Chapter 2

ENGINEERING FABRIC ARCHITECTURE

Brian Forster, Marijke Mollaert

2.1 Introduction

Fabric structures provide widespan enclosures of great spatial interest and variety, require minimal supporting elements of "hard" structure and provide very good overall levels of natural daylight. The purpose of this chapter is to outline the nature and characteristics of this structural type and to describe the primary issues that designers deal with and make decisions about.

From an engineering point of view fabric structures are thin membranes of constant thickness which by virtue of their surface shape and inherent large deflection behaviour are able to support the imposed loads required by Building Codes. They are modestly prestressed to enhance their stiffness.

Whilst "tents" have a long history the origins of our contemporary fabric structure technology are to be found in the nineteenth century. For instance the mechanical spinning of yarn and weaving of cloth enabled large portable tents to be created for the travelling circuses that abounded in the latter part of that century. Tents such as the "Chapiteau" (Figure 2.1) were up to 50m in diameter and made from machine woven linen or hemp canvas[1]. The "Chapiteau" was supported near its centre by four King poles situated around the circus ring. The canvas hangs from these to frequent perimeter poles that are stayed by ropes anchored into the ground. Between the perimeter and the King poles there is a further ring of Queen poles set at 60° to the ground, their function being to lightly pretension the cloth, so as to diminish surface movement and flapping.

