to define the cutting patterns and cable geometry. The increasing power of computers and developments in surface rendering graphics with "walk through" views has more or less superseded the intermediate stage of stretch fabric models.

Formfinding

The process of formfinding is that by which the prestressed equilibrium form is developed. The objective is to create a model of the intended structure from which the geometry of the components can be found and in which the forces, stresses, volumes and environmental responses are known. As discussed above, this can be done by physical modelling, geometrical calculations or by calculations involving static equilibrium on the computer.

Physical modelling

Physical modelling of prestressed surfaces can be carried out using soap films (Fig 2.3). These model a perfect membrane with equal surface tensions in all directions but they are very difficult to measure. Another method is to use stretch fabric of one form or another, such as ladies' tights (Fig 2.4), lycra

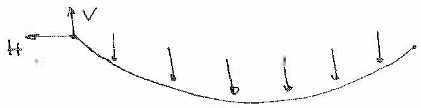
Approximate methods of Calculation

1. Cylindrical membrane strip of unit width under pressure loading.

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

$T = W \times R$. —— ①

2. Forces in hanging cable under uniform vertical load.



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

Cable hangs in a parabola such that:

$$y = \frac{4d}{S^2}(Sx - x^2)$$

$$\left.\begin{aligned} \text{Horizontal force} \quad H &= \frac{WS^2}{8d} \\ \text{Vertical force} \quad V &= \frac{Wl}{2} \\ T &= \sqrt{H^2+V^2} \end{aligned}\right\} —— ②$$

Table 2.1 Basic geometry of surfaces

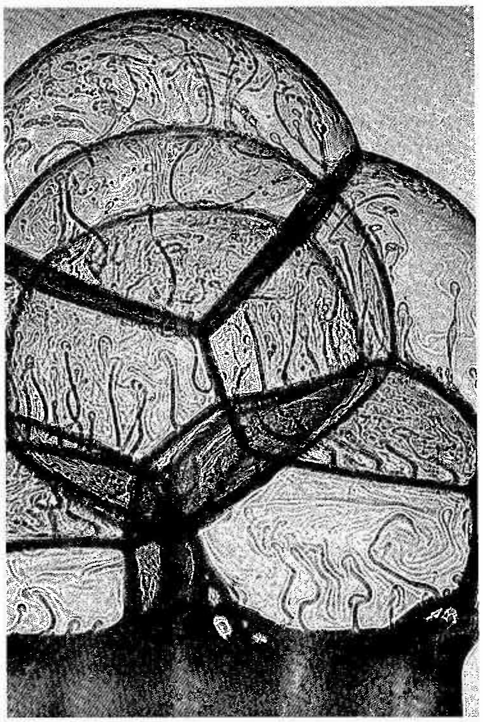


Fig 2.3 Soap 'bubble' model

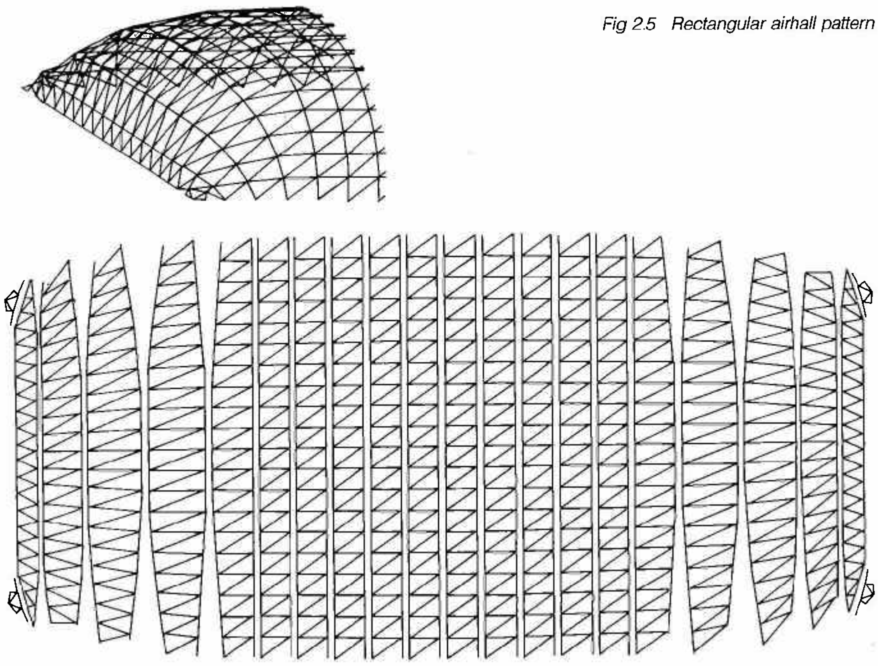


Fig 2.5 Rectangular airhall pattern

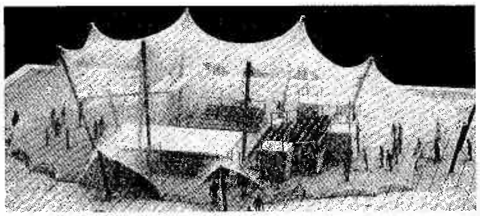


Fig 2.4 Stretch fabric model

fabric, or heat shrinkable PVC foil. This last material can be used to make a fairly rigid model from which cutting pattern measurements can be taken using paper strips. Stretch fabric models are unlikely to produce a surface with known surface tensions but are a good representation of overall constructional forms (Refs 2.3, 2.4, 2.5).

Originally, accurate physical modelling for cable net structures was carried out using fine wire and small cable clamps. This method was used by Frei Otto for both the West German Pavilion at Montreal and for the swimming pool structure at the Munich Olympic Park (Ref 2.6). All the component geometry was then measured from these models and the forces in the elements were all calculated by hand, generally using equation b of Table 2.1. With experience and by choice of the appropriate formulae in Table 2.1, one can make estimates of the forces in cables and fabrics supporting masts, and anchorages on the basis of the preferred form. In a real situation the stretch of the cables or fabric under externally applied loadings allowed the curvatures to change usually reducing the forces caused by local 'high' load concentrations. Movement of the boundary cables caused by stretch in the anchorage system, or in an adjoining field has the same effect. Hence a full and accurate analysis can only be carried out using a non linear computer program which takes into account the displacements of the surface under loading and calculates the forces under the 'improved' geometry after deformation under load. Techniques used in our office are based on 'dynamic relaxation' the theoretical principles of which are given in Table 2.3 (Ref 3.1).

Geometric modelling
For pneumatic forms, physical modelling is practically impossible. Air hall cutting patterns in the past were developed using a pragmatic geometric approach in which the angles of the corners of the gore line were matched up to obtain a sort of best fit (Fig 2.5). Usually this resulted in bulges and a lot of wrinkles in the corners.

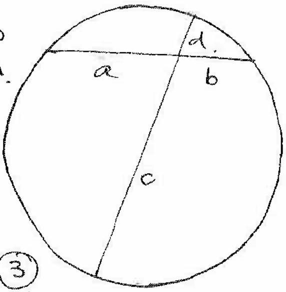
Otto has demonstrated that a pneumatic form can be generated from a series of cones. This principle is used in a commercial computer program to generate cutting patterns for rectangular air halls. (Ref 2.1c). Geometrical curve fitting procedures are also used to obtain quick computer models for prestressed surfaces. These are not good enough for building to and are generally used to generate data for old fashioned computer procedures using stiffness matrix solution methods, which cannot handle very large displacements from the equilibrium position.

Calculation of static equilibrium by computer
In this method the surface is modelled as a pattern of elements, usually triangles (or as bar elements in the case of cable nets). In the form finding mode, the membrane elements are set to have a constant pre-determined stress no matter how much they change their size. This process is physically equivalent to soap film modelling except that a soap film can only have a constant uniform surface tension, while in the computer model the tensions can be varied. (Fig 2.6). Boundary cables can be modelled as elastic cables with a given length, or can be assigned specified tensions. Masts, tie backs, edge beams and arches can also be included in the model. The same model can be used for load analysis and for establishing the cutting patterns and cable lengths. The TENSYL suite discussed later in David Wakefield's article is probably the best program available and it is constantly being improved and updated. (Refs 2.7, 2.8, 2.9).

In TENSYL the shape is controlled by specific warp and weft stresses in the various areas of fabric, thus necessitating a trial and error procedure to get the required form. However, with the increasing capacity

3. To calculate the Radius of a Surface from the Span and the dip.

for any two chords of a Circle $a \times b = c \times d$.



hence if $a = b = S/2$

$$(S/2)^2 = (2R - d)\,d$$

or $R = \dfrac{S^2}{8d} - \dfrac{d}{2}$. — ③

Note. for a hanging Cable with a small dip. $R \doteqdot \dfrac{S^2}{8d}$. Hence equation ① becomes $T = \dfrac{wS^2}{8d}$. this is similar to equation ②.

If a physical model has been made the local radii can be found by measuring the dips in an appropriate Span. Equation ① can then be used to obtain estimate of tensions. Tensions in Ridge and Tie backs can then be calculated by resolving forces at mast heads in the measured directions. Before computer methods were available many Tents were totally calculated by this method using accurate models and careful measurement.

Cutting patterns were also developed from models by laying on strips of paper.

Table 2.2 Equations of equilibrium

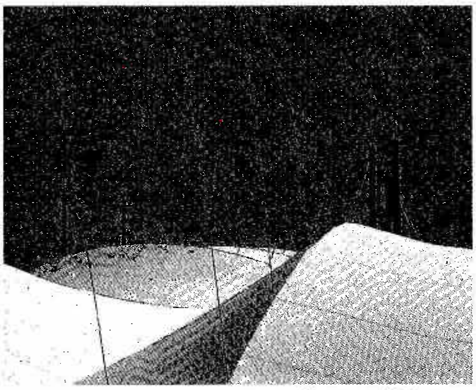


Fig 2.6 Computer form model

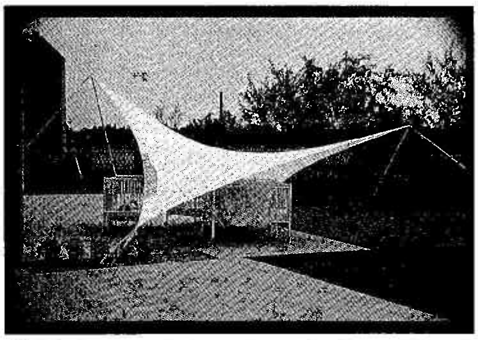


Fig 2.7 Minimum surface bounded by 4 cables and 2 masts

and speed of computers and the development of user friendly programs, the trial runs take less time, and data can be varied quickly so that the required form can be readily developed. The operator must nevertheless understand the physical principles involved.

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

Structural performance as a function of form

A highly stressed membrane must be supported all round by a boundary which makes a closed, but not necessarily circular, ring. The significance of this can be demonstrated with a soap film which is initially formed in a circular wire ring. If the ring is open, the film immediately ruptures. The boundary ring need not be flat and can be formed of cables. A uniform stress surface within such a boundary is known as a minimum surface, (Fig 2.7) – the minimal surface bounded by four cables with two masts.

A minimal surface, within a given defined boundary, has the least possible surface area and the minimum strain energy, hence it can be said to have maximum structural efficiency. It is possible to modify the surface by changing the ratio of stresses in the prestressed condition. To return to the previous example, if the surface tension in the direction between the high points is increased, the surface will rise in the centre. From the point of view of overall design requirements, it may be desirable to do this to improve the headroom in the building, to modify the visual appearance of the surface, or to improve the performance of the particular structure to the range of loadings it must resist.

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

Behaviour under load

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

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

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

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

Dynamic behaviour

Surface stressed structures tend to have large deflections compared with bending stiff structures. They also have natural frequencies of oscillation which could theoretically respond to wind flow or turbulence to produce dangerous freed oscillation. This behaviour has been studied extensively by Davenport and others (Ref 2.10), but in practice coherent wind induced oscillations have not been observed in properly tensioned prestressed membrane structures.

The same is not true of air supported structures. In this case it is the mass of enclosed air which controls the oscillation of the roof. If the shape of the roof is such that the surface experiences local short term positive pressures greater than the internal pressure, so that the roof is locally deflected inwards, this can activate oscillations of the internal air which can become resonant. For large and important structures this effect should be studied in a wind tunnel during the design stage.

Classification of form

Each field of fabric within a whole structure which may be composed of a number of such fields must be bounded and determined by the type of supporting elements at its structural boundary. These can be rigid elements such as beams, walls, arches or flexible cable elements such as eye loops, boundary or ridge cables on masts (Fig 2.8). As it is

4. effect of Cable stretch.

Stretch in a cable or membrane strip under load reduces the radius and hence reduces the Tension. This effect is particularly important for straight or nearly straight cables.

Cable strain: $\frac{\Delta l}{l} = \frac{l - l_o}{l_o} = \frac{T - T_o}{K}$.

K = stiffness = E.A.

Rearranging this equation we have

$$l = \left[\frac{T - T_o}{K}\right] l_o + l_o$$ —— ④

Arc length. $l = R\theta$

θ is the included angle of the arc in Radians

$$\therefore\ l = R \sin^{-1}\frac{S}{2R}.$$ — ⑤

Combining this with equation ① we have

$$l = \frac{T}{W}\sin^{-1}\left[\frac{SW}{2T}\right].$$ — ⑥

Combining this with equation ④ the general equation for a Radially loaded cable is.

$$\left[\frac{T - T_o}{K}\right] l_o + l_o = \frac{T}{W}\sin^{-1}\left[\frac{SW}{2T}\right]$$ —⑦

this is a non linear-equation which can be solved iteratively for T. This can readily be done using an HP 28S or 48SX Calculator which has a 'Solve' Routine.

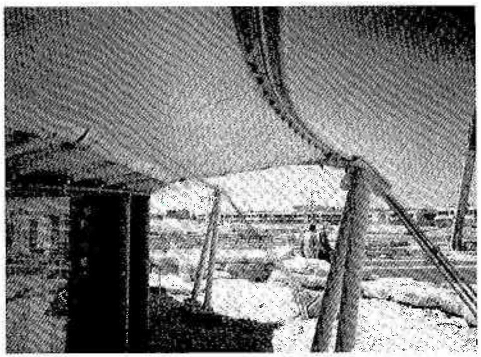


Fig 2.8 Engineering components of Diplomatic Club roof

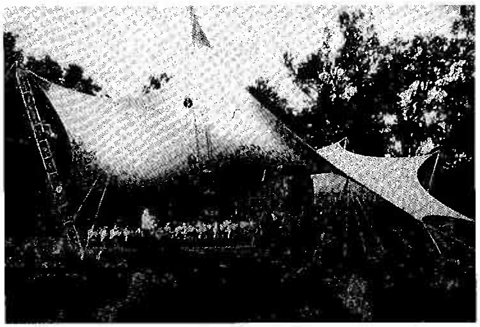


Fig 2.9 Washington Symphony Tent

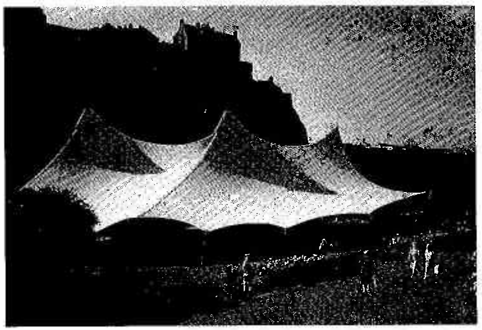


Fig 2.10 Edinburgh Ross Bandstand

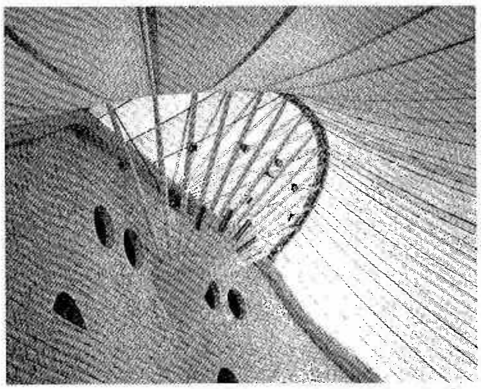


Fig 2.11 Top detail, Diplomatic Club

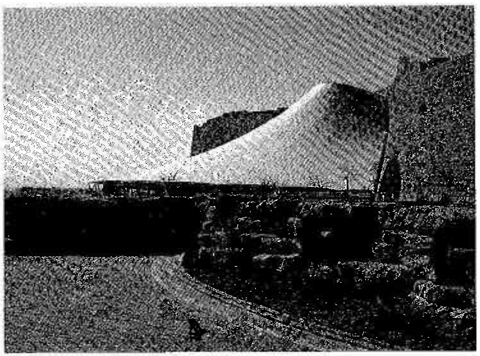


Fig 2.12 Exterior of conical rose at Diplomatic Club

difficult to form a useful space with a single 'saddle' surface, a building will usually consist of a number of fields arranged together and anchored to a range of boundaries. The correct determination of the boundaries from the range outlined below is probably more significant to the overall success of the design than choice of the surface itself.

Masts and ridges

A membrane cannot be supported by a point. This is well demonstrated with a soap film which instantly bursts. Generally at a mast point there will be two ridge cables, sometimes three or four, which transfer the uniform stress in the fields to the concentrated load at the mast. Examples of tents with such masts and ridges which have been developed by the practice include Jeddah Sports Centre (Fig 6.14), Washington Symphony Orchestra Tent (Fig 2.9), Baltimore Tent (Fig 1.10), and Edinburgh Ross Bandstand Tent. (Fig 2.10).

Conical forms

With conical or pseudo sphere forms, there are often a large number of radial cables coming together at the mast (Fig 2.11). These usually lay freely under the fabrics, the tension is constant and the fabric can slip over the cables. Typical examples of these forms from the practice are found in the Diplomatic Club, Riyadh (Fig 2.12), Bath Panorama, Liverpool Garden Festival (Fig 2.13), Heart Tent, Riyadh (Fig 1.14) and the Pool Covering, Pensacola (Fig 4.9).

Ring supports

A single membrane can be supported by a large ring. Again, soap film modelling demonstrates the problem. If a film is created between an inner and an outer ring, the inner ring can be lifted to form a doubly curved surface. If the rings are moved further apart, it will be found that at a certain point the film will always burst. This happens because the meridional radius of curvature becomes greater than the circumferential radius. At this point the conditions of equilibrium cannot be met so the film bursts. With a real fabric, the meridional tension can be greater than the circumferential tension, and reinforcement can be added by doubling the cloth or by broad-seaming so that the ring can be smaller than that which the soap film theory predicts. Even so, a relatively large ring is still required. An example of this technique can be seen in the permanent structures for the Hajj Terminal (Arch/Eng: SOM) (Fig 1.11) or the new Mount Stand at Lords (Arch: MHP/Eng OAP).

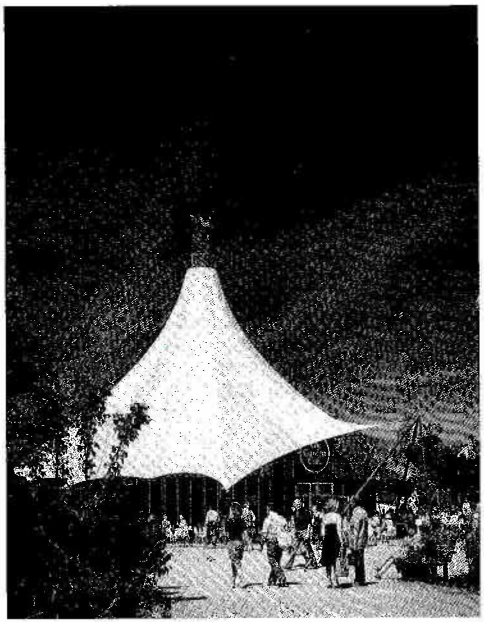


Fig 2.13 Tent for Liverpool Garden Festival

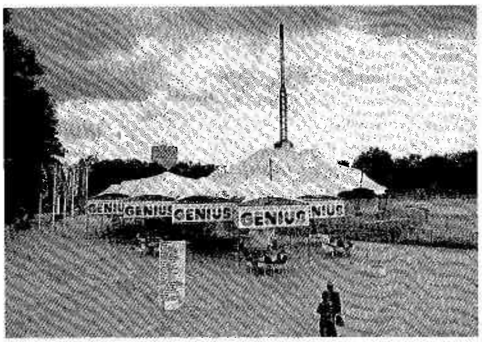


Fig 2.14 British Genius – Exhibition and entrance tent

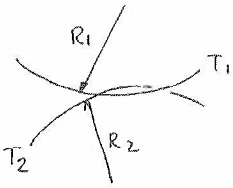
Humped tents

Originally this system, which does not use cutting patterns, was devised by Frei Otto. The woven fabric is made up flat and without shaping along the seams. During erection the fabric is supported on domed supports so that the angle between the directions of weave are changed, so allowing it to distort into a doubly-curved surface over the support. The British Genius Exhibition Tent, Battersea 1977 is an example of this type of 'humped' form (Fig 2.14). The tent was subsequently re-built in PVC with a

5 Doubly Curved Surfaces.

for doubly curved surfaces equation ① becomes

$$\frac{T_1}{R_1} + \frac{T_2}{R_2} = P. \quad -⑧.$$



R_1 & R_2 are principal Radii of Curvature
T_1 + T_2 are Corresponding Tensions / unit width.
P is pressure loading.

The principal radii of curvature are the max & min and follow lines at right angles to each other on the Surface.

With Anti Clastic curvature the centres are on opposite sides and R_1 & R_2 have opposite signs. Hence for the prestress equilibrium condition $\frac{T_1}{R_1} + \frac{T_2}{R_2} = 0$.

under load P from above T_1 will increase while T_2 will decrease in the extreme T_2 will become slack when

$T_1 = P \times R_1$.

Tents are invariably prestressed anticlastic surfaces. hand calculations can be carried out from model measurements using the procedures described in 3 above.

patterned and fabricated membrane. The Staffordshire House atrium roof (Fig 4.8) is also a humped tent with a fully patterned membrane.

Hump can also be made as a linear arch supporting the fabric on a ridge line, and this principle has been used in the Portobello Market Canopy (Fig 2.15), and at the RFAC, Glasgow (Fig 4.6).

Eye loops
Frei Otto and Larry Medlin devised a system of mast head support using a loop (Fig 1.8) picked up at one point, which he used for the Montreal Pavilion. The system has occasionally been used subsequently by Larry Medlin and more recently by FTL Associates. Indeed, a similar system is used for the permanent cable roof to the Institute for Lightweight Structures (IL) in Stuttgart, designed originally as a trial structure for Montreal by Frei Otto and engineers Leonhardt and Andra (Fig 2.16).

Funicular arch support systems
The chain analogy for predicting the line of thrust of an arch was first observed by Robert Hooke in 1640. It is possible to support a membrane by an arch which has no bending and is itself stabilised by the membrane. This formfinding process can only be carried out using an equilibrium computer process (Ref 2.9). The arch is only moment-free under ideal prestress conditions. Under imposed loads, moments are generated and there are stability problems requiring the addition of bending stiffness. Frei Otto's entrance arch for the Cologne Bundesgartenschau demonstrates how slender the membrane stabilised arch member can be. For larger structures engineers have shied away from thin arches restrained by the membrane in preference for self-stabilising trussed arches, although the original proposal for Kuwait's Sports Stadium (Fig 1.7) assumed this would be possible at the larger scale of the project. Recently engineers Schlaich and Partners at Munich Skating Arena, and we ourselves at Stoke Garden Festival (Fig 2.17), have preferred the self stabilised trussed arch form.

Surfaces supported by compression ring beams
The classic example of this form of construction is the Raleigh Livestock Arena (Fig 1.4). The saddle surface roof is formed between two inclined parabola arches covering an area of 92m × 97m. The surface is formed with cables varying from 13mm to 32mm diameter at 1.8m spacing. The cladding used is one of profiled steel covered with insulation and bitumen waterproofing. More recently, Frei Otto designed a roof structure for a church at Bremen (Arch: Carsten Schrock) which consisted of a cable net spanning between laminated wood arches. The late Sir Ove Arup proposed a design for a sports hall in Denmark along similar principles.

This system of boundary arches to the net has also been used for a roof at Dulwich College and for the Calgary Olympic Saddle Dome (Fig 2.18), both engineered by Jan Bobrowski & Partners, the latter for which Buro Happold were the proof engineers. In these examples the cladding is of reinforced concrete plates and the finished structure becomes a concrete shell.


Leighton Gibbons

Fig 2.15 Portobello Market Canopy

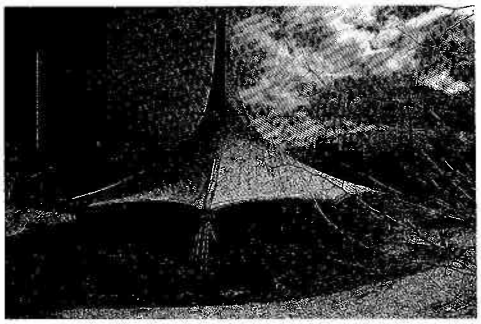


Fig 2.16 Institute for Lightweight Structures

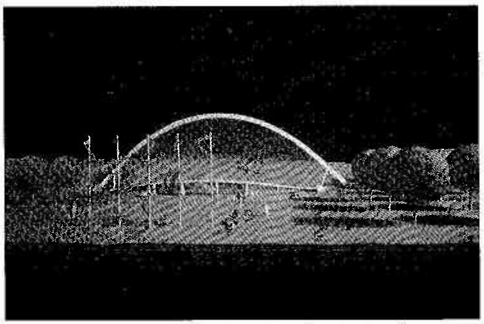


Fig 2.17 Stoke Garden Festival model

Air supported cable restrained roofs supported on a ring beam
For the US Pavilion at Expo '67 at Osaka, Davis and Brody, the architects, as a cost saving exercise, adopted a low profile cable restrained air supported roof enclosed by an earth berm – an idea which had been promoted by the father of air supported

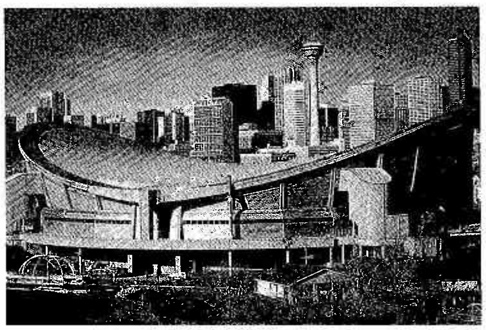
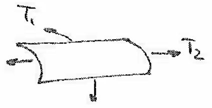


Fig 2.18 Calgary Saddle Dome

Pneumatic structures.

With pneumatic structures R_1 + R_2 have the same sign hence equation ③ applies. In a 2 way spanning panel of fabric the pressure can be taken totally by T_1 or T_2. There is no simple way of estimating the ratio of T_1 to T_2 since in many cases this depends on the crimp condition of the fabric.

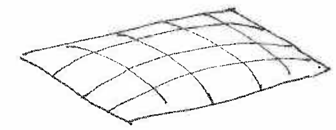
For a pressurised cylinder



$$T_1 = PR_1$$

$$T_2 = \frac{PR_1}{2}$$

For fabric panels bounded by cables it's wise to assume that the pressure is carried totally by yarns spanning in the short direction



Hence $T_1 = P \times R_1$

The condition at the panel ends demands that some tension goes into the T_2 direction therefore assume that $T_2 = \frac{1}{2}T_1$ or greater.

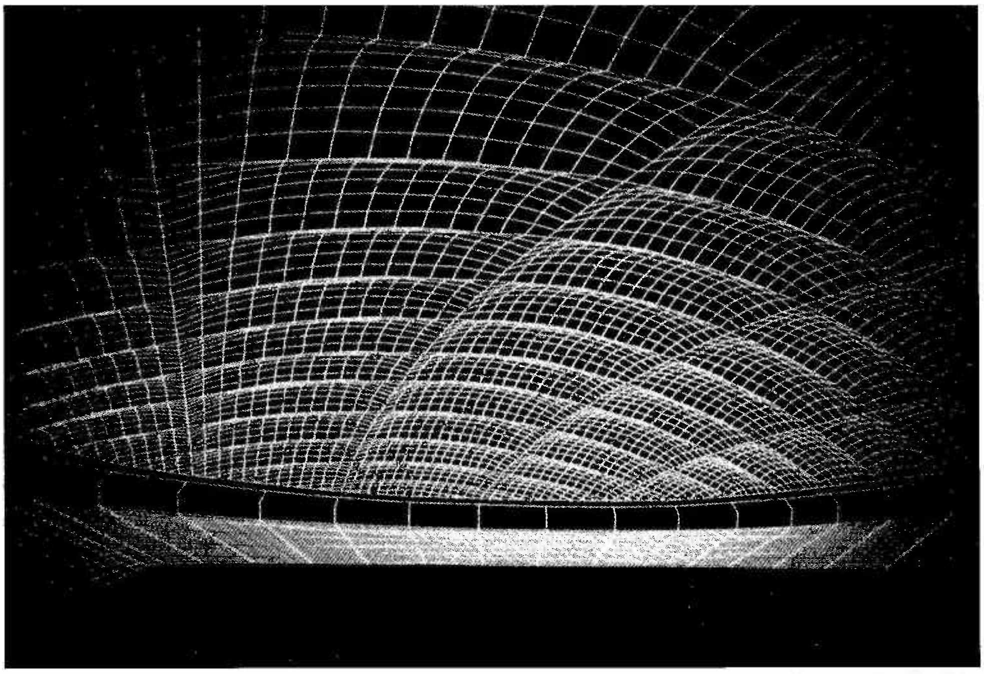


Fig 2.19 *Bristol Air House*

structures, Wally Bird. To solve the problem of anchorage, the engineer David Geiger proposed to use a moment-free compression ring. With the diagonal cable arrangement this ring became elliptical in form. The roof material was, in this case, PVC coated glass fibre cloth laced to the cable net.

Bird and Geiger realised that this form of construction could be used for covering stadia. The development of teflon-coated glass fibre cloth which met the US fire requirements allowed the design of these structures to proceed. The first developed was the Unidome, followed by the Silver Dome at Pontiac where the air supported roof was adopted after construction of the stadium had commenced. A similar development was anticipated by our own project at 58° N (Fig 1.17) and in our recent proposal for a 20,000 seat enclosure in Bristol (Fig 2.19).

Subsequent developments in the USA have been aimed at minimising first costs by using larger panels of cloth, with performance in service however being neglected. Some of these stadia in the northern half of America have experienced problems with snow drifting in the valleys causing local inversions which can lead on to damage and total deflation of the roof. The cure lies in the use of smaller panels, a higher inflation pressure and greater snow melt capacity, together with better form determination and patterning – all of which increases the initial cost. Air supported structures however, remain the most economic structural type of enclosure of large spans but they require to be properly detailed and managed.

Structural design of the details

Cable or tension structures utilise linear or two dimensional elements in tension as their primary load carrying elements. To create useful spanning or space-enclosing structures, the tension elements have to work in conjunction with compression and sometimes bending elements (Ref 2.11). From an architectural point of view, the separation of the tension, compression and bending elements leads to a visual expression of the way the structure carries loads which, for some types of structure, has become quite fashionable in recent times (Ref 2.12).

Such expression has become possible because of the enormous development in the techniques of structural analysis and 'form' determination. These have provided an accurate, fair and precise loading envelope for each and every structural component. The process of numbering, detailing and preparation of fabrication drawings can then proceed with reference to engineering characteristics of the individual elements (Ref 2.13) (Ref 2.19).

Cables

Wire rope cables are spun from high tensile wire. For structural work the cables should be multi-strand, typically 6 × 19 or 6 × 37 with independent wire rope core and galvanised Class A. Hoisting ropes with fibre core are usually ungalvanised and heavily greased, and are to be strictly avoided. For increased corrosion resistance, the largest diameter wire should be used and the cables can be filled with zinc powder in a slow-setting polyurethane varnish. This is done during the spinning process. E Youngs modulus of elasticity, varies as outlined below for cables of different composition.

For solid steel bar E = 210 kN/mm^2
For strand E = 150 kN/mm^2
For wire rope E = 112 kN/mm^2

In steel rope or strand, the above E values apply after the construction stretch has been pulled out of wire rope by load cycling to 50% MBL. In wire rope the construction stretch can be as much as 0.5%. This is of the same order of magnitude as the elastic stretch in the cable at maximum working load. In standing rigging, rigging screws or turn buckles are used to tighten the cables and to pull out the construction stretch, or in the case of steel rod, to allow for construction tolerances.

The life of a cable is reduced by corrosion and fatigue. The tension fatigue life of cables has been studied by various researchers over the years. On the basis of this it is wise to limit the maximum tension in a cable to 40% of the MBL for long life structures. For temporary structures, with a life up to ten years, 50% is acceptable. Generally the internal damping of clad cable net structures or of coated fabric structures is high so one would not expect a large number of cycles at high loads. Corrosion of galvanised cables in a covered situation can be considered negligible. External cables should be galvanised and filled with zinc paste. In this condition a life of 50 years can be expected in normal environments. The use of plastic sheaths is doubtful if water and corrosive agents can enter. The resulting corrosion can be worse than if the cable is unprotected and it cannot be inspected. Generally in a cable nearing the end of its design life, wire breaks can be seen and the cable should then be replaced. Cable fittings should be arranged to allow easy replacement.

For greater corrosion resistance, filled strand or locked coil strand cables can be used. These can also be fitted with a shrunk on polyurethane or polypropylene sleeve.

Stainless steel apparently offers total corrosion resistance but in some aggressive atmospheres or if air is excluded, intercrystalline corrosion will occur and it can be more damaging than with carbon steel cables.

Cable end fittings

The end terminations must ensure that the load is applied axially and must allow enough rotation at the

DYNAMIC RELAXATION

The principles of general equilibrium of node i, having mass m_i velocity $v_i = \dot{x}$, acceleration $\ddot{x}_i = v_i'$, and linked to adjacent nodes with geometry x, under externally applied forces $P(t)$ at time t can be described by Newton's 2nd Law.

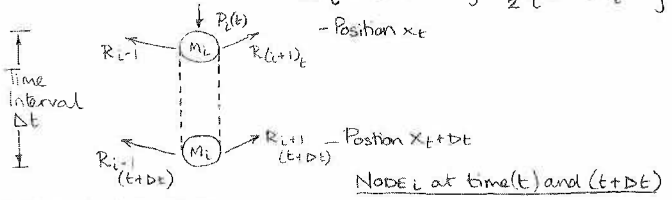
Mass × Acceleration + Damping × Velocity + Stiffness × Displacement = Externally Applied Forces.

$$M_i \ddot{x}_i + C\dot{x}_i + K x_i = P(t)_i \qquad (1)$$

Residual Forces $R_i^{(t)}$ are the difference between external and internal forces on node i at time t

$$R_i^t = P(t)_i - K x_i = M_i v_i'^t + C_i v^t \qquad \text{from (1)}$$

in difference terms $R_i^t = M_i \frac{1}{\Delta t}\left\{v_i^{t+\frac{\Delta t}{2}} - v_i^{t-\frac{\Delta t}{2}}\right\} + \frac{C_i}{2}\left\{v_i^{t+\frac{\Delta t}{2}} + v_i^{t-\frac{\Delta t}{2}}\right\}$



Node i at time (t) and $(t+\Delta t)$

giving a recurrence relation for Nodal Velocities.

$$v_i^{t+\frac{\Delta t}{2}} = v_i^{t-\frac{\Delta t}{2}} + B_i\left\{R_i^t\right\}$$

where

R_i^t = nodal residual force at time t
$v_i^{t+\frac{\Delta t}{2}}$ = nodal velocity vector at time t
M_i = nodal mass matrix.
Δt = time interval between iterations of calculation.

New nodal residuals $R_i^{(t+\Delta t)}$ calculated from updated nodal coordinates x_i^t

$$X_i^{t+\Delta t} = x_i^t + \Delta t\left\{v_i^{t+\frac{\Delta t}{2}}\right\}$$

ie Position at time $(t+\Delta t)$ = Position at time t + Time Interval × Velocity of Node i

Then.. Nodal Residual Forces Calculated

$$R_t^t = P_i(t) - C\dot{x} - Kx$$

ITERATIVE CALCULATION UNTIL Residuals small and Equilibrium between applied and internal forces.

Table 2.3 Principles of dynamic relaxation

pin so that even if the cable moves there is no bending induced.
The simplest and cheapest type of termination is swaged Talurit Eye made round a thimble. This would connect into a clevis type connection or onto the pin of a shackle. If it is necessary for the shackle body to be threaded onto the eye, then a reeling thimble must be used.

Swaged end terminations are the neatest and most streamlined fittings. However, hot-poured zinc terminations still have to be used for very heavy cables exceeding 50mm. They are still occasionally used for smaller cables but generally swaged fittings have replaced them. Epoxy with steel balls as a filler can be used in place of zinc. This material offers an improvement in fatigue life at the termination.

Bull dog grips
These are used to make a site connection. However, they are ugly and damage the rope. The ball type 'iron grip' is a better alternative.

Cross clamps for cable net construction
The standard detail development from the German Pavilion at Montreal onwards is a three-part forged steel clamp of which the two outer parts are identical (Fig 2.20). For a smaller structure the cost of dies for a forging may be too great, and consideration must then be given to using machined aluminium components. CNC milling machines can produce these very quickly and cheaply.

Boundary cable clamps
Forged steel clamps are generally used for the attachment of net cables to edge cables. A bent plate clamp can be used as a low cost alternative. Machined aluminium clamps could also be used where only a limited number of attachments are required.

Choice of fabrics for structural use
The range, reliability and quality of industrial fabrics for structural use is wide. A considerable choice of material properties is available to suit the particular requirements of any one project (Ref 2.14) (Table 2.4).

The commonly used coated fabrics are PVC-coated polyester, teflon-coated glass fibre and silicone-coated glass fibre. PVC is a versatile coating which can be applied to all base cloths. It is usually modified by the introduction of additives to produce a cheap stable, flexible and fire resistant coating which is easily joined by radio frequency welding. The polyester base cloth provides a strong, dimensionally stable and tolerant engineering fabric. It degrades with time through reactions mainly to UV light and rainwater. This degradation hardens the coating and makes it brittle. In a well-stressed tension structure the fabric does not flex much and this is not a problem. Unfortunately the appearance suffers with discoloration and dirt retention, and this usually determines the end point of the fabric. New fluoropolymer surface lacquers however, reduce the discoloration. Even so, a useful life of about ten years should be expected, with replacement of the membrane thereafter unless special requirements as to top coating are provided for.

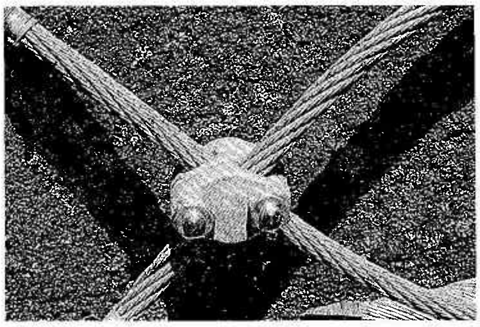


Fig 2.20 Cross clamp for Jeddah Sports Centre

Teflon-coated glass fibre was developed to overcome the disadvantages of PVC/polyester. It is self-cleaning and inherently fire resistant. Neither the glass base cloth nor the teflon coating degrade in sunlight. In these respects it seems to be an ideal material. Its strength is reduced by damage from creasing during fabrication and installation, and by the ingress of water. The teflon coating is quite soft and can be easily abraded. From the point of view of abrasion resistance, handling and ease of folding, its engineering properties are difficult, and because of this, the fabric needs to be patterned, fabricated and installed with great care (Ref 2.15).

Silicone-coated glass fibre was seriously developed by ODC, a Dow Corning subsidiary. After some five years of development a satisfactory product was finally achieved and the firm ceased manufacturing. However Dow Corning are still supplying the resins to another coater who is able to supply cloth to the same specification. The coating apparently offers excellent durability and, being more flexible, it does not suffer the same mechanical damage as teflon/glass. It can meet the requirements of Class 1 spread of flame to BS 476 Part 7. The fabric is seamed by gluing, which requires the skills of a specialist fabricator. Both teflon/glass and silicone/glass result in a cost per m² of finished fabric equal to about three times that of PVC/polyester. Because of this, owners usually prefer to have a PVC roof and replace it every ten years or so, when their building will be returned to its pristine glory.

From a purely structural viewpoint, in addition to fire resistance, robustness against abrasion and tearing, dimensional stability and resistance to ageing with time, biaxial stress strain characteristics become very significant in the accurate patterning of engineered forms.

As well as construction stretch which is different in the warp and weft directions, fabric suffers from crimp interchange and in the case of polyester fibre fabrics, creep. Construction stretch and creep are allowed for in the patterning of the fabric by compensating the patterns so that they stretch out to their correct size under prestress.
If a glass fibre fabric with 10kN/m warp tension and 5 kN/m weft tension is loaded so that these loads are reversed, the weft will extend by about 2% while the warp will shrink. This is because the weft yarns straighten out and the crimp in the weave goes into the warp. This effect is called 'crimp interchange' and accounts for most of the extension of glass fabrics where the fibres themselves are very stiff.
Load/extension ratios (EA) in kN/m width for straight yarn in fabric, that is for uniaxial tension in the warp direction, are given below.

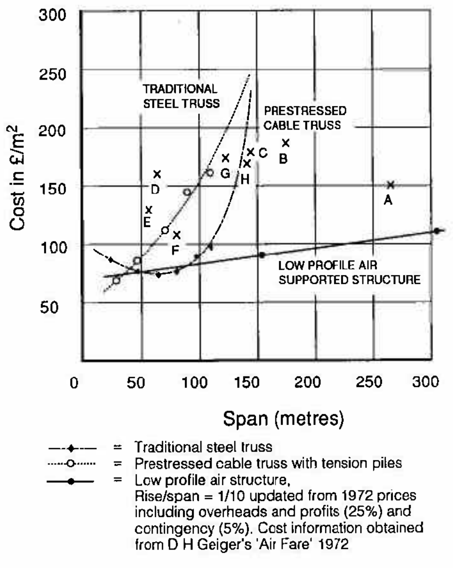
	MBL	EA
Glass fabric	180 kN/m	6,900 kN/m
Polyester Type II	90 kN/m	670 kN/m

Engineering justification

In the early days of modern tension structures, design comparisons with naturally occurring phenomena and forms were frequently made (Ref 2.16). The engineers calculations were primitive (if no less effective for that), the knowledge of components rather incomplete, and the geometry for the contractor to build to, extremely time consuming to determine. Undeterred, engineers and architects continued to pursue a whole range of designs since from an engineering standpoint, the light structural weight of flexible tension structures allows very large areas to be covered economically and elegantly (Ref 2.17). This possibility is clearly demonstrated by theoretical considerations of optimum span in relation to lattice, cables and unsupported structures (Fig 2.21). Indeed, a survey of such long span structural types has also established this trend (Fig 2.22). However, all the technology has now developed and a considerable body of knowledge exists for us to solve such problems.

The structural analysis of these structures is non-linear and requires specialist use of sophisticated computer programs, and considerable experience in form determination and selection of component hardware. The flexibility of the structure itself means that deflection under load can be large, so that careful consideration of a structure's behaviour under environmental loadings is required. Being sophisticated pieces of engineering, careful and knowledgeable communication to the contractor of the special requirements for the erection of these constructions is necessary for economic prices and reliable quality to be obtained (Ref 2.18).

Fig 2.21 Cost comparisons for different structural types



× = Air supported roof project costs

A	Feasibility study to cover a township in Northen Canada (119,096m²)	£149m²
B	Pontiac Stadium (37,026m²)	£185m²
C	University of Iowa (16,693m²)	£179m²
D	Milligan College (3, 279m²)	£156m²
E	Santa Clara (5,376m²)	£136m²
F	US Pavilion, Osaka (10,811m²)	£109m²
G	Calgary Olympic Coliseum Feasibility Study (44,000m²)	£174m²
H	Bristol Stadium Feasibility Study Note : only cost of membrane and cable. (25,000m²)	£168m²

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

Much hard earned knowledge has been acquired during the solution over the years of a great many practical design commissions and through this interaction process. However, the challenge to design and construct elegant and economic buildings using the possibilities offered by surface stressed structures still remains today.

Ian Liddell

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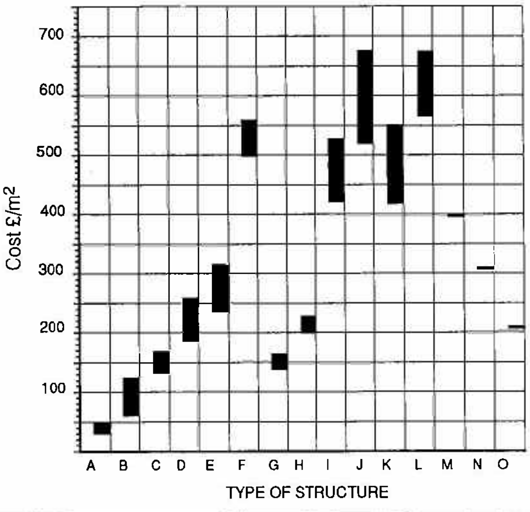
AVERAGE PRICES ON A 'FLUCTUATING BASIS' AT NOVEMBER 1983
Prices are based upon the total floor area measured between external walls and without deduction for internal walls.



KEY		£/m²
A -	AIRHOUSE	30 -50
INDUSTRIAL BUILDINGS		
B -	FARM SHEDS	60 - 120
	FACTORIES	
C -	LETTING (incoming services only)	135 -170
D -	LETTING (including lighting, power & heating0	190 -260
E -	OWNER OCCUPATION (light indusrial use)	240 - 320
F -	OWNER OCCUPATION (high technology production)	500 - 560
	WAREHOUSES	
G -	LOW BAY - LETTING (no heating)	135 - 160
H -	LOW BAY - OWNER OCCUPATION (including heating)	200 - 230
	OFFICES FOR OWNER OCCUPATION	
I -	LOW RISE (non air-conditioned)	430 - 530
J -	LOW RISE (air-conditioned)	520 - 680
LEISURE CENTRE		
K -	DRY	420 - 550
L -	WET	570 - 670
M -	SPORTS HALL	390
N -	SCHOOL GYMNASIUM	320
O -	KILMARNOCK LEISURE CENTRE	220

Fig 2.22 Market survey of long span structures

Table 2.4 Material properties

Material	Cost/m^2	UTS (for 1000g foil	EL	Durability	Translucency	Fire Resistance	Colour Ranges	Applications
FOILS								
PE Foil PVC Foil	20p 50p			E	88%	Not	Clear or Black	Very low cost greenhouses.
Woven orientated PE strips and PE Foil	30p 70p			E	70%	Not if Clear Not	All inc. Clear Clear or black	Large low cost greenhouses and Pool Shelters.
Polyester	£5 For 1000g Material			B	95%	Not	All	Air cushions for Tokyo Roof
FEP	£10			A	95%	A	Clear	Durable clear foils for high light transmission roofs. Span limited to 1.0m for FEP and 2.0m for EFTE. Can be reinforced with wires overlaid.
ETFE Tefzel	£10			A	90%	A	Clear	
COATED FABRIC								
PVC Coated Polyester Cloth	£2–£7	20—200	16%	D–C	30%–8%	B	All	Widely used for air houses and fabric structures. Can be coloured, opaque etc. High translucent materials are less durable.
PVC Coated Nylon	£2–£7	20–200	20%	D–C	30%–8%	B	All	As above but less popular because of poor dimensional stability and creep.
PVC Coated Kevlar	?	100–400	5%	C	opaque	B	All	Would only be used where high strength is required, jointing problems. Must be opaque to protect Kevlar.
Hypalon Coated Polyester		20–300	19–20%	C–B	opaque	Not	All but not translucent	Used for radar domes. Hypalon degrade and powders on the surface – can be repainted.
PVC Coated Polyester with Tedlar (PVF^2 laminate)	£3–£8	50–200	16%	B	7%–20%	B	All	Used occasionally in USA. Laminate provides a stay clean surface. Welded joints have low strength.
PVDF Coated Polyester	£15–£20	50–150	16%	B–A	?	B	White	New product. No example known.
PVDF Coated Glass Cloth	?	40–100	6%	A	35%	A	Milky	New product. No example known.
PTFE Coated Glass Cloth	£30–£40	30–200	6%	A	5%–15%	I	White and limited colours	Has been widely used for "permanent" fabric structures. First example now 11 years old.
PTFE Coated Kevlar		50–400		B–A	Zero	A		Used for radomes.
Silicon Coated Glass	?	30–200	6%	B–A	15%–30%	B	Clear	New material. Two structures are currently under construction in America by ODC.
REINFORCED FILMS								
Polyester Reinforced PVC	£1.50–£2.50	10–30KN		D	80%	Not if clear		Widely used for windows in structures and clear sheeting on scaffolding.
FEP or ETFE film reinforced with glass, Kevlar or Steel Wire Mesh				A	50%–80%			Considerable research has gone into this material but at present it is not in commercial production.

Interactive Graphic CAD for Tension Structures

Computer techniques are an essential feature of the successful design and implementation of tension structures. TENSYL is an integrated program suite for the shape generation, load analysis and fabrication geometry processing of membrane and cable net structures. Developed originally for the HP9845 desktop computer, and gradually enhanced for a wide range of projects over the last 10 years, TENSYL has now been completely rewritten to exploit the developments in computer technology over that period. The general aim of the new version was for a significant increase in the speed of the CAD process, through faster computation and improved user interaction. As the basic numerical techniques behind the program are now well established, most effort has concentrated on the user interface.

The vehicle for this development is a technical 'workstation' computer. Such hardware features a high performance processor, coupled closely to a high resolution colour graphics display, our choice being a Hewlett-Packard 9000/350 workstation with SRX graphics processor. This latter drives a 19″ colour monitor with 1280 × 1024 pixel resolution and simultaneous display of over 16 million different colours. The computer uses the UNIX operating system and TENSYL is written in the 'C' programming language.

With access to hardware of such power and sophistication, the challenge is to develop software that best exploits it. Fully interactive colour graphics, coupled to an effective user interface are the key. These techniques have been applied to business software, notably on the Apple Macintosh, and to some drafting packages in the construction industry, but their use for engineering analysis software is still comparatively rare.

The user interface

In TENSYL there is a graphical image of the numerical model under consideration on the monitor at all stages of the program, and the user has control at all times of the orientation and range of that view. Simultaneously, a menu of commands is displayed on the right hand side of the screen (Fig 3.1). These commands may themselves perform a function directly, or provide access to a further, more detailed, menu of commands which temporarily overwrites the calling menu. Whilst retaining the user selected view, the screen image will be automatically modified to show information relevant to the current menu. For example, node restraint conditions (Fig 3.2) or element specified stresses (Fig 3.3) are displayed when appropriate.

Interaction with the menu commands, and directly with nodes and elements displayed, is through an on-screen cursor which is positioned and activated using a two button mouse. Varying labels adjacent to

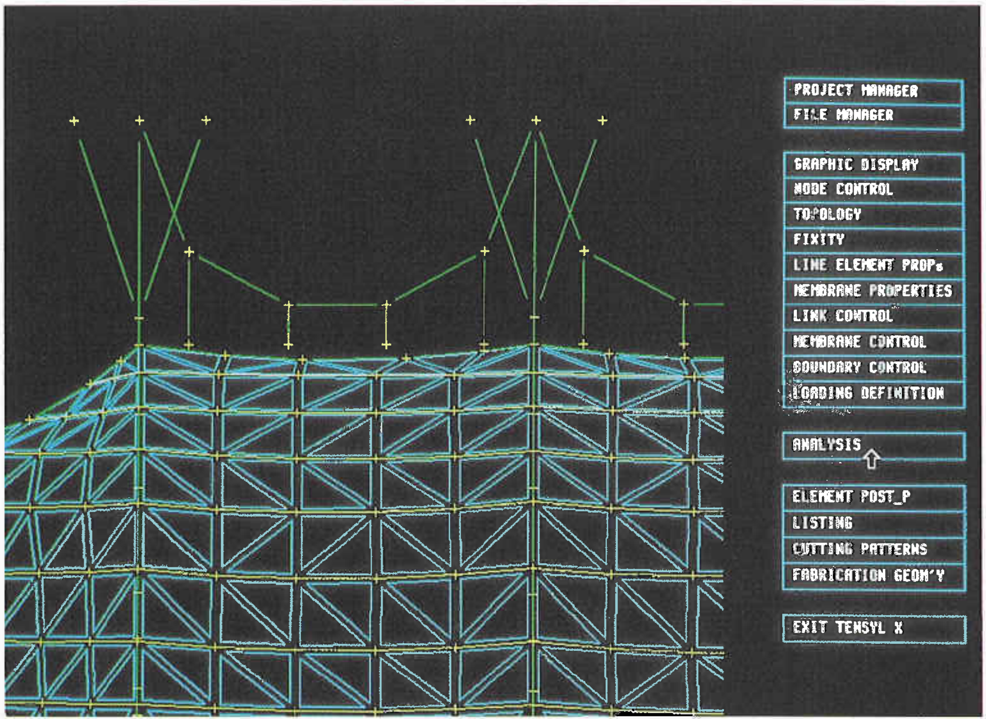


Fig 3.1 TENSYL main menu

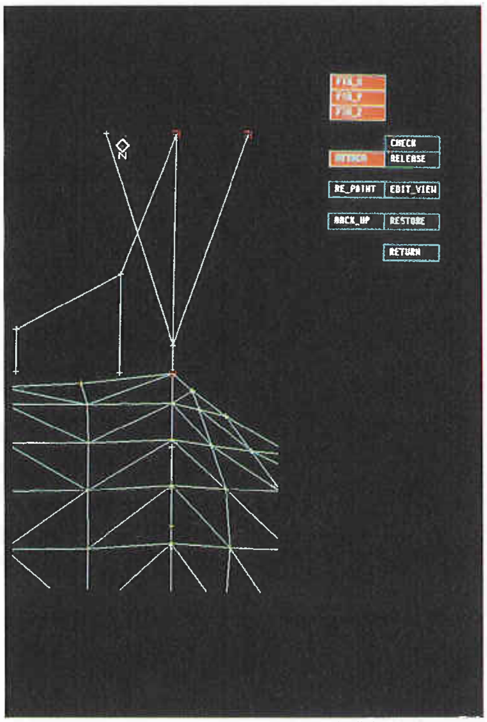


Fig 3.2 Node fixity assignment

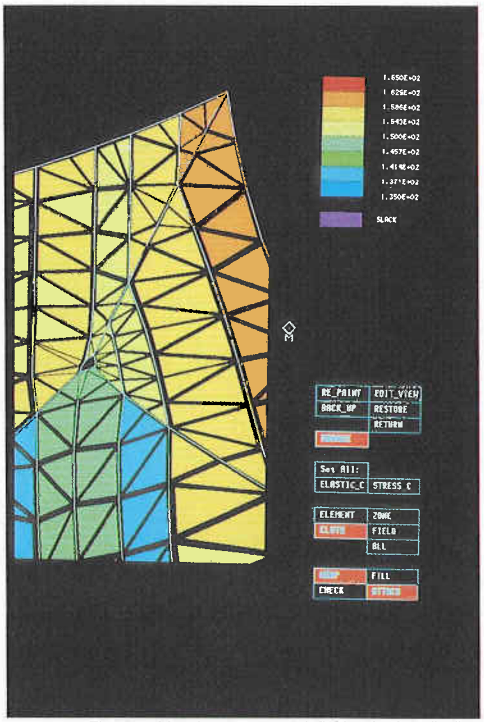


Fig 3.3 Membrane stress definition for formfinding

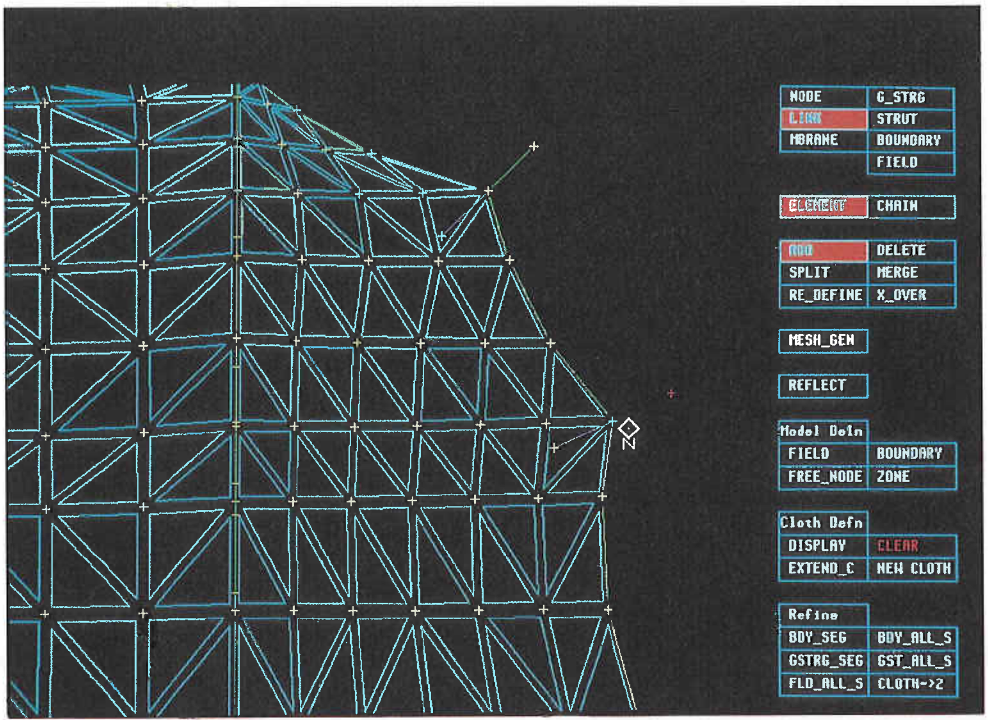


Fig 3.4 Local mesh editing – addition of a link element

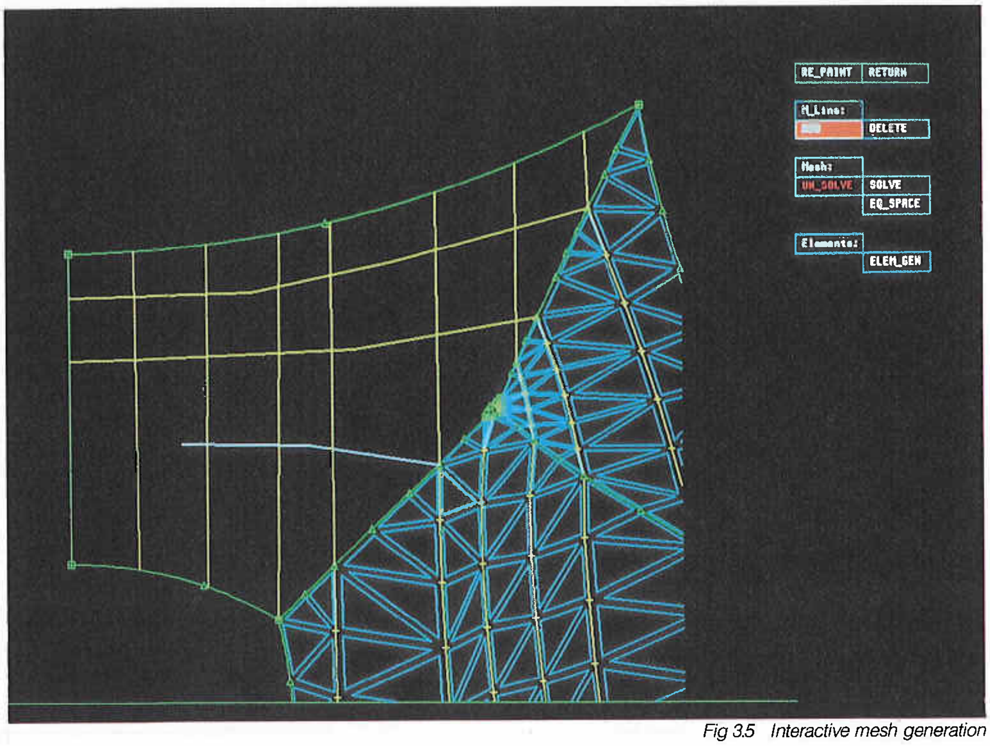


Fig 3.5 Interactive mesh generation

the cursor indicate to the user the next information expected by the program. In Fig 3.4 TENSYL is waiting for the user to pick a second node as part of the interactive addition of a cable element. Generally the left hand mouse button performs an action, such as element picking or command selection, whilst the right hand button switches control between model and menu interaction modes. It is also used to cancel or step backwards through part completed command actions.

Direct keyboard entry of data is kept to a minimum. When necessary, a prompt and editing display zone is activated below the graphics display area.
To facilitate learning and use, the interface style has been kept consistent throughout the various levels of the program. The numbers of different colours and symbols used at interactive stages is deliberately limited, as too great a variety of on-screen information can become counterproductive.

The design procedure

To initiate the numerical model, the node co-ordinates of membrane system points must be keyed into the computer. Boundary lines are then defined between system points, and approximate initial curvatures established by the use of temporary mid-side nodes. For a single field structure these boundary lines denote edge scallop cable lines. With a multi-field structure, the boundaries between fields are representative of ridge cable lines.

The mesh generator then operates on a field by field basis, with the options of node continuity or discontinuity along common boundary lines. Membrane and cable net meshes are generated on the basis of a rectangular topology. Within a screen display of a field's boundaries, the mesh outline is sketched as an orthogonal grid. These mesh lines may be established in any order, using delete and amend options as the grid is built up (Fig 3.5). This mesh may then be 'solved' to generate the spatial co-ordinates of node points at line crossovers.

Once solved, membrane and geodesic line elements are then automatically generated within the rectangular topology. The boundary line definitions are automatically updated for the refined model. Having exited the mesh generator, then individual elements of any type may subsequently be added, deleted or edited directly on the screen. Node restraint conditions may also be indicated graphically with direct attachment or detachment of a selected combination of translational fixities. There are no limits to the number of restraints, as these are held within a node's internal data structure. Likewise element elastic properties and specified stress levels are attached and assigned on screen. Elements are filled with varying colours to illustrate magnitudes of stress.

Form generation and load analysis use the same analytic section of the program. The graphic display during analysis shows both plan and elevations of the problem, which are updated at interim solution points as the analysis proceeds. The node with the current maximum out-of-balance residual force is flagged, to aid the detection of physical instabilities. Analysis control parameters and load case numbers are assigned via on-screen edit boxes.

Individual nodal loading coefficients have been assigned interactively on a separate command page. Up to five sets of coefficients may be held at any one time. These coefficients are multiplied by wind or gravity loading factors when defining a particular load case. Combined cases are permissible, together with the application of an internal pressure which might represent the inflation of an air-supported structure or an internal wind pressure.

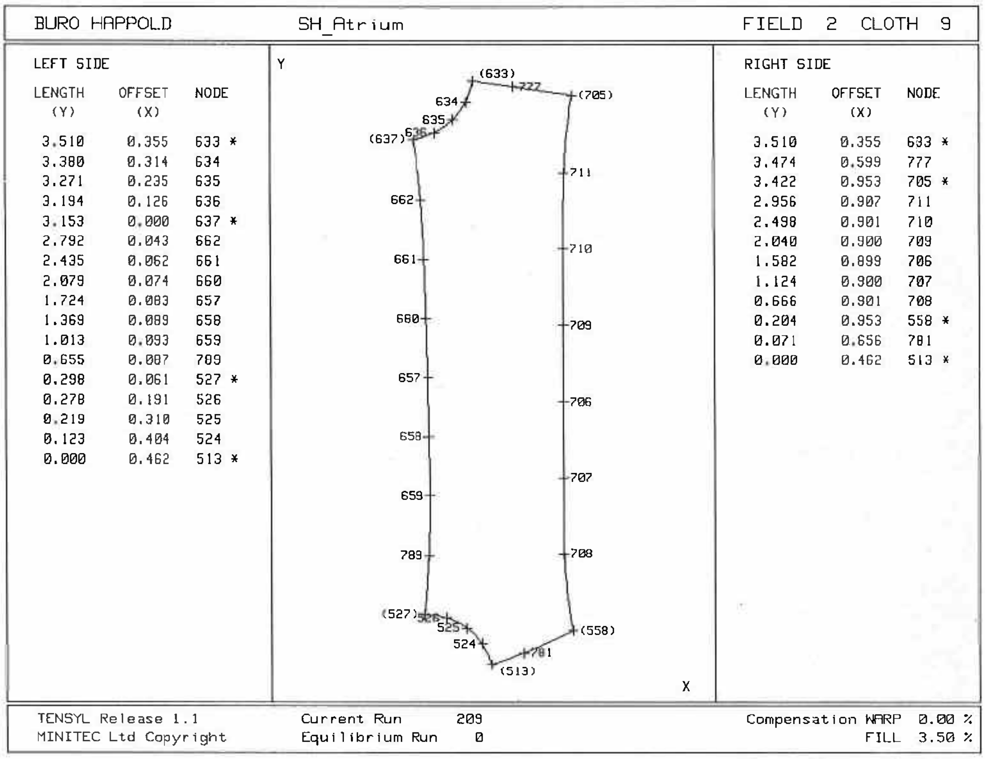
The post processing module gives a colour display of element stresses, and facilitates the rapid assimilation of a large amount of data. Hard copy listings of all results and co-ordinates may be output via a laser printer, which can also be used for graphics dumps of the screen image.

The fabrication geometry module provides for the generation of membrane cutting patterns (Fig 3.6) and associated component geometry, such as masthead and membrane plate angles. Adjustment of boundary node positions for cloth width optimisation is assisted by an on-screen display of all the unfolded cloths associated with a particular field.

Structure visualisation

An advanced structure visualisation module has been included in TENSYL to aid the interpretation of complex surfaces and their relationship to adjacent solid elements. (Fig 3.7) Coupled with the high form computation, this creates a powerful interactive facility for architectural interpretation at preliminary design stages, as well as providing high quality images for presentation to the client. This module of TENSYL makes full use of the SRX graphics coprocessors attached to the workstation. These provide hardware implementation of hidden surface removal, smooth surface shading, multiple light sources and full surface texture and specular reflection modelling (Fig 3.8). In addition the surface representation of complex elements is assisted by the support of non-uniform rational spline surfaces.

The analytic model has been supplemented by the addition of further modelling primitives. These include general brick elements, walls, floors, and straight or radiused tubes or rectangular sections. (Fig 3.9) Individual textures and colours may be assigned to these additional elements, which may also be displayed in outline form as wireframe models.



```
BURO HAPPOLD                SH_Atrium                         FIELD  2  CLOTH  9

LEFT SIDE                                                     RIGHT SIDE

LENGTH    OFFSET    NODE                                      LENGTH    OFFSET    NODE
  (Y)       (X)                                                 (Y)       (X)

 3.510     0.355    633 *                                      3.510     0.355    633 *
 3.380     0.314    634                                        3.474     0.599    777
 3.271     0.235    635                                        3.422     0.953    705 *
 3.194     0.126    636                                        2.956     0.907    711
 3.153     0.000    637 *                                      2.498     0.901    710
 2.792     0.043    662                                        2.040     0.900    709
 2.435     0.062    661                                        1.582     0.899    706
 2.079     0.074    660                                        1.124     0.900    707
 1.724     0.083    657                                        0.666     0.901    708
 1.369     0.089    658                                        0.204     0.953    558 *
 1.013     0.093    659                                        0.071     0.656    781
 0.655     0.087    789                                        0.000     0.462    513 *
 0.298     0.061    527 *
 0.278     0.191    526
 0.219     0.310    525
 0.123     0.404    524
 0.000     0.462    513 *

TENSYL Release 1.1          Current Run        209          Compensation WARP  0.00 %
MINITEC Ltd Copyright       Equilibrium Run    0                         FILL  3.50 %
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Fig 3.6 Typical cutting pattern

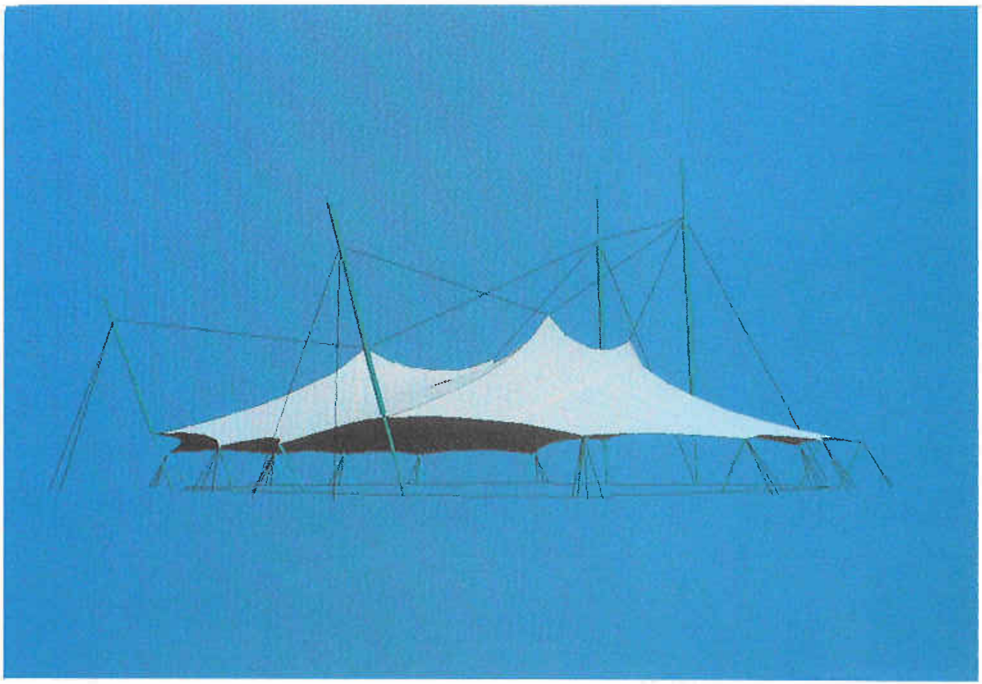

Fig 3.7 Membrane clad cable net structure

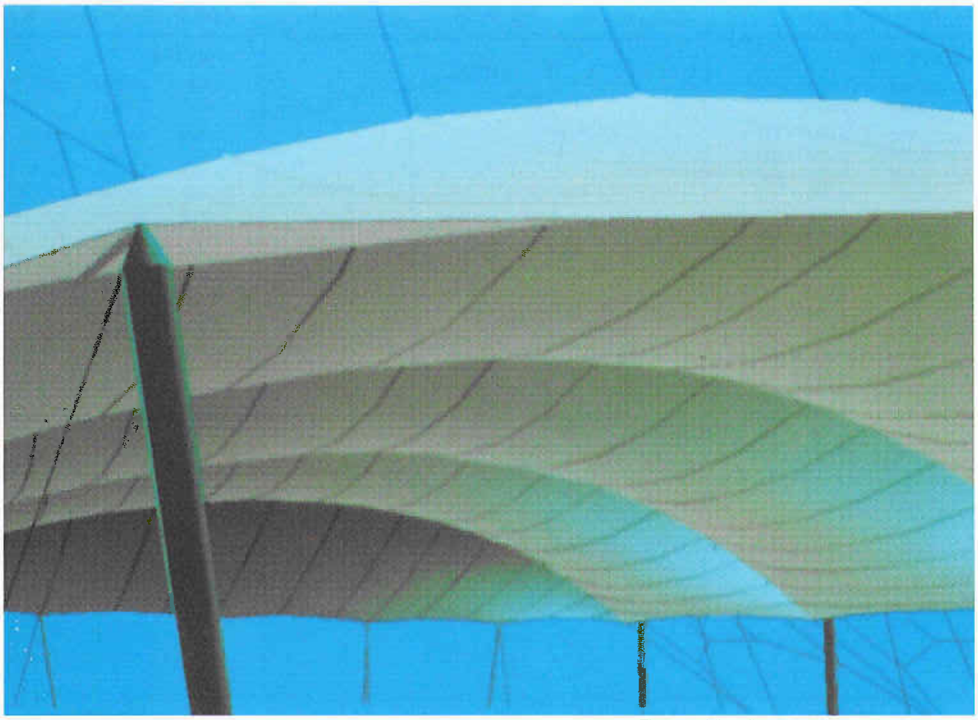

Fig 3.8 Visualisation of internal appearance

Fig 3.9 Additional modelling primitives

Fig 3.10 Proposal for timber bridge

Varying degrees of transparency may be assigned to membrane elements or planar sheets to simulate transparent fabrics such as foils or window glazing. The available lighting options include ambient, parallel, point and case light sources, all of which may be assigned differing intensities, locations and colours through direct on-screen editing. Similarly, element textures and colours may be adjusted, and the combined overall effect is immediately displayed on screen.

The additional modelling primitives may also be used independently of the analytical model for the visualisation of any type of structure (Fig 3.10). TENSYL has been further used to study the layout and visual impact of new buildings within an established area.

The combined visualisation model may be viewed in perspective from any chosen point. The observer's angle of view is selected by specifying the equivalent focal length of a 35mm camera lens. The graphics processor permits rapid incremental changes in both view point and sight point, whilst retaining the full graphics enhancements. Double buffering of the image ensures flicker-free transitions, and a 'walk through' facility allows the designer to visualise internal impressions of the structure whilst moving backwards or forwards, turning left or right and looking up or down. (Figs 3.11, 3.12)

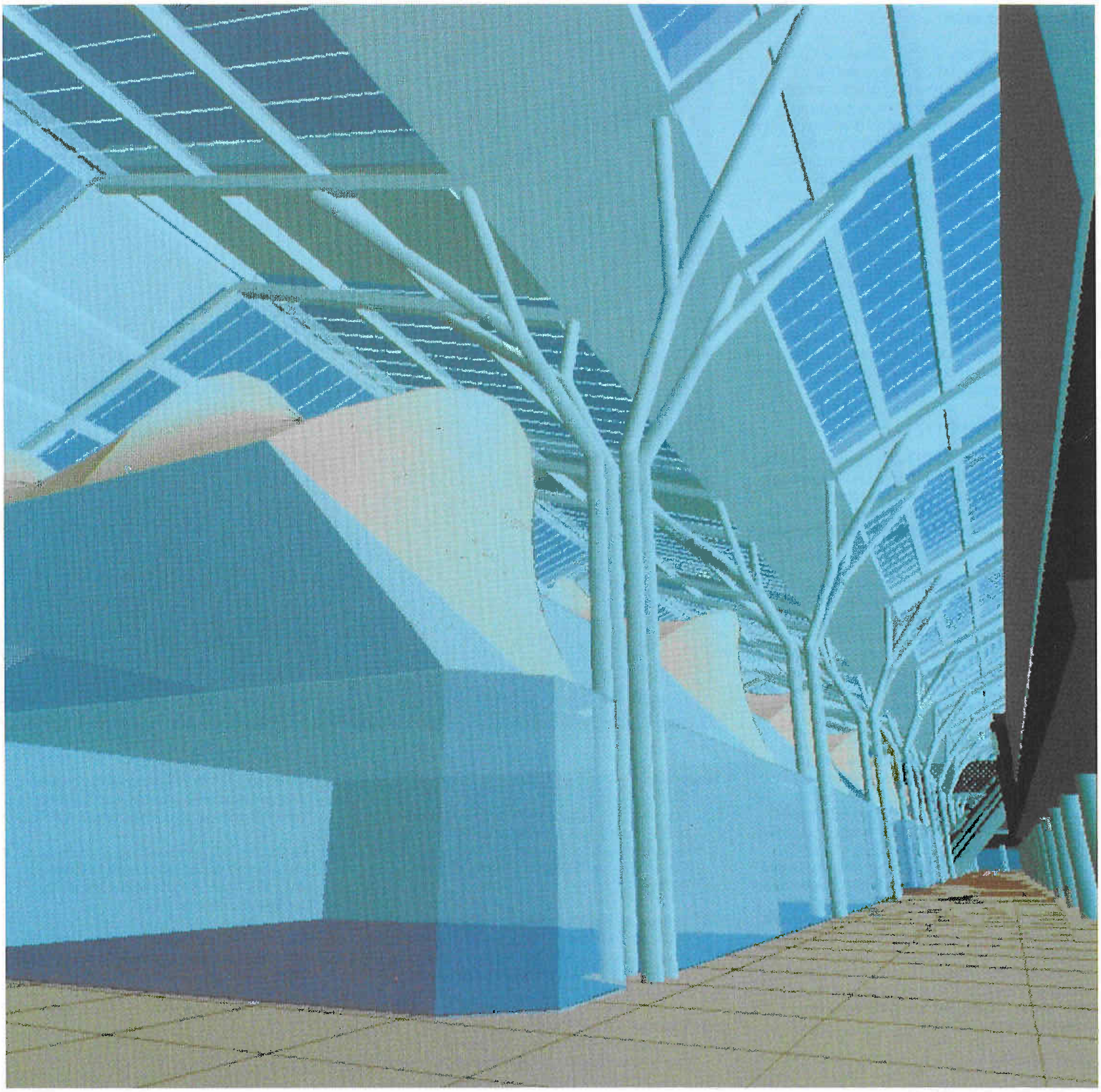

Fig 3.11 Interior of shopping mall

Benefits in practice

The potential benefits of a fully interactive CAD system have been realised in the new TENSYL program. From an engineering user's standpoint the system has proven easy to learn, and popular in use mainly because of the elimination of tedious manual manipulation of large data files. Early projects indicate a minimum five-fold improvement in total time taken for numerical model assembly and application. The analytic section of TENSYL now computes about sixty times faster than the old version.

When coupled with the high quality visualisation capability, this speed of form generation and adjustment makes it practical for the architect to work directly alongside the engineer at the preliminary design stage. This joint interactive involvement can only benefit the project, and has particular relevance with the increasing use of tensile elements integrated into a total building.

Future developments

The work to date on the TENSYL program provides a base for development in the future. The software itself has been written in a modular form, with libraries of routines such as graphics, menus and visualisation controls suitable for other interactive applications.

Specific technical developments for TENSYL include integrated mesh refinement and pattern width adjustment, more comprehensive component scheduling, enhancements for cable network processing and the addition of fully non-linear beam elements. These extensions are currently underway with the support of a DTI/SERC Teaching Company Scheme which is being operated jointly with City University.

Future developments in computer graphics are directed towards the production of 'photo realistic' images, with improved hardware implementations of ray-tracing and radiosity visualisation techniques. However, having produced these images on screen, the problem of producing hard copy of a similar quality still remains. Reasonable photographs may be taken directly from the screen, and machines are available to make colour slides directly from the computer RGB video signal but at a high unit cost. Hard copy colour printers have yet to achieve the necessary resolution and colour range. For presentation purposes, hardware is also becoming available to assist in the production of video tapes from screen images, permitting the dynamic presentations of a scheme.

David Wakefield

Fig 3.12 Interior of shopping mall

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Recent Developments in the Design of Tension Structures

In recent years Buro Happold, and in particular the Special Structures Group, have worked for a large number of different clients on an extremely wide range of projects using tension structures. In doing so, either as part of an architectural and engineering team, or as a direct appointment, our design techniques and skills have been continually updated and improved, particularly when projects have sought to utilise the full potential of new materials and techniques in construction.

Such a project range has inevitably yielded an improvement in flexibility and in the efficiency and effectiveness in handling the design of tension structures in our office. Whilst we have been using a suite of formfinding and analysis programs developed in-house over the past ten years, the recent investment in a new generation computer and in the development of a new software package has brought us to a higher level of sophistication. The system, TENSYL, has been described in detail by Dr David Wakefield in the previous article.

The advantages which the new system has brought include a very short learning period to handle the program requirements, thus opening the package to a wide usage among designers; almost instantaneous analysis of very large models, permitting a greater flexibility with analysis time; and a very high quality solid graphics output capable of allowing immediate visualisation of the design. Because of the speed of input and analysis, such graphics can readily be obtained at the start of a project, both to help the design team as a whole to visualise the outcome and to provide us with an excellent design check on final form, deflection shapes, and stress contours under load. Indeed, the final output is presented in a form which enables the fabricator to mark and cut the cables and membranes allowing for the effects, where necessary, of constructional stretch, crimp interchange and prestressing. In the case of membranes, patterns can be arranged to minimise wastage, which for permanent, long life, high unit cost materials such as PTFE cloths can be very important to the end cost of the project.

Further potential developments include much greater use of computer drafting for structures in which detailing is of a standard or repetitive nature, and for presentation of component schedules.

Fig 4.1 Membrane roof for CFAN tent

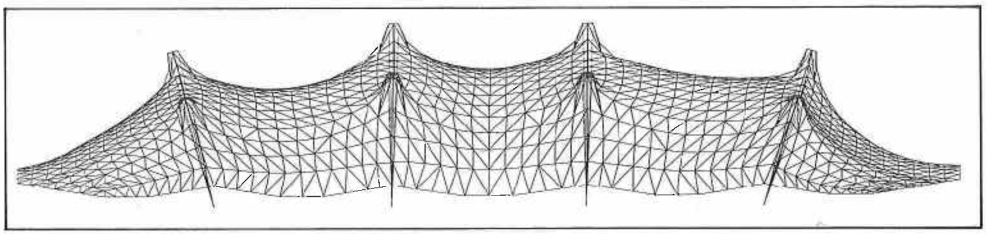


Fig 4.2 Computer elevation of CFAN tent

Fig 4.3 Pink Floyd umbrellas

Large, small and unusual commissions

The largest of the structures developed by the group during 1988 was an arena 130m long × 65m wide × 35m high, destined to travel the country providing a venue for major events. It is later expected to lead on to development of a design for a 9,000 seat arena. This project is on a similar scale to the mobile auditorium built for clients 'Christ for All Nations' (CFAN) in 1986, consisting of a wavy coloured PVC coated polyester membrane roof supported on 12 internal steel masts (Figs 4.1, 4.2). With an overall length of 130m and width of 95m, and holding an audience of up to 40,000 people, the CFAN structure itself comprises two end and three internal fields of heavy polyester membrane, each approximately 95m wide by 23m long. With such large fields, reinforcement belts had to be welded into the fabric to prevent the propagation of tears through the fields when under extreme loads. The structure was originally designed to be easily re-erected so that it could be transported between various locations in the African continent. It is now proposed to bring this structure to Europe. In contrast, the major challenges of the new arena are to provide a completely column-free space and the greatest possible degree of mobility, both in terms of transportation and erection.

The smallest structures designed in the past year were a series of lighting umbrellas for Michael Laird and Partners, designed to provide focal points for open plan office areas. A successful prototype was made by Landrell Fabric Engineering and we await further developments. In some way these are reminiscent of our umbrellas designed for the 1978 Tour of America by the Pink Floyd music group. (Fig 4.3) These were made from cotton polyester fabric and mounted in light aluminium frames.

Our most unusual commission undertaken in 1988 was to design a high speed airship, able to travel at 185 kph. This involved developing a hull with an internal pressure sufficiently high to achieve the stiffness necessary to keep the hull straight when turning (Figs 4.4, 4.5). As the elements of conventional pressure airship construction are not able to handle these internal pressures, a new construction system had to be originated, using an

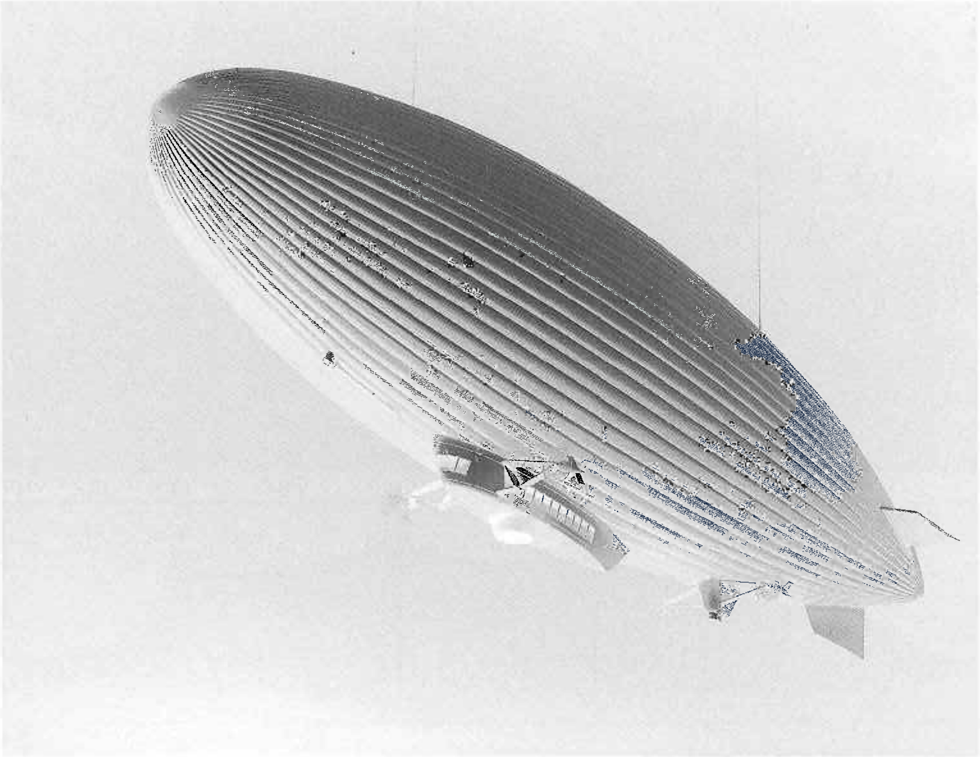


Fig 4.4 High speed airship

internal network of high performance kevlar belts within the membrane envelope. This design is now complete in our office and the next stage is to construct a prototype airship for a full programme of testing.

However, tension structures are not generally designed for such a high degree of flexibility, and rarely demand the mobility of a travelling arena. Most clients have a single site where a permanent or semi-permanent enclosure is required. The flourishing leisure industry is currently presenting rapidly growing opportunities for designers to provide tension roofs covering events of all types. For a dolphinarium in Windsor Safari Park we provided a semi-circular roof to cover the audiences during the shows (Fig 4.6). Although sheltering them from the rain, the structure still permits spectators to get wet when the dolphins get rough! Such flexible structures can be built quickly to avoid disrupting events on the ground – the highly sculptured appearance appealing aesthetically to the crowds. A 1,000m² roof has also been erected over a ride at Blackpool Pleasure Beach for which our clients were Landrell Fabric Engineering. The ride was working after only one day's interruption during the installation of the roof membrane. (Fig 4.7)

During 1988 three smaller but interesting structures were designed and successfully built. At the Glasgow Garden Festival we designed a canopy for the Royal Fine Arts Commission on behalf of fabricators Clyde Canvas. The challenge here was to create a perimeter without the more usual scalloped edge formed by arcs of cables, each meeting another at a point. In this case the perimeter was wavy, undulating smoothly and without obvious tie back points. This demanded that as well as scallop cables (or in this case polyester webbing belts) in the tensioned concave parts of the perimeter, there had to be curved tubes in the convex compression parts. These were tied back to side masts with short rod links carefully positioned to overcome the tendency of the tube to flip over.

In order to provide an alternative venue for the 1988 Bath Arts Festival during the refurbishment of the Assembly Rooms, in conjunction with several other local companies, we designed a temporary tension roof to hang within the vast arched span of Green Park Station. It extended 70m with a span of 20m, weighed 2kg/m² and was supported on small diameter cables, with internal wind uplift on the inside being resisted by its upwards curvature. The whole roof was erected in 12 hours overnight,

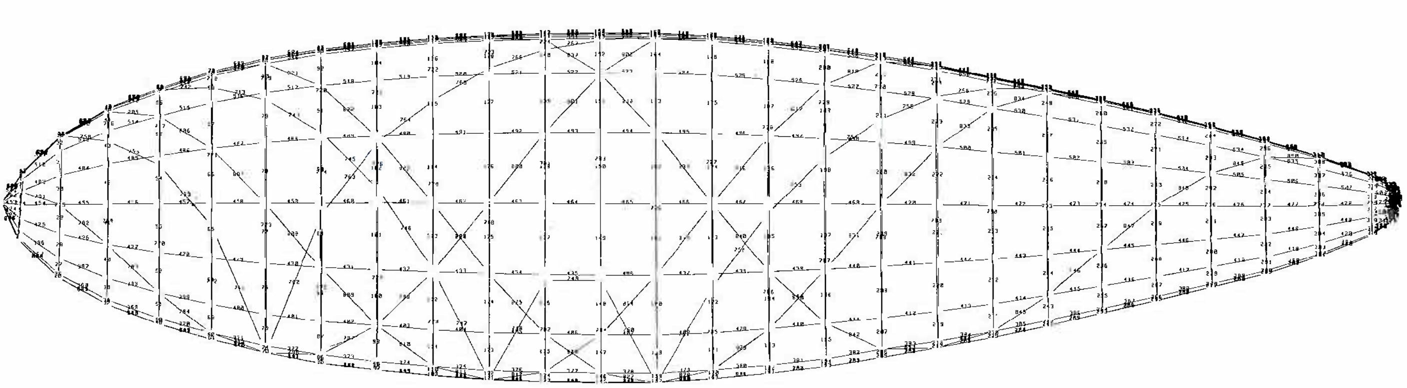
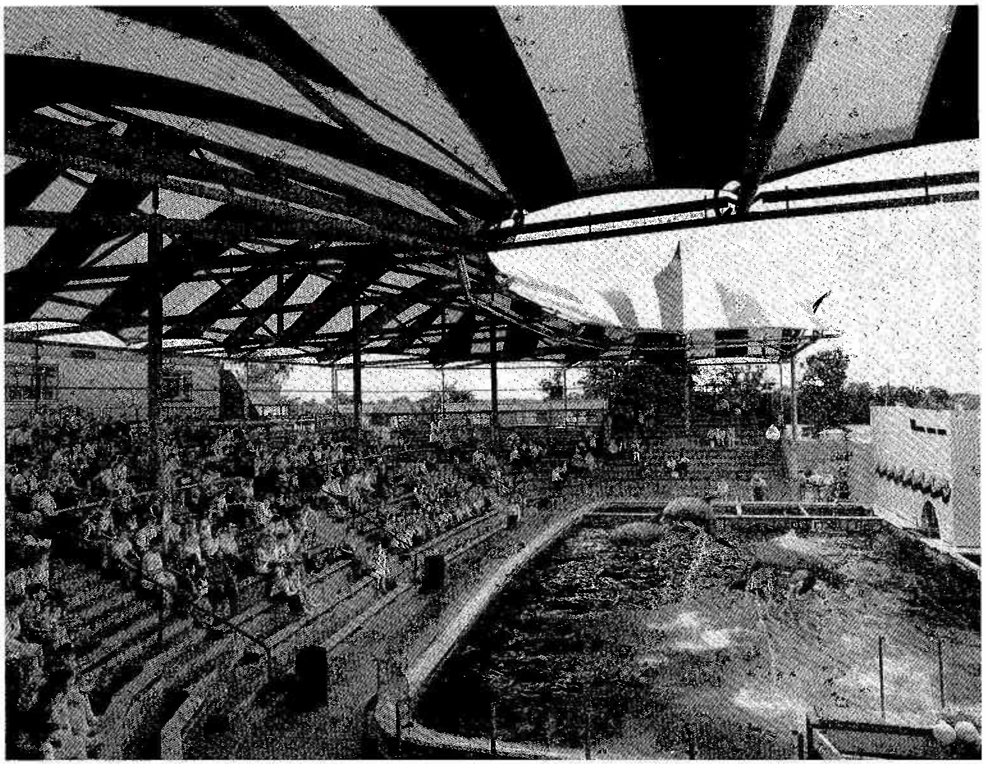
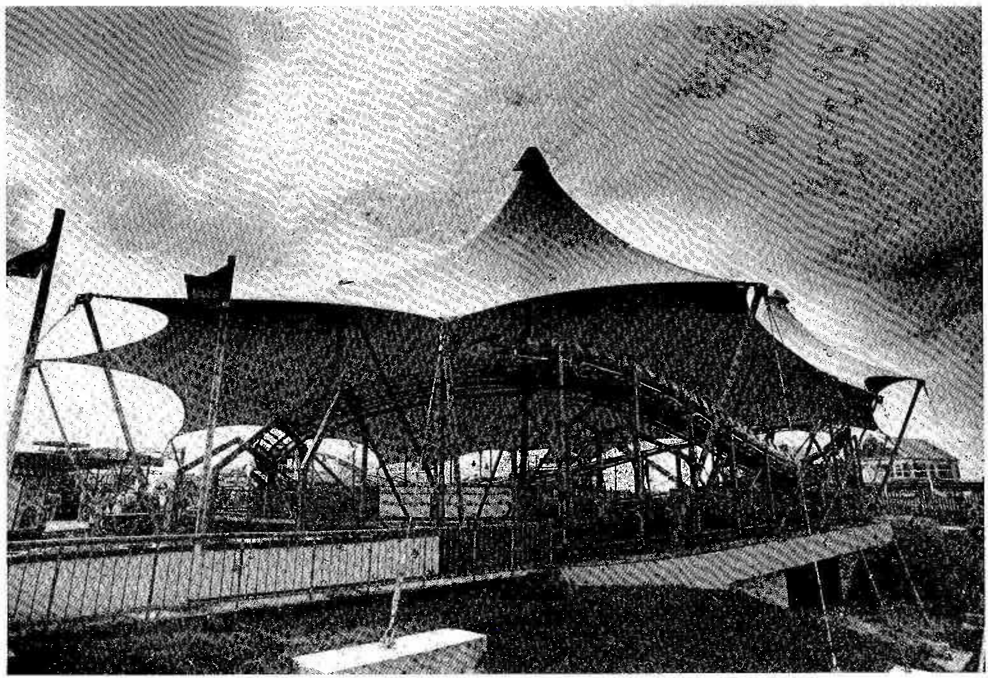


Fig 4.5 Computer structural analysis for airship design



Coast Publications

Fig 4.6 Windsor Safari Park Dolphinarium



Landrell Fabric Engineering

Fig 4.7 Ride at Blackpool Pleasure Beach

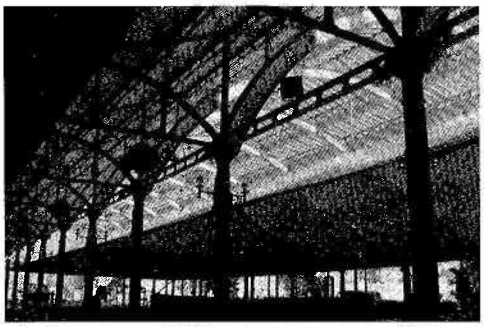


Fig 4.8 Bath Arts Festival roof over Green Park Station, Bath

avoiding interruption to normal use of the adjacent car park. Being of flamespread resistant, white translucent PVC coated polyester fabric, it provided an economic watertight cover and suitable environs for display of a wide range of modern art. (Fig 4.8)

The third of these smaller projects involved the provision of temporary cover over a courtyard to accommodate architects Sheppard Robson's fiftieth year celebration party. This canopy was designed 'upside down'. Rather than have central masts pushing the membrane up to generate double curvature, central ropes were used as pull-down, creating inverted cones.

Towards a technology of permanence

The acceptance of these forms of construction as a viable alternative to conventionally glazed or clad rigid frame structures has been important for the development of tension structure engineering. Such acceptance appears to be growing in the light of continuing experience and understanding of the performance of the materials.

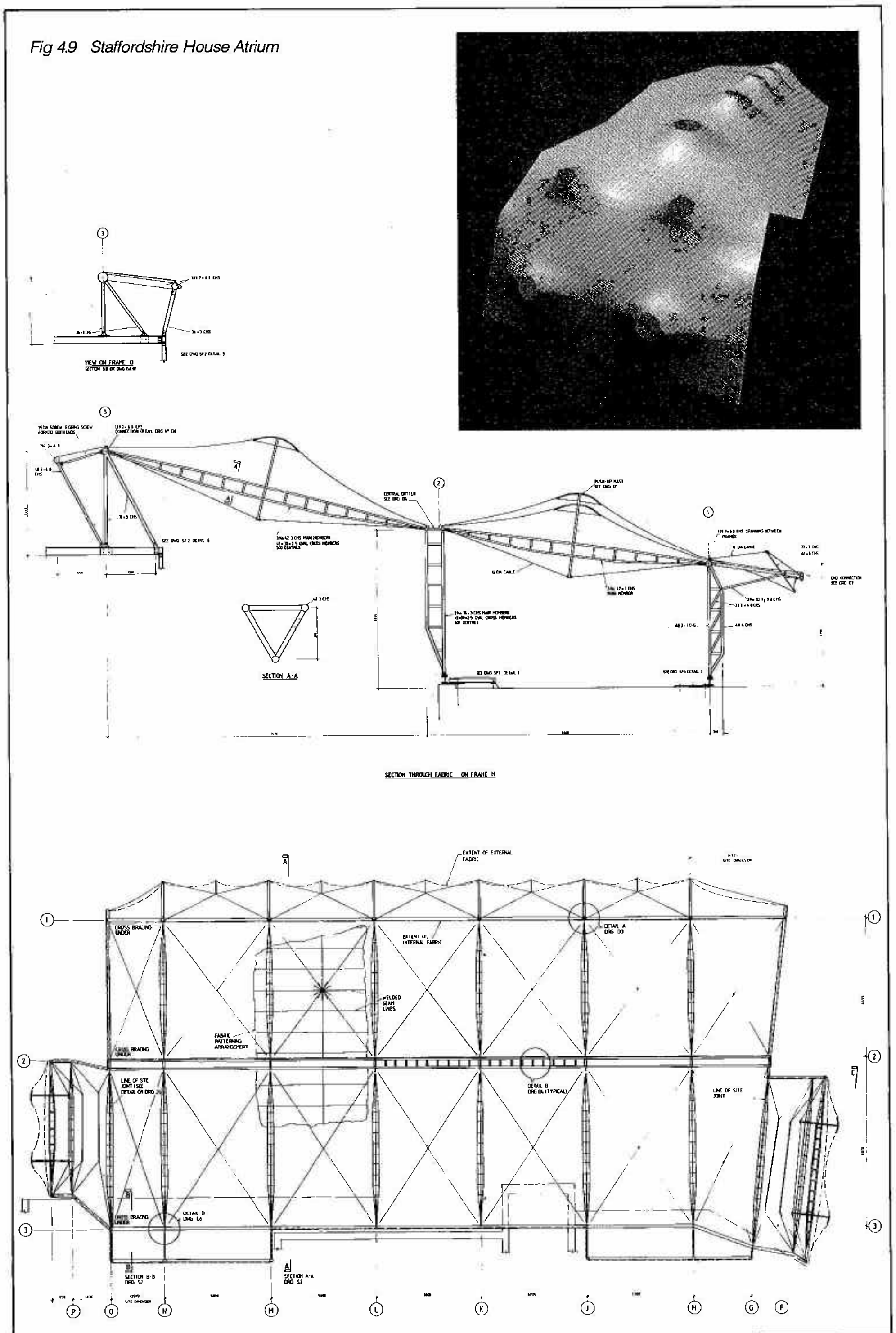
Indeed, perhaps the most exciting development for designers of tension structures is this growing acceptance by clients and their architects that such constructions can be used for permanent roofs, whether over a stadium, an office atrium, public building or leisure centre. In fact, Buro Happold did receive a citation from the Institution of Structural Engineers in 1987 for innovation in tension structures for permanent building construction. Nevertheless, uncertainties remain amongst clients, and sometimes their architects, over the basic ground rules in relation to design life, cost and internal environment – indeed, sometimes the very procedure for designing all aspects of a tension structure in contrast to a conventional structure. Another obstacle has been the need for local authorities to look beyond the normal approved documents of the Building Regulations since these do not specifically relate to membrane structures. In this context, there is perhaps a lesson to be learned from North American or European practice, where a 'proof engineer' with suitable specialist experience or knowledge is appointed to review the design and advise the Local Authority on its adequacy. Such a solution was employed to underwrite Bobrowski's design for the Calgary Saddledome when we ourselves were the proof engineers, or indeed for our own aviary at Munich when Prof Kupfer, proof engineer for the Munich Olympics, was employed.

The other principal obstacle has been the fear that the design life of the tension membranes was insufficient to match the investment required of the project. Consequently, teflon-coated glass fibre has long been the customary choice for structures where longevity and permanence are of prime importance. The very high cost of the material has done much to limit its use. Indeed, whilst frequently used for such structures by many designers, including Buro Happold, worldwide to great effect, the material has not yet been approved for use in the UK. The grounds for non-approval to date are that when subjected to a particular form of laboratory combustion test, pure teflon has been shown to produce toxic bi-products. The onus is now on the potential user to demonstrate that in a true fire situation, conditions cannot be achieved which would give rise to unnecessary toxic products. Research is now well underway to provide this information. In the meantime, the continual improvement in the non-stick lacquers for PVC-coated polyester fabrics has provided a sufficient enhancement in long term appearance of these materials to reduce interest in the expensive teflon/glass option, and to enable permanent structures to be erected with confidence.

We have recently designed, with Ron Herron Associates, one such permanent structure in central London as a covering for an atrium within a major office refurbishment at Staffordshire House for Imagination Ltd. (Fig 4.9) The accurately patterned membrane of fluoropolymer coated PVC polyester material is divided into 14 panels approximately 7.5m × 5.0m. Each membrane panel is supported on a domed top flying post of stainless steel wires spanned between light bowstring steel and aluminium support beams. This design clearly expresses the advantage of translucency offered by such materials in providing the enclosure to an 'intermediate' environment. Added to this is the extreme lightness of construction and ease of erection that has been possible using such techniques of accurate prefabrication and minimum weight. This roof is now under construction and well demonstrates an important new application of such flamespread resistant materials in the UK.

Silicone-coated glass fibre fabrics are presently being used where high translucency is sought. The silicone can be unpigmented and the glass does not suffer UV degradation. However, in achieving a silicone composition with the necessary fire rating, weldability is sacrificed. Fabricators use gluing

Fig 4.9 Staffordshire House Atrium



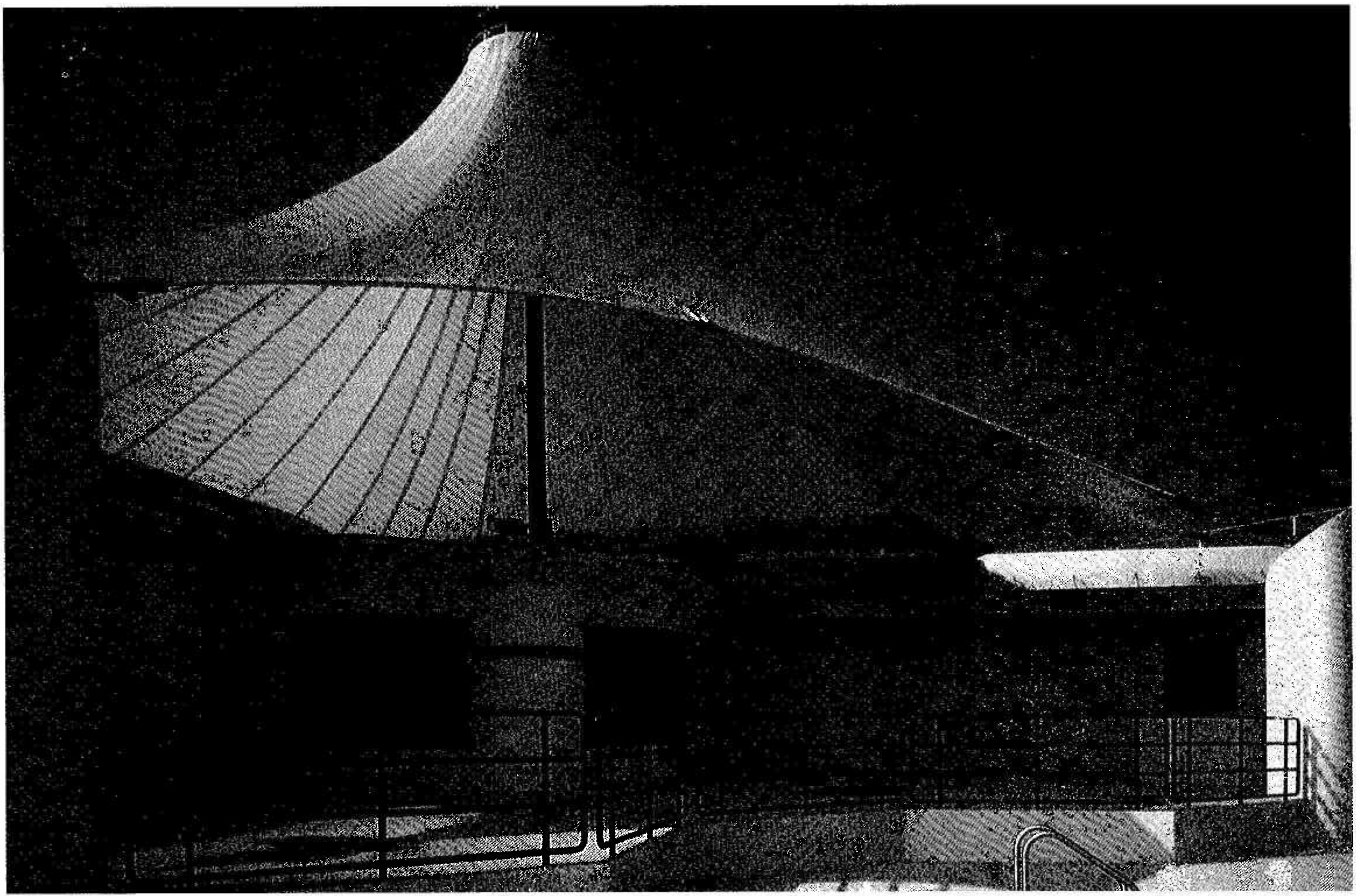


Fig 4.10 Awning over swimming pool, Pensacola, Florida

techniques as an alternative without apparent difficulty. The material can achieve a class 1 spread of flame and class AA fire penetration to BS 476. The single masted conical awning to the municipal swimming pool at Pensacola, Florida, (Fig 4.10) used just such a fabric, radially patterned with 4" glue seams to ensure integrity.

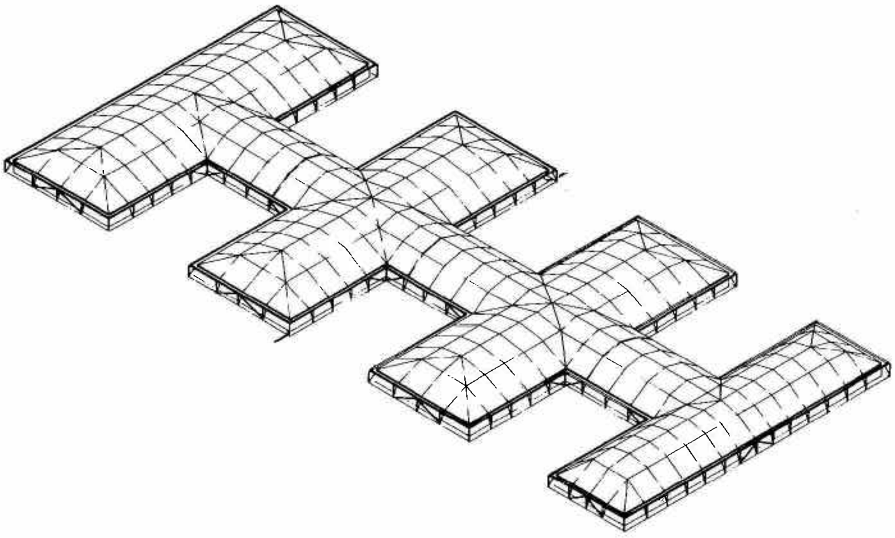
Foils and films of polymer without a structural fabric are of growing interest. The ETFE and FEP foils available have completely different mechanical properties from fabric-supported membranes being isotropic, and of low stiffness, yet having a fair resistance to tear propagation. To date such foils have been used to admit a high measure of vector modelled light for leisure activities, swimming pools and horticultural uses by way of individual inflated cushions up to 5.0m or so in size, restrained by small stainless steel wires and held within an overall structural grid. They are highly translucent and very inert. Although clearly not as versatile as more conventional fabric based materials, they are highly appropriate where a support matrix can be provided. Indeed because these cushions also provide a thermal performance rather better than double glazing for approximately a quarter of the weight, we proposed their use as the principal covering element to the 58° N project. As a development of this earlier proposal the practice is now working on a design for an atrium for a new hospital in London with architects Sheppard Robson. (Fig 4.11) This will use $4.0m^2$ inflated cushions of a clear foil material, ethylene tetra fluoro ethylene (ETFE), supported within a grid shell of GRP ribs. This will ensure a light transmission equal to that of glass, yet will require a far less heavy support system across the atrium.

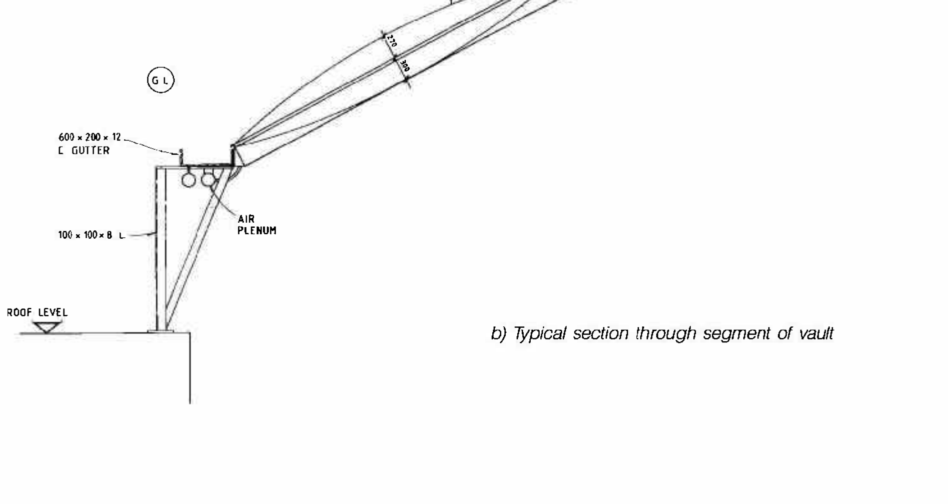
Where to now?

As the engineering techniques for flexible surface stressed tension structures near the completion of a further cycle of improvement, attention again becomes focussed on the gaps in our skills and scientific knowledge. The large scale and extreme lightness of such projects, now well defined in many other ways, demands fully modelled wind tunnel tests. Past results have shown surface pressures well below those originally chosen on the basis of conservative estimates. This in turn allows the designs to be modified to offer savings in excess of the expenditure on the wind tunnel model and tests themselves.

In consequence, great importance is attached to the accurate definition of the applied wind and snow loadings. These are notoriously hard to predict when

Fig 4.11 *Atrium, Westminster and Chelsea Hospital, London.*
a) Axonometric view of roof





b) Typical section through segment of vault

each structure can have a highly individual and complex shape. Through the many past projects, we have built up a collection of reference data from wind tunnel tests on doubly curved roofs of various kinds, useful when estimating wind loads. However, realising that this is not always an adequate technique, we are discussing with Michael Barnes and David Sykes of City University, London, the possibility of creating a sufficient database which can be called upon to automatically establish wind loading coefficients for any new surface.

Already the quality of data which is extracted from wind tunnel tests is far superior for design of flexible tension structures to any available from conventional codes. New high speed pressure sampling enables the analysis to extract extreme values of loading which relate to a chosen appropriate averaging time for a critical gust. By fitting a series of extreme values to a probability distribution it is possible to predict the most likely value of pressure within the design life of a structure. This gives a reliable set of maximum surface pressures for any wind direction in the design of a structure. Because the results are most carefully established, they are almost invariably lower than loads which could be taken from conventional codes for simpler shaped buildings based on conservative assumptions.

So hopefully, one can follow from the trends outlined above the technical developments originating from the early advances in numerical and computational techniques required for analysis, which made it possible for the engineer with suitable experience to reliably determine the problem on hand. Then came the patterning techniques that widened the choice of form and enabled accurate control of final stresses. This in turn stimulated the production and use of more specific and flexible fabrics and materials, which in turn has been exploited by designers, fabricators and clients to resolve the many practical problems of enclosing and covering ever larger spaces for less cost and less material.

The wheel has gone full circle and once again engineers are becoming interested in the accuracy of their loading assumptions, and in matching the demands of architects and clients with techniques of design that provide an ever greater flexibility of approach to building structure.

Mike Cook

Aviaries: Munich, San Diego and Hong Kong

Project data

Munich	**Client**	Tierpark AG
	Architect	Jorg Gribl with Frei Otto
	Structural Engineers	Buro Happold
	Contact Engineer	Dieter Herrschmann
	Contractors: Concrete works	Gebruder Rank GmbH
	Contractors: Structural steel work and mesh	L Stromeyer GmbH
	Completion Date	1980
	Size	4,500m² ground plan
	Cost	2.1M DM (includes landscaping)
San Diego	**Client**	San Diego Zoo
	Architect	Buss Silvers Hughes Assoc. with Jorg Gribl
	Structural Engineers	Buro Happold
	Contact Engineers	Buss Silvers Hughes Assoc.
	Completion Date	1981
	Size	1,000m² ground plan
	Cost	$450,000

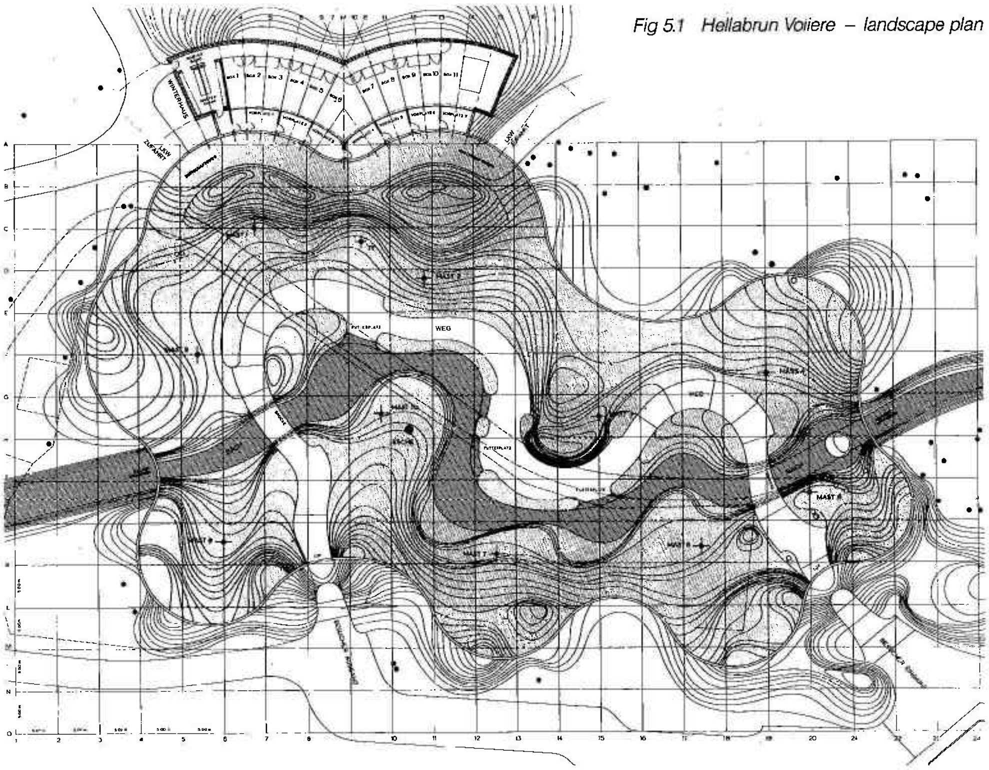


Fig 5.1 Hellabrun Voliere – landscape plan

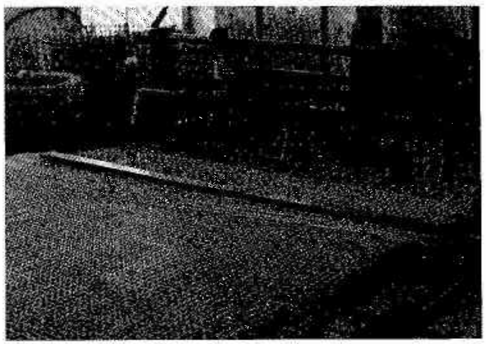


Fig 5.2 Crimped woven wire mesh

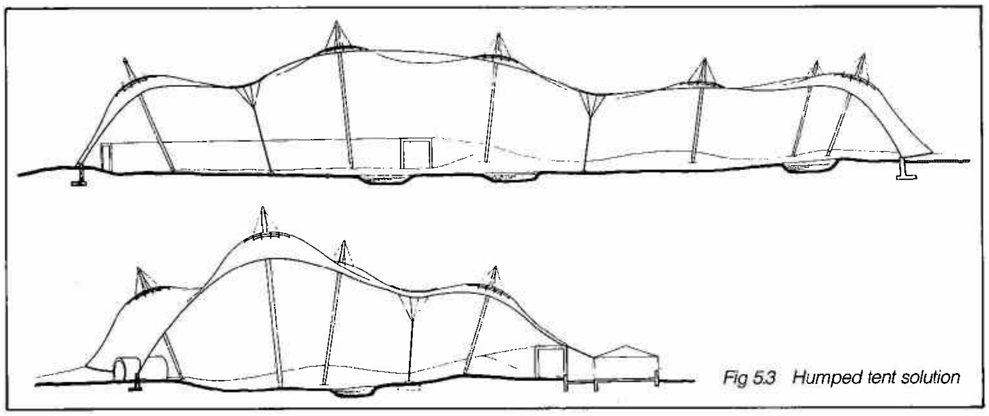


Fig 5.3 Humped tent solution

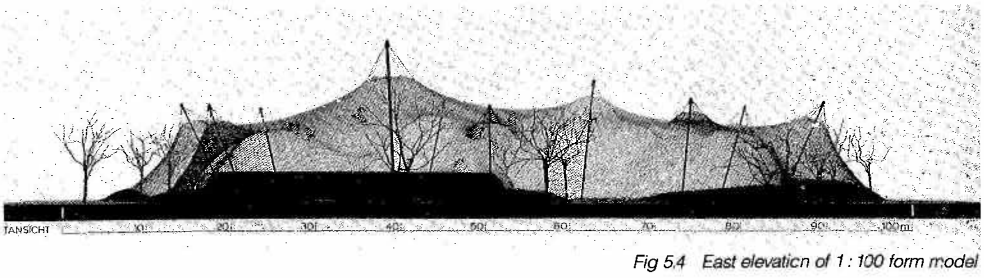


Fig 5.4 East elevation of 1 : 100 form model

Initial deliberations

In 1976 Jorg Gribl was commissioned to design a large walk-through aviary in Munich Zoo adjacent to the River Isar. He asked Frei Otto to consult with him in the design who, in turn, recommended Buro Happold for the engineering design. Ideally the architect was searching for a structure "as a cloud" some 90m × 40m in which birds in free-flight could be seen against the surrounding landscape – but one which could adequately support the substantial snow loadings of the Munich area (Fig 5.1).

Initial designs involved consideration of meshes hung from primary cable nets and supported on masts. However, it was felt that these would stretch and result in looking 'baggy' following frequent snowfalls. Ideally, a springy structural mesh material was required, capable of absorbing the additional load. It was then realised that meshes of crimped woven wires, as used elsewhere in the zoo for guard panels to some of the cages (Fig 5.2), might possibly be employed as a structural mesh using the techniques of "humped" cotton fabric tent. Double curvature of this surface could be introduced by changing the relative angle between the two directions of the mesh (Fig 5.3) during montage. This structural idea was clearly technically possible and capable of being developed into an elegant form.

At the same time, consultation with the zoo experts had confirmed that the mesh spacing of 60–65mm should be sufficient to let small birds in, but still exclude larger predators – thus retaining the ecological balance of the internal landscape.

Design of the aviary

In order to investigate further the landscaping and flight pattern possibilities using this technique a 1 : 100 scale form model was made at Frei Otto's Atelier (Fig 5.4). This also allowed the design team to jointly investigate appropriate mast positions, wall inclinations, surface curvatures and, from the engineering point of view, the resulting average stress patterns under loadings.

Hong Kong

Client	Ocean Park, Hong Kong
Design and Structural Engineering	Buro Happold
Architect	Leigh & Orange
Contact Engineers	Ho-Happold
Contractor	Kent Ho
Complete Date	1985
Size	3,000m²
Cost	HK$3.5M

A statistical evaluation of Munich weather data showed that the worst 24-hour snow fall amounted to 35cm at an approximate density of 150kg/m³. Assuming that one third of the snow would fall through the mesh, the resulting load on the aviary would be 35kg/m² on the plan. Loading, including self-weight of 40kg/m², was therefore agreed with proof engineer Prof Kupfer with the provision that the structure should be checked for an ultimate loading condition of 100kg/m². This latter load correlated with the likely maximum accumulated monthly snow fall on the ground.

Elaborate hand calculations based on the curvatures of the agreed form model after deformation, and assuming support to the mesh from steel "mushrooms" hung from each mast (see Section 1–1 Fig 5.3), established the need for a mesh of 3.2mm diameter crimped wires at 62.5mm centres. This produced a spacing of approximately 16 wires per metre strip of mesh.

After careful research, and with further advice and testing from Harry Reiter of the University of Bath, a 304 low carbon austenitic stainless steel wire (Din 4301) was chosen. Such a mesh would weigh 2.5kg/m² and could be butt welded using TIG argon shroud gas welding with the appropriate filler material. This material and jointing technique would provide a sufficiently robust mesh with the right reserve of strength and which would not be subject to significant permanent deformation under every day loadings (Fig 5.5). Further TIG welding would enable the 2.5m wide woven rolls of mesh to be reliably jointed to create a continuous 95m × 50m structural sheet of appropriate plan form which would have tolerable corrosion resistance in the relatively clean Munich air.

Overall conditions of vertical and horizontal equilibrium under various conditions of loading enabled wall anchorage and mast support forces to be assessed. Mesh support mushrooms, masts and foundations could then be sized, and engineering designs were presented to the client and proof engineer in September 1977.

Structural analysis

In addition to the detailed static calculations by hand, a further accurate 1 : 100 scale model of micro wire mesh was constructed to prove the "humped tent" concept. However, it was felt that further calculations were advisable to more accurately model the 'non-linear' performance of the "elastic" and the "elasto-plastic" performance of the mesh material itself under different limiting load states. The prestress form was therefore optimised by Dr Michael Barnes using 'dynamic relaxation' and further analysed under 40kg/m² of snow loading conditions (Ref 5.1). This analysis gave a maximum loading on the central mast of 76 tons and accurately established mast sizes and anchorage forces for the progress of detail design calculation (Fig 5.6).

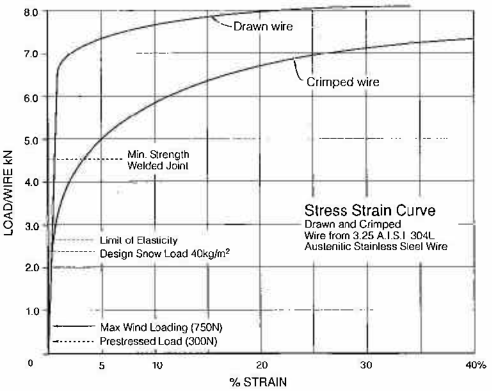


Fig 5.5 Stress/strain curve of 3.2mm diameter stainless steel wire

In order to investigate ultimate performance further, non-linear load analysis was carried out – this time using elasto plastic finite bar elements under incremental loadings of 25kg/m² up to the agreed ultimate loading of 100kg/m². This analysis established the sequence in which areas of the mesh would undergo plastic extension, and determined maximum deflections of the order of 2.5m for the mesh surface under snow loading. In such conditions, no element would attain the designated minimum ultimate strength likely in the welded wire joints (Table 5.1)

The design and form of mesh was accepted by the

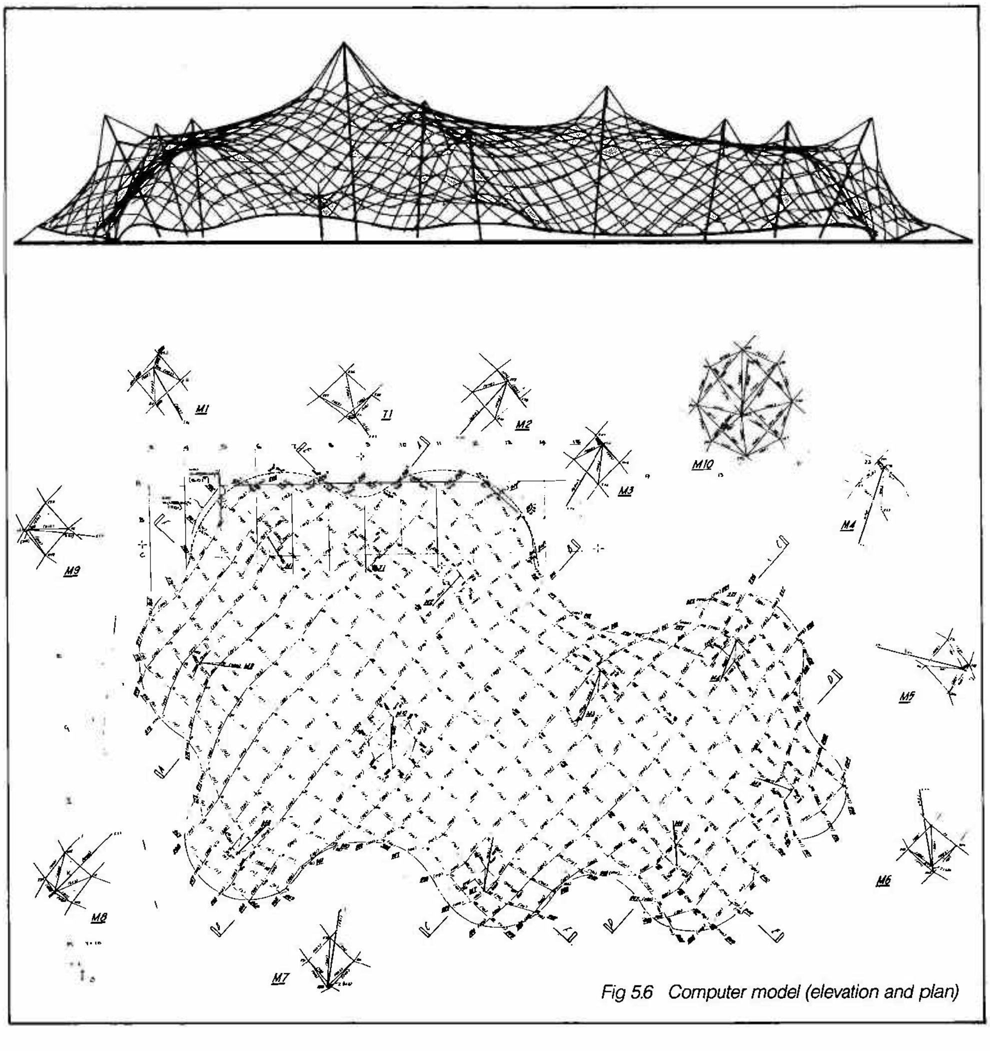


Fig 5.6 Computer model (elevation and plan)

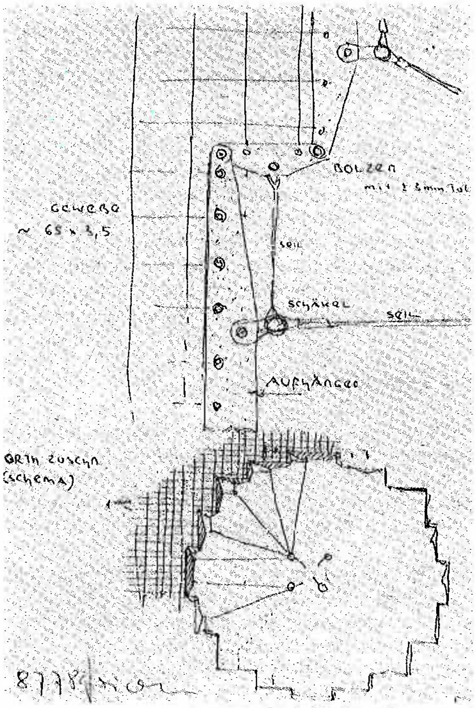


Fig 5.7 Otto's pantograph proposal

proof engineer as satisfactory. However, construction studies indicated that a large mature ash tree in the middle of the site would have to be removed to provide space for the assembly of the steel 'mushroom' support to the central mast, M10. Both the client and the architect wished to save this old ash tree, so it became necessary to look for an alternative to the mushroom support at the mast top areas, permitting construction of the aviary around the tree.

Otto suggested the use of a pantograph system of mesh support members (Fig 5.7). This proposal required considerable physical modelling at a scale of 1 : 20 in order to investigate the stability of the resulting mast top concept under various forms of loading (Fig 5.8). Sufficient engineering understanding was gained to enable detailed non-linear analysis of the central mast zone to proceed under loadings imposed from the overall analysis. This accurately confirmed the stress levels to be expected in the meshes (Table 5.1) in relation to the capacity of the mesh, and further enabled the structural design of the mast supporting the 10mm and 12mm galvanised wire rope cable arrays for the final mast top configuration to be completed (Ref 5.2). However, to ensure that all construction movements and all resulting stresses from the loaded meshes could be accommodated, a full scale 1 : 1 design of the 500mm long plate of the zigzag pantograph element was required (Fig 5.9).

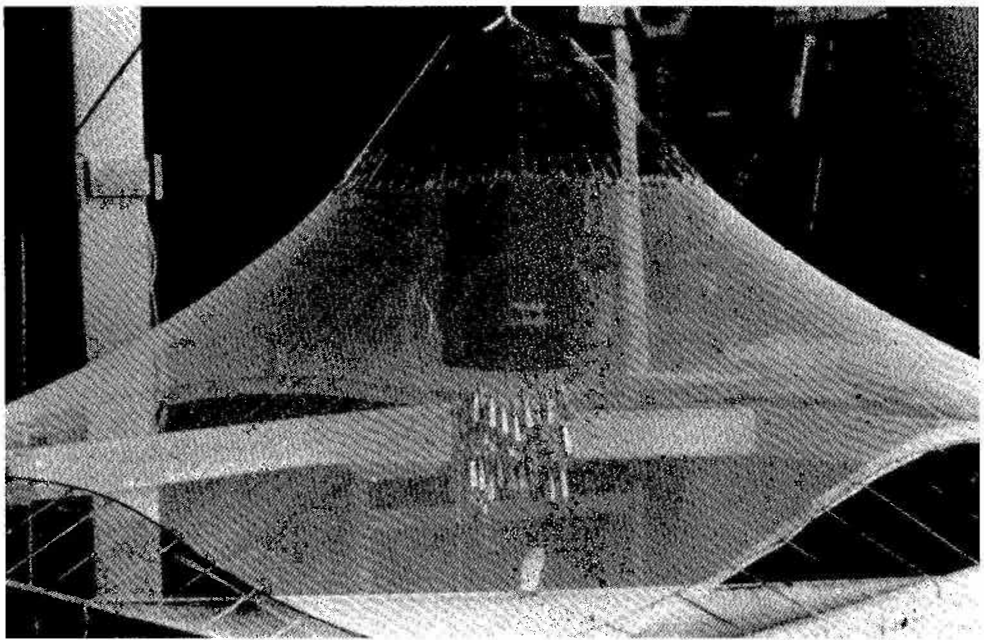


Fig 5.8 Physical modelling of mast

Table 5.1 **Stress in Mesh**

	Force per Wire kN/m	Force per Metre kN/m
Prestress	0.3	5.0
Snow Loading (40kg/m²)	2.50	40.0
Limit of Elasticity	2.90	46.4
Ultimate Loading (100kg/m²)	4.04	64.4
Breaking Strength of Weld	4.57	74.7
Breaking Strength of Crimped Wire	8.00	128.0

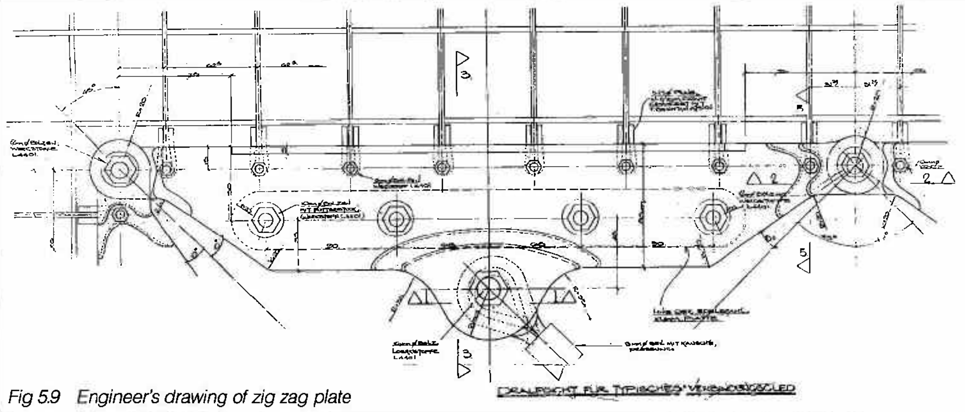


Fig 5.9 Engineer's drawing of zig zag plate

Formfinding and construction evaluation

In order to pre-determine the final stressed shape of the aviary, further computer refinement of the overall form was made on a 2.5m grid. The precise shape of the original flat sheet of welded mesh, and its topographical relationship to the concrete boundary walls could then be established and passed on to the contractor. Additionally, using the zoom-in technique employed for the detailed structural analysis of central mast M10, the detailed geometry of all ten mast tops and single tie-down zones were further analysed on a 500mm grid. This permitted the calculation of all lengths of the mast top cable arrays which could then be passed to the contractor to facilitate accurate pre-fabrication and marking of the cables without wasted effort. (Fig 5.10)

Quite apart from detailed numerical analysis, considerable effort was given to discussion of various methods of construction and erection. In the end, an arrangement was selected whereby with all the masts temporarily stayed in approximately their final positions, each quadrant of cables at a mast was attached via a 4 × 1 mechanical advantage shackle system, linked by a single cable to a Tirfor at the base of each mast. This was the easiest method of raising the mesh off the ground from its original flat position to its final designated shape. By sequentially raising each mast top area, the boundary of the original flat mesh could be drawn in to its final position on the concrete boundary walls.

Stromeyers, after discussion with their own welding consultant, adopted the suggested welding procedure but ingeniously manufactured a special clamp grip whereby the individual wires would line up for accurate butt welding. Initially, problems occurred in the welded joint due to the fact that welded butts joining two wires were often undercut. Consequently the combination of reduced metallic area and loss of strength due to heat of the weld produced joints of insufficient strength. However, after initial teething problems, and with some further advice from Mr Reiter, welding became relatively easy and reliable.

The decision was made to weld the 2.5m widths of mesh as woven into 15m wide rolls some 40–50m long in the factory, and to then transport them on low loaders to site where they were carefully laid in the correct location. The argon shroud TIG welding system was also transported with the mesh and, utilising a protective system of small tents, welding of the on-site joints proceeded without further problem.

Erection went generally as planned, except in the final event the erection foreman elected to disregard the requirements for careful geometrical control, so causing considerable problems in forming and stressing to the correct shape. (Fig 5.11) Much secondary control had to be undertaken on site in order to produce a satisfactory wrinkle free stress form which could be finally clamped off onto the anchoring boundary walls in reinforced concrete. (Ref 5.3)


Fig 5.10 Mast top detail

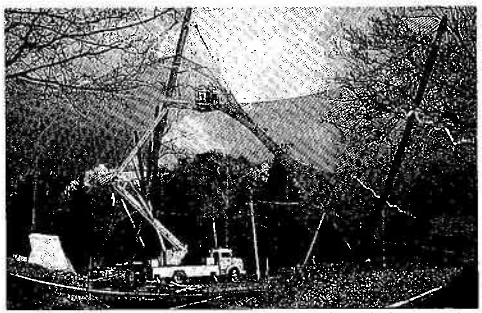

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Fig 5.11 Munich aviary during erection

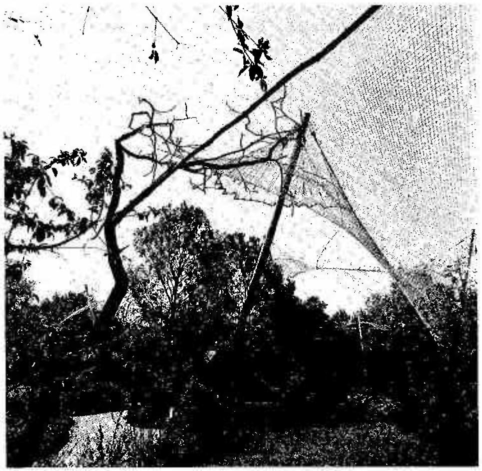
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Fig 5.12 Completed aviary

Once the aviary had been successfully erected, Tierpark were able to proceed with landscaping. This has now matured satisfactorily and only a vestige of the enclosing structure remains, as a backdrop to this internal walk-through landscape (Fig 5.12). The whole structure has been adequately test-loaded to form Europe's largest igloo to date and, in 1985, received a commendation for architecture from the Bund Deutscher Architekten (BDA). (Fig 5.13)

San Diego and Hong Kong

The technique for producing large free-form aviaries has now spawned two additional smaller flight cages – one of 1,000m² for San Diego Zoo in California, and another on an awkward sloping site at Ocean Park in Hong Kong, approximately 2,700m² in plan.

A similar erection process was involved for San Diego (Fig 5.14) where mesh, this time of 2.7mm stainless steel wires at 25mm centres was used. Smaller wires could be used at lower stresses, because of the different internal ecological balance required and furthermore, because San Diego is a temperate zone without snow loading. A cable


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Fig 5.13 Stainless steel reinforced "Igloo"

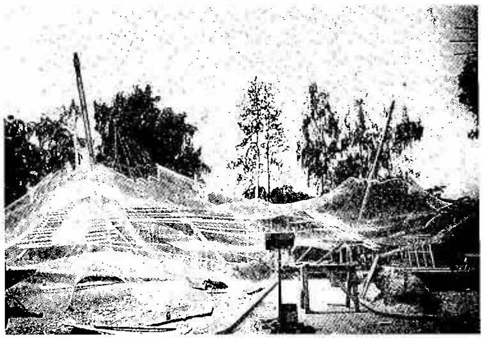
Fig 5.14 San Diego Aviary during erection

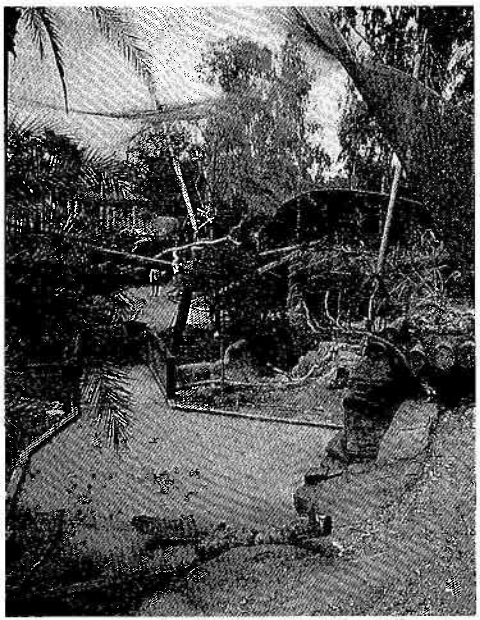

Fig 5.15 Cable net boundary at San Diego

boundary was adopted in preference to an anchored one in order to join the aviary to an existing flight cage (Fig 5.15). A vertical mesh of chainlink fencing hung from this cable boundary then divided the existing meso aviary from the new flight zone.

The 2,700m² aviary in Ocean Park, Hong Kong used the same 12 gauge (2.7mm diameter) mesh at 25mm centres. This aviary is located on a steep valley slope with a central stream which made the selection of the correct geometry and the modelling of the final cage extremely difficult (Fig 5.16). In the event, the contractor chose to buy plain wire from Japan, and to crimp and weave the wire and then weld it into its finished fabric form on the site – an ingenuity which is symptomatic of the enterprise of the Hong Kong culture, and which resulted in an economical construction of this interesting flight cage. Because of the aviary's location close to the sea, low carbon 316 austenitic stainless steel mesh, which has an additional molybdenum content, was chosen to enhance the resistance to corrosion from chlorides. (Fig 5.17)

Innovation in the 'engineering' environment is never easy and is extremely time-consuming to achieve. Nevertheless, these aviary constructions hopefully demonstrate that economy and elegance can be achieved in a total sense, where minds of different skills are brought to bear in the solution of an unusual problem. Munich, in particular, represents the successful collaboration of architect, designer and engineer.

Michael Dickson

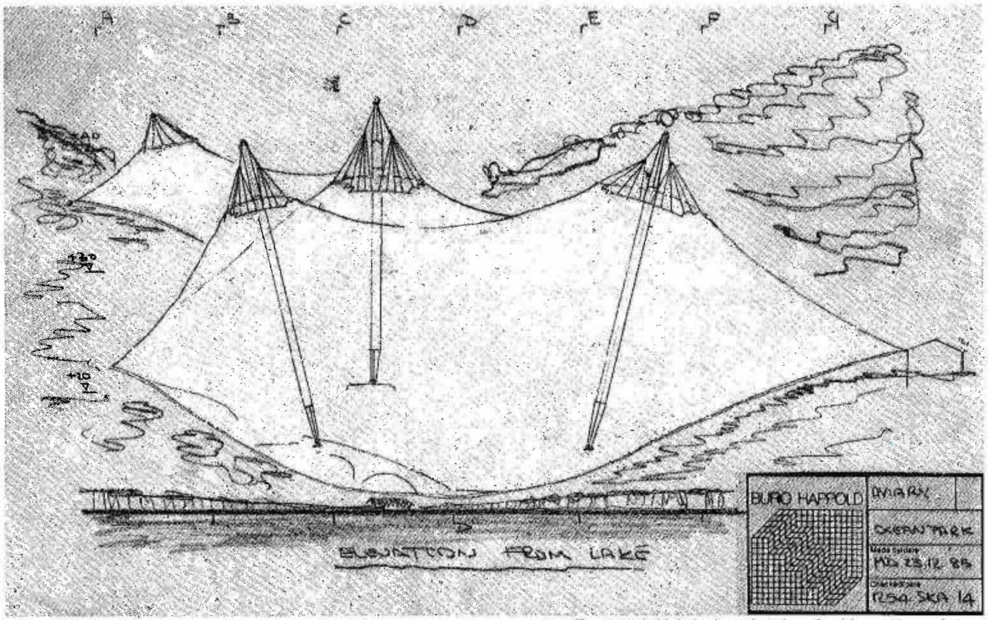

Fig 5.16 Initial design sketches for Hong Kong Aviary

Fig 5.17 Seaward view from Hong Kong Aviary

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5.2 Barnes M R and Wakefield D S, 'Dynamic relaxation applied to interactive formfinding and analysis of air-supported structures'. Design of air-supported structures, IStructE, Bristol 1984.

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5.4 Dickson M, 'Notes on the interaction of research and design in the execution of long span structures', SFB 64, International Symposium 3, Stuttgart 1985. p231–4.

5.5 "Strictly for the birds", Building April 1980 pp28–30.

King Abdul Aziz University Sports Hall, Jeddah

Project Data

Architects	Frei Otto, Buro Gutbrod
Structural Engineers (Roof)	Buro Happold
(Concrete Works)	Ove Arup and Partners
Services Engineers	Brandi Ingenieure
Quantity Surveyors	Widnell and Trollope
Main Contractor	W S Try (International) Ltd
Sub-Contractor (Cable net works)	Habegger (Thun)
(Membranes)	Sarna
Completion Date	1979

Cost:	**SR/m²**	**UK£/m² equivalent**
Steelwork and cable net	1063	52.4
Outer membrane	393	19.4
Inner membrane	265	13.1
Foundations and ground slab	2500	123.4
Services and finishes	4221/m²	208.3m²

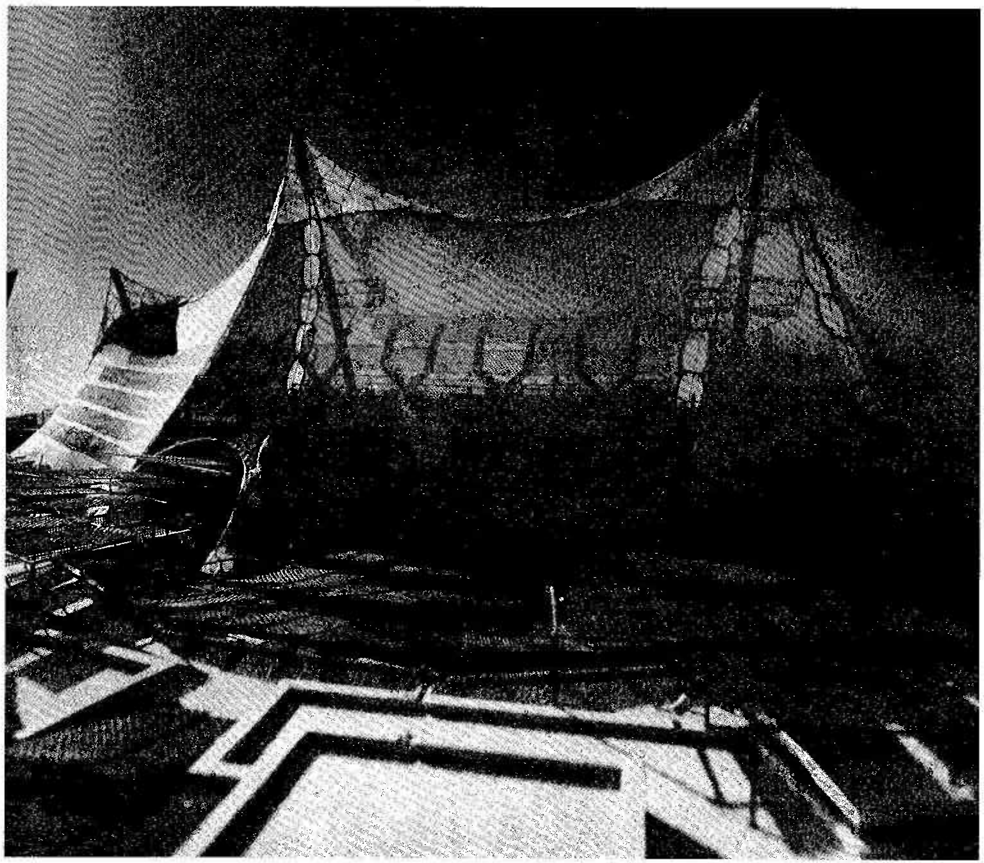

Fig 6.1 Architectural model, Jeddah Sports Centre

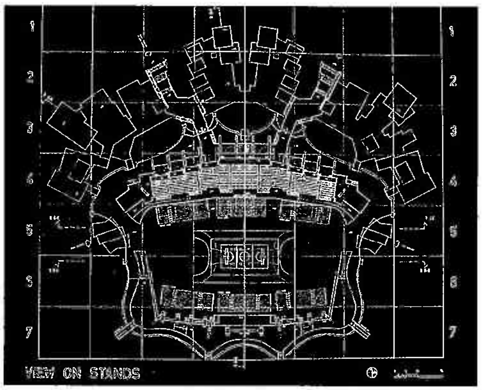

Fig 6.2 Plan of Jeddah Sports Centre

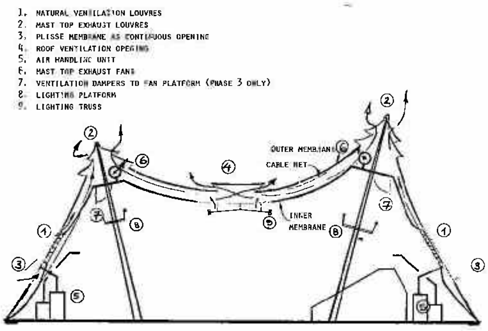

Fig 6.3 Environmental section

Although it stands over 27 metres high and covers an area exceeding 9,500m², the sports hall at Jeddah's King Abdul Aziz University is unmistakenly Arabian in architectural concept. Designed by Professor Frei Otto and the Stuttgart architectural practice of Buro Gutbrod, with engineering design by Buro Happold, the structure is a vast and beautiful tension structure which despite its scale, is strongly reminiscent of the traditional Bedouin tent form (Fig 6.1).

Preliminary design concept

The story of this unusual project starts in 1976 when the University decided that it needed a major sports stadium, complete with the accommodation necessary for the usual ancillary support facilities and administration. The consultants responded with an imaginative scheme comprising a large tent-shaped enclosure situated within a multi-purpose sports village (Fig 6.2). The tension structure enclosed a playing area approximately 85m × 40m, bound by a tiered grandstand which provided fixed seating for over 1,300 spectators on the north side, with room for a further 1,000 removable seats along the south perimeter. The space was to be air-conditioned and artificially illuminated. The enclosure was initially conceived as an insulated dead weight roof constructed of concrete panels hung from a steelwork cable net structure, and clad in non-ferrous or stainless metal shingles.

As a consequence of the added deadload and elaborate cladding system, the estimated cost of the proposed scheme was approximately £16m. During design development in 1977, the budget was drastically cut to £5m. Although the client accepted that only the covered stadium could be provided for this reduced sum, it was necessary to reappraise both the initial structure and cladding concept to obtain an enclosure which could be realised within the limited budget.

In lieu of the heavyweight roof, a double membrane fabric cladding was considered and compared with an insulated metal clad roof covering. It was believed that both constructions could be achieved within the budget without compromising the requirement for a large, column-free playing area, particularly if the cheaper PVC-coated polyester fabric was used instead of the longer life PTFE-coated glass fabrics. However, it was decided that the cable net structure should be designed to cater for the 20kg/m² self weight of an insulated metal roof so that the University could substitute such a cladding at a later date after the membranes had reached the end of their useful life and when funds became available (Fig 6.3). Good quality PVC-coated polyester fabrics, such as that then being developed by Sarna, were at the time estimated to have approximately 15 years design life in the hot sunny Saudi Arabian climate.

Formfinding and structural analysis

The early development of the geometric form of the tent surface was carried out at Frei Otto's Atelier and at the Institute for Lightweight Structures (IL) in Stuttgart. The first concept forms of the heavy weight roofs had been defined by rough hanging chain models and when the transition to lightweight prestressed double curved cable nets was made, soap bubble models were studied to gain insight into the form of the minimal surface (Fig 6.4). The surface geometry of a soap film attached to given boundaries is of very great interest to the cable net designer. Due to the fundamental physical laws of

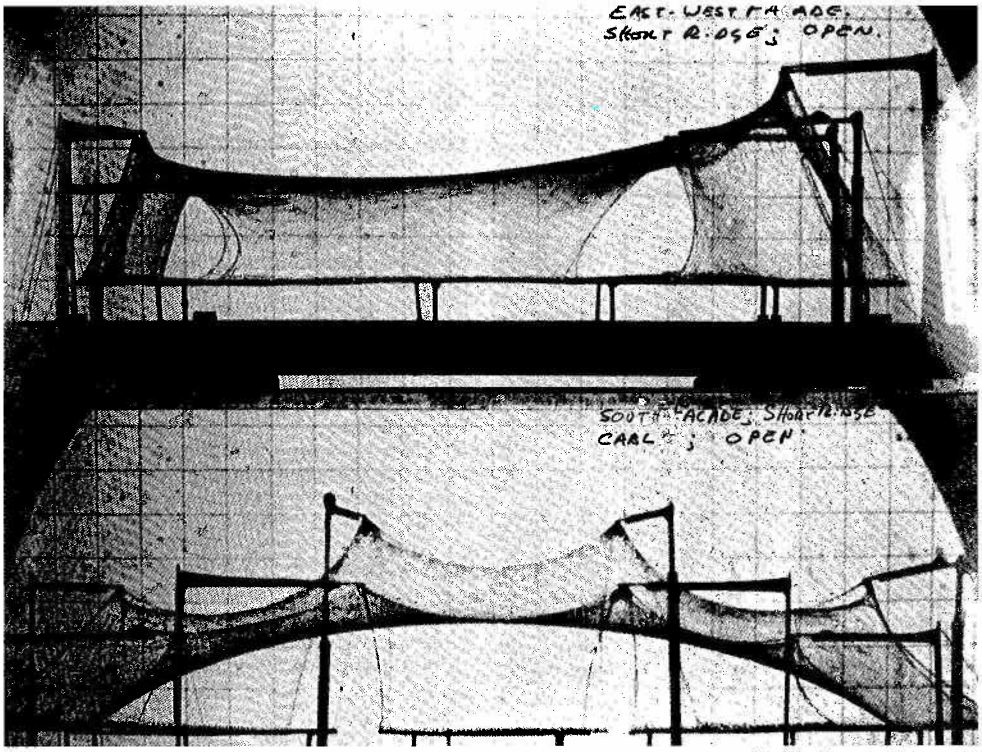

Fig 6.4 Soap bubble model

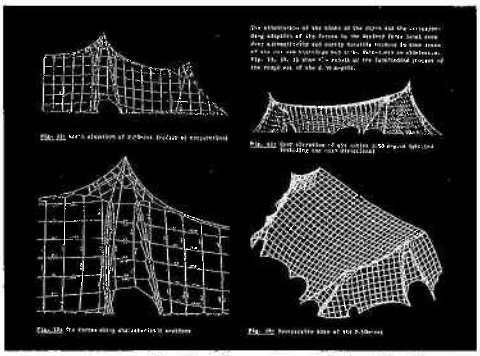

Fig 6.5 Computer analysis with 2.5m grid superimposed

surface tension, the shape taken up by a soap film formed between given boundaries is compatible with constant and equal tensions at all points on the surface with principal curvatures at right angles, thus capable of matching the directions of the cables themselves in a cable net. Consequently, orthogonal cables arranged to form such a surface have constant 'pre' tensions along their entire lengths in both directions. Following the soap film studies, a first generation 1 : 100 scale fabric model, with chains for edge cables, was made which was later refined into the 'final' model used as the base for all geometric formfinding.

It is worth noting here that this design was being carried out at a time when the numerical techniques for the analysis and formfinding of prestressed cable net and tension fabric structures were in their infancy and only 'labour' intensive main frame analysis systems were available (Ref 6.1). The processor speeds and memory limitations of the then state-of-the-art desktop computers (HP 9825) were quite inappropriate for the non-linear analysis that we are able to carry out as routine today (Ref 6.2). Consequently, much greater emphasis was then placed on the development of design through accurate scale models as used on the Montreal and Munich Projects. (Ref 6.3)

Although the final Jeddah model was measured accurately on the special measuring table at the IL and this geometric data was used both for final structural analysis and cable cutting pattern development, the early models served as the basis for crude geometric measurement of radius of curvatures (r) and for overall hand calculations of the forces (s) on the basis of s = q × r where q is the load intensity applied to the membrane. The pre-tender structural design of the cable net was therefore based on the best geometry available at the time. Prior to the construction of the final 'form' model, and lacking 'detailed' computer verification of the equilibrium form, this had to be based on the crude curvature measurements from both the soap film model photographs and the first generation fabric model. Experience has shown however, that the force levels predicted by such hand calculations are a reasonable basis for structural sizing of net cables and element detailing.

The final model for Jeddah was completed in late 1977, several months after the award of the construction contract. This model was both physically measured and stereoscopically photographed to obtain the boundary conditions and initial form basedata for the numeric formfinding and later load analysis, and for cable net/fabric patterning work. Working closely with Michael Barnes of the City University, London, the numerical formfinding and loaded state behaviour was investigated for several prestress levels using a basic 5.0m (10 cable) grid. The dynamic relaxation method of non-linear analysis as described earlier was used with the crude mesh half models for the symmetric load cases (Fig 6.5). Formfinding took several hours to converge on the University's ICL 2900 (Ref 6.4). This 5.0m numerical model, derived for analysis purposes, was later taken and improved by the IAG (Institut Auswendung der Geodesie) to a 2.5m grid model from which all boundary cable zones could be refined (Ref 6.5).

The distribution of the prestress and the geometry of a cable net determine the load bearing behaviour. The magnitude of the prestress forces govern the allowable deformations and an optimum level of prestress must be established which is both economic and effective in limiting deflection. Increasing prestress to control deformations is always an uneconomic solution. A change of curvature and hence geometry is a preferred engineering solution but one that was not freely available in those days when the physical form model, despite its inherent scale and construction inaccuracies, was held as the goal to be achieved. Furthermore, there are no definitive rules on the necessary amount of prestress. It was felt that a prestress level that would prevent every cable from going slack under full loading was unnecessarily heavy and uneconomic. As a consequence, a criterion was adopted defining the maximum surface area that was allowed to go slack under load. It was found that a prestress level in the range of 2.0–2.5 tonnes/metre was sufficient to limit slack areas, and this was also believed adequate to limit deflections and to control dynamic behaviour. Ultimately, only 80% of this figure was sought from the contractors and no adverse responses under unloading have yet been observed (Ref 6.6).

Design development

The results from the 5.0m grid loaded state analysis have predicted force levels not exceeding 4 tonnes/

cable, and confirmed the need for a net of 12mm diameter cables (breaking strength = 10 tonnes) at 500mm centres. The total enclosure was designed to be made up of 15 separate cable net fields carried on 8 steel masts. Each field is trimmed with a 38mm diameter boundary cable (breaking strength = 93 tonnes), which in turn is either affixed to the high level ridge cables, to the mast stay cables, or to the ground anchorage points. The ridge cables consist of four 38mm diameter ropes and the mast stay cables consist of a pair of similar ropes. An elegant detail at the head of the lower masts allows the four ridge rope group to bifurcate to form two pairs of ropes which continue as mast stay cables. The lower net boundary cables are secured to the ground by steel anchorages set into an irregularly shaped 500mm deep reinforced concrete ring beam, pinned to the ground with 10.5m long ground anchors at 3m centres. The main ridge and stay cables are anchored via end clamps at 16 major tie down positions into steelwork fabrications. These are bolted into concrete anchorage blocks, each prestressed into position by a group of ground anchors.

The masts consist of 800mm diameter and 600mm diameter steel tubes tapered at their bases, and detailed to incorporate a sand pot bearing and a jacking point for the stressing of the cable net by raising of the masts. The heads of the mast are profiled into the top of a 'carpenter's' sharpened pencil to seat the local ridge cable geometry without eccentricity of force on the mast. The detail ensures that the cable and mast axis system lines intersect at the theoretical mast head system point thus virtually eliminating force eccentricities, and ensuring the economy of a true 'pin ended' condition for the mast design.

Erection considerations also played an important part in the detailed design of the steelwork components (Fig 6.6). The mast heads were detailed such that the ridge and stay cables rested over the mast head in detachable saddles, so that the mast saddles could be delivered onto the profiled mast top without difficulty. The cables were to be fixed into the saddles while the net was on the ground, and the erection was to consist of the simultaneous lifting of the 16 cable saddles to their respective seatings on either side of the mast heads using specially designed lifting frames attached to the top of each mast. Although the final geometry of the net could be accurately determined, it was realised that flexible connections would play an important part in ensuring a rapid and trouble free lift as the net fields took up their predetermined form.

The connection of the net boundary cable to the ridge and boundary cable was a particularly important detail (Fig 6.7). Flexibility was achieved by means of the electric resistance welded links coupling the boundary cable clamps to the body clamp mounted on the ridge/stay cables. The finished components were protected against corrosion by 'hot' dip galvanising.

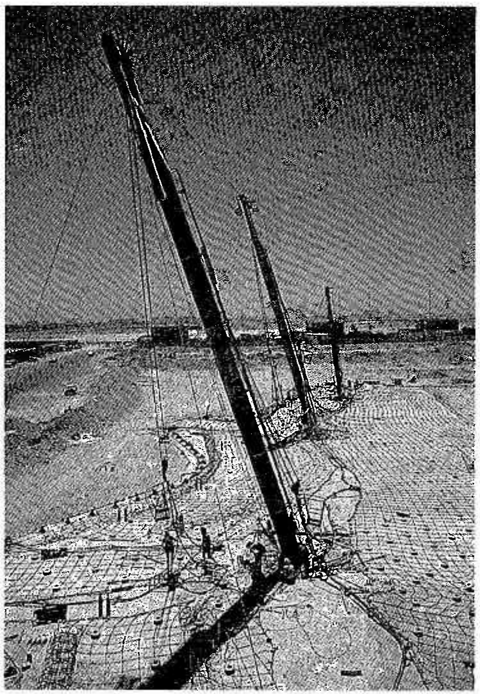

Fig 6.6 Preparations for lifting cable net

Construction under way

The main contract was tendered in 1977 and was won by W S Try (International). A specialist subcontract for the fabric covering and cable net steelwork structure was tendered simultaneously and was awarded to a Swiss joint venture comprising Sarna, a coated membrane manufacture and tent fabricator, and Habegger, a specialist supplier of cable car systems. Whilst work started on site in early 1978 on the construction of the foundations and ground slab, detail design, shop drawing production for the steelwork, and the final patterning and calculation of cable cutting schedules proceeded in Europe. Detail construction method studies were undertaken between consultants and contractors to establish the required means of erection and to verify any modifications to details consequently required (Ref 6.7).

A compehensive fabric and component testing programme was also initiated with the aid of the specialist facilities of the Otto Graf Institute, the University of Stuttgart and the laboratories of the component manufacturers and the ETA, Zurich.

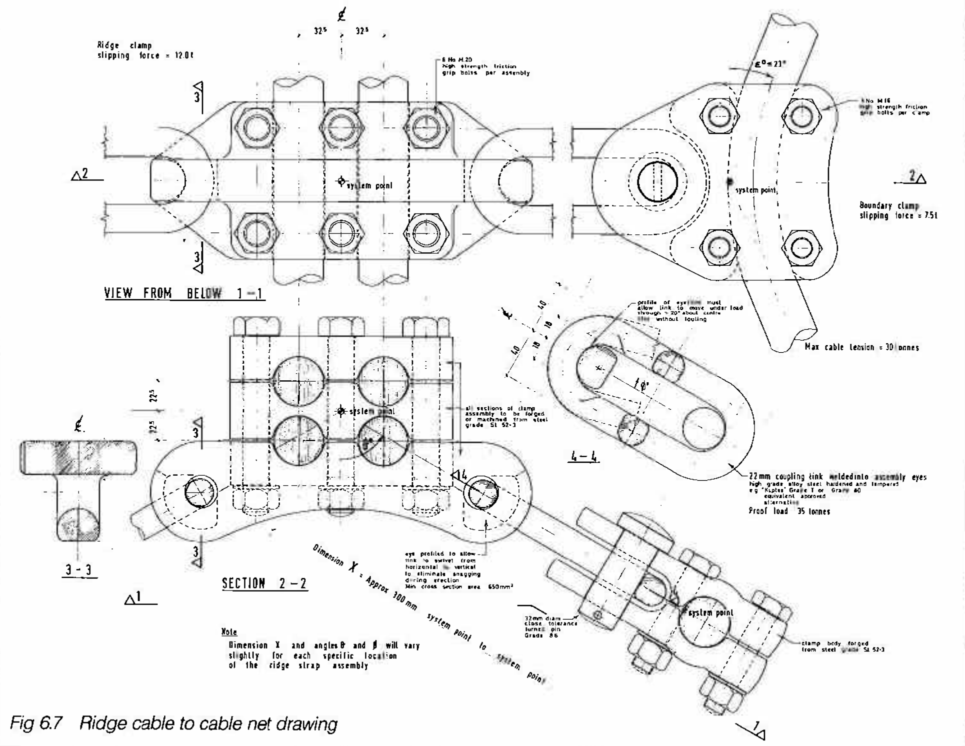

Fig 6.7 Ridge cable to cable net drawing

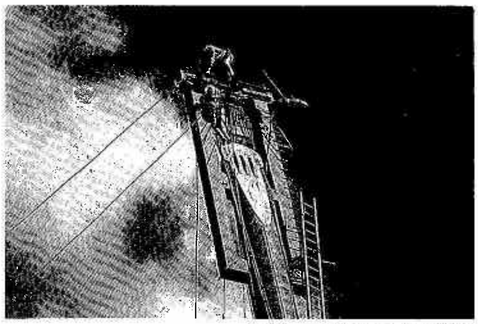

Fig 6.8 Mast top during lifting

Fig 6.9 Erection of cable net

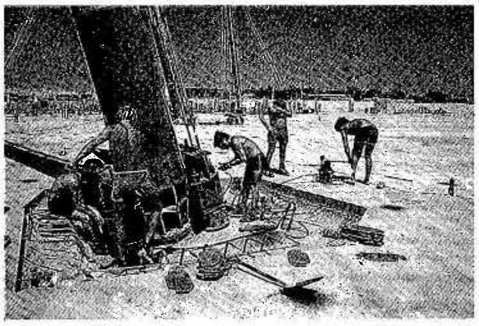

Fig6.10 Jacking of mast bases

Production of the steelwork components took place during the latter half of 1978 and were shipped to site for a start on the cable net erection in January 1979. The masts were transported to site in segments and the first site operations involved welding up the 30m long masts, and the installation and casting in of the mast base sand pots. Following weld certification testing, temporary erection steelwork was assembled at the mast heads, which were then craned into position. These were placed at their approximate final inclinations into their respective sand pots and guyed off with a system of temporary guy cables as had been determined by earlier method studies (Figs 6.8, 6.9, 6.10).

The assembly of the cable net fields and boundary cables then proceeded. A comprehensive cable numbering and marking system had been decided upon during production of the cable schedules, and this proved invaluable on site both in allowing cables to be sorted into their correct location and orientation with minimal abortive effort, and in enabling errors of manufacturing to be identified at the absolute earliest opportunity. This was a critical requirement when replacement cables had to be sourced from Europe. The cables were laid out on the finished ground slab and assembled into nets. At each intersection a mild steel galvanised drop forged node clamp was fitted to secure the cables together. The complete laying out and clamping took approximately eight weeks for the 10,000m² of net which included approximately 40,000 cross clamps, 3,500 boundary clamps and 500 node and stay cable clamps. The final operation prior to lifting was the laying out of the ridge and stay ropes and their assembly into the mast head saddles and into the ridge and stay strap blocks, followed by the interlinking of the cable net fields. During the cable net assembly, the ground anchorage steelwork was installed and checked for position and alignment. Whilst the net was on the ground both the outer and inner membrane fixing nodes were identified and the approximate fixing details added. The complete net assembly took approximately 12 weeks.

The entire net assembly in the air weighs approximately 8kg/m² with a further 8kg per sq. metre of ground plan of steelwork in the masts and anchorages. Studies on the computer model had shown that upon lowering each mast by approximately 450mm the prestress was fully dissipated and the mast loads were reduced to the respective net weight gravity load. A system of lifting cables, pulleys and electric powered hydraulic tirfors was designed to simultaneously lift the 16 mast head saddles to the 8 mast tops. It was estimated that the force needed to lift the heaviest saddle was approximately 12 tonnes and this was achieved using 3 tonne tirfors and the appropriate number of pulley blocks to gain the necessary mechanical advantage.

The primary lift took approximately seven days in May 1979. During this time the tangled mass of cables bundled on the ground unfolded into a graceful light metallic orthogonal spider's web which was rendered even more elegant by the pattern of the galvanised fabric support disks glistening in the sun. Once the mast head saddles had been secured in their respective seats, and the temporary erection steelwork and mast head guys removed, the second stage of the erection could get underway to give the net its final stress distribution and geometry. (Fig 6.11ab) The mast bases are designed to accept a steel through beam to facilitate jacking. The through beam is supported on two crossbeams, so allowing jacking against the top of the base sand pot which is in turn cast in the concrete base at the correct angle. All four jacks are interconnected to a single cell keeping the load effectively axial. During erection the

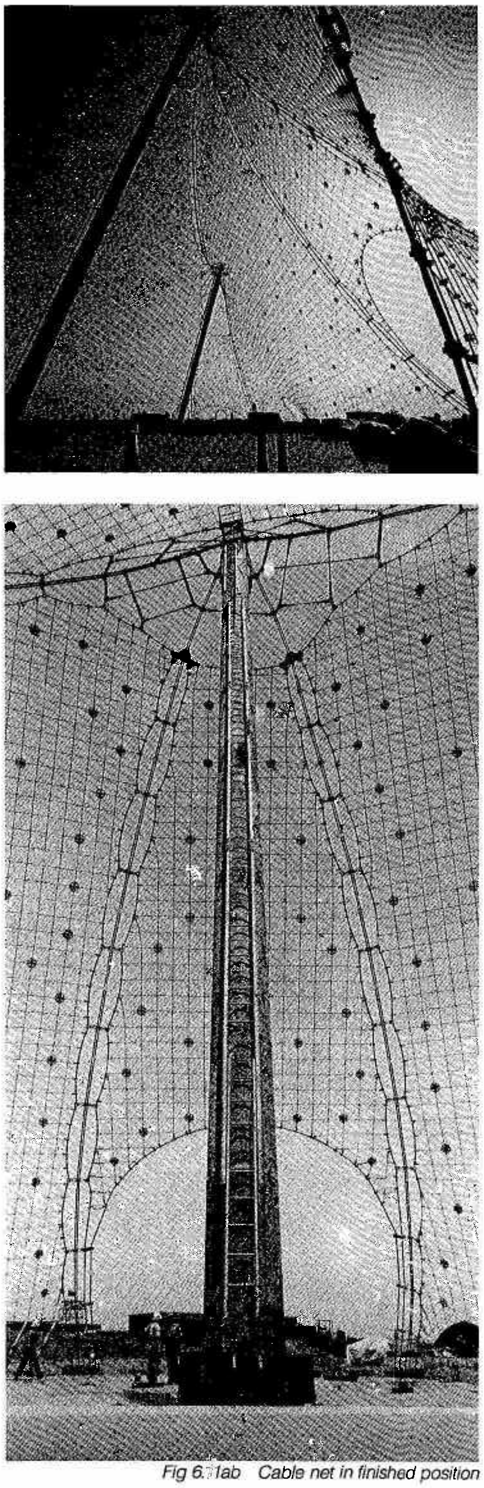

Fig 6.11ab Cable net in finished position

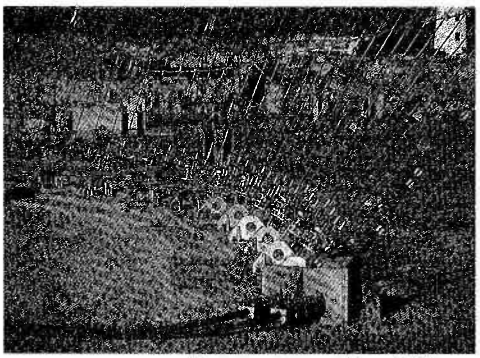

Fig 6.12 Cable net boundary fixings

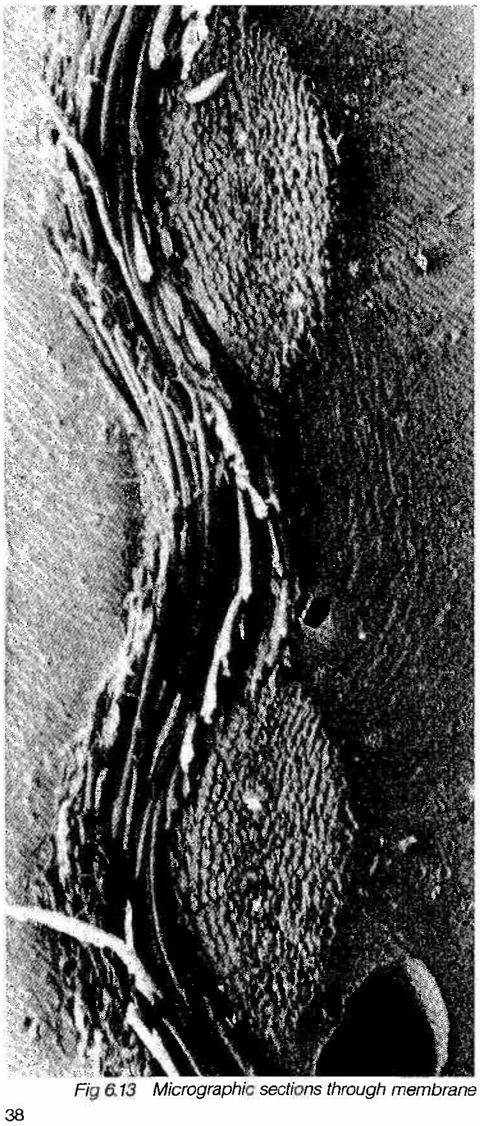

Fig 6.13 Micrographic sections through membrane

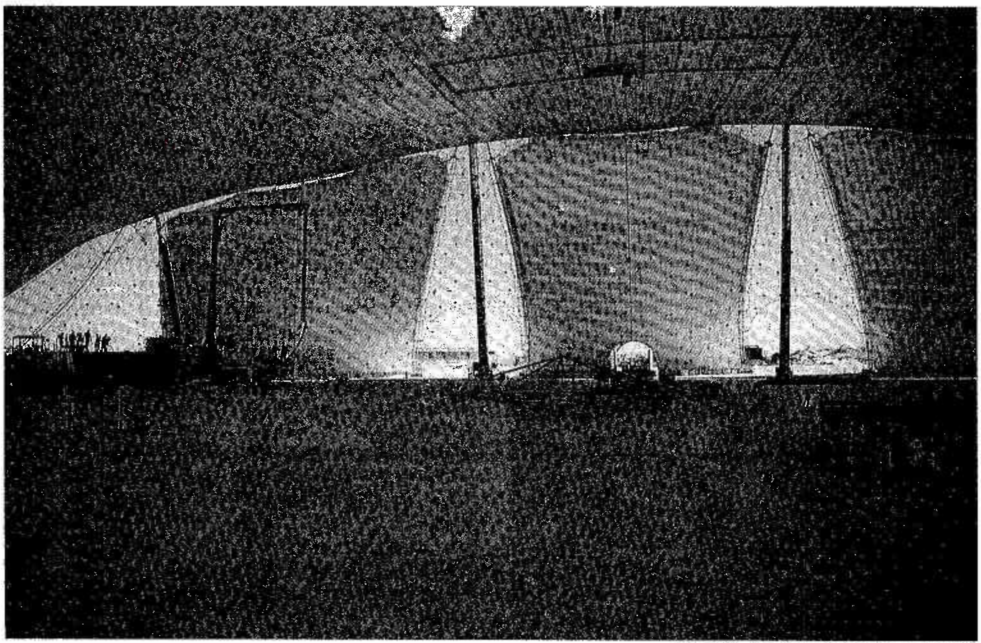

Fig 6.14 North wall membrane panels

masts were jacked in pairs until the theoretical mast lengths were achieved. However, due to cable relaxations and inadequate cable prestretching, it was found necessary to exceed the theoretical jacking distance to obtain the required prestress. The geometry of the cable net was then checked at key locations and found to be well within expected tolerance of the theoretical position. Following minor adjustments and jacking at the perimeter stay anchorages to equalise the stay and boundary forces, the net was accepted and erection of the membrane cladding could proceed (Fig 6.12).

The external roof membrane provided by Sarna was specially developed to meet the design specifications required in the strong Saudi Arabian sunlight to gain the necessary 15 year design life, and has since been widely used elsewhere. An ivory colour was chosen by the architects so that when the membrane was new, at least 70% reflectivity and approximately 7% transluscency would be provided. To improve tear resistance, a double thread grid weave fabric was used, itself being precoated before the application of a polyvinyl chloride coating. Sufficient additions of this coating were applied to enable the membrane to remain plastic with time and attain the required resistance to flame spread of B1 to DIN 4102. The final membrane was top coated with acrylic lacquer to allow for improved cleaning, producing a strength of 75kN/m and weighing 1.5kg/m². (Fig 6.13) Extensive laboratory testing was undertaken to verify welded joint efficiencies, biaxial constructional stretch and strength properties, as well as resistance to ageing under xenon lamp testing. Indeed, full scale fire testing was carried out at Hoechst's fire hangar in Frankfurt to verify the combined performance of inner and outer membrane as installed.

The PVC-coated polyester cladding membrane was patterned to follow the cable net geometry, but to lie in a local plane 150mm outside the cable net. The membrane was supported off the cable net by special 'springy' supports at 28m centres. The roof membrane was fabricated in panels of 20m × 20m which were joined together on site by means of custom designed clamped seams. The membrane was designed and patterned for a prestress level of 200 kgf/m. This force level was applied at the boundaries of a membrane panel by stressing the fabric against the cable net using light pull winches. Due to the temperature and time dependent creep properties of the fabric, the prestress load was maintained for an agreed time before the membrane was punched to enable the support plates to be fixed.

The clamped seams between panels were executed in situ on the net before stressing of subsequent panels could continue. Erection proceeded outward from the centre of the roof to the boundaries, where the fabric is anchored on to boundary rods independently fixed to the ground beam or to the ridge stay cables. The wall panels were fabricated as single piece membranes, as clamped site joints were undesirable. The north wall fields were particularly large measuring approximately 30m × 20m (Fig 6.14). The wall membranes were further complicated by having extensive 'plisse' sections incorporated into them which were heavier than the plain membrane and more fragile. These plisse areas allow ventilation of the space between the inner and outer membranes. Needless to say, the erection of the north wall membranes called for every reserve of both the contractor's skills in erection planning and on the spot improvisation, as well as physical strength and patience from the workforce. Erection of each wall membrane panel was commenced at first light at approximately 5.30am, and it was generally possible to secure even the largest panel, albeit in a temporary condition, before noon the same day (Fig 6.15). The complete erection and stressing of the 9,000m² outer fabric was completed in approximately three and a half months. (Ref 6.8)

To provide the tent envelope with the improved insulation properties necessary for an air conditioned space, a secondary inner membrane is included which serves both to produce the desired insulation air gap and as a decorative inner ceiling and wall surface. This membrane was also fabricated in a PVC-coated polyester fabric, and was required to have a 50% transluscency and a measure of structural strength, together with a resistance to fire equal to B2 to DIN4102. Tests were also conducted to ascertain the level of needling of the finished fabric necessary to provide the acoustic absorption required over the main sports arena. Erection of the inner membrane was deferred until all the major construction activities within the tent were complete. Consequently dust deposits on the inner fabric were minimised, so preserving it in a pristine condition for handover.

The inner membrane was erected by joining together several panels and winching the completed lining and its support 'pretzels' up to the cable net. The pretzel supports were then attached to the fixings previously incorporated during first cable net erection (Fig 6.16). Finally, the complex mast top 'pagoda' structures were installed complete with fly mesh to provide housing and louvres to the extract fans at the top of each mast (Fig 6.17) and an Arabian tent at a scale never seen before was complete.

Eddie Pugh

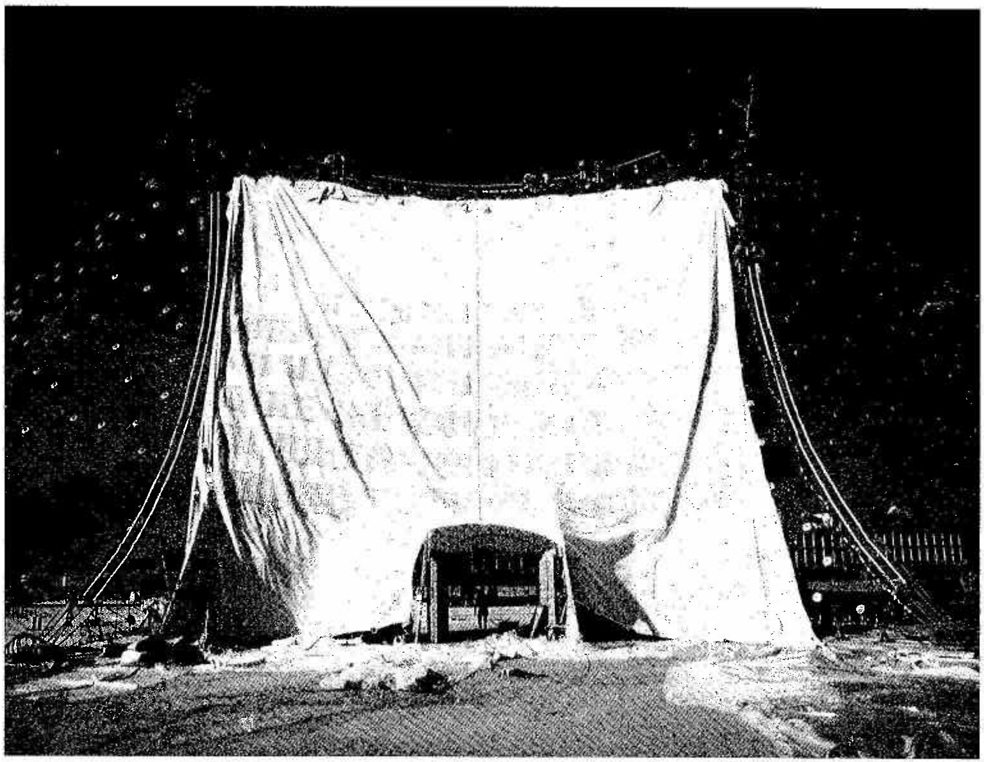

Fig 6.15 Membrane erection

Fig 6.16 View of finished interior

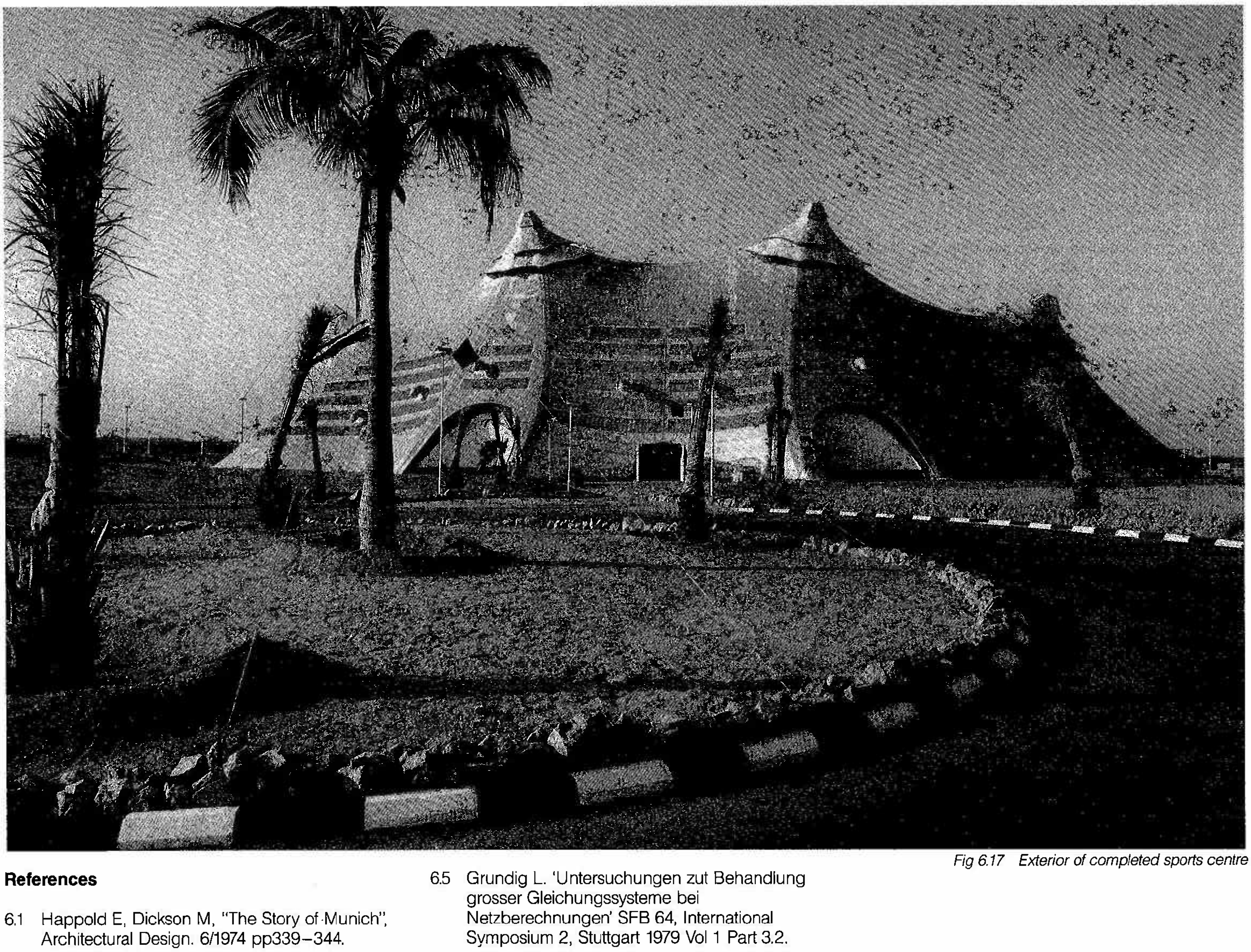

Fig 6.17 Exterior of completed sports centre

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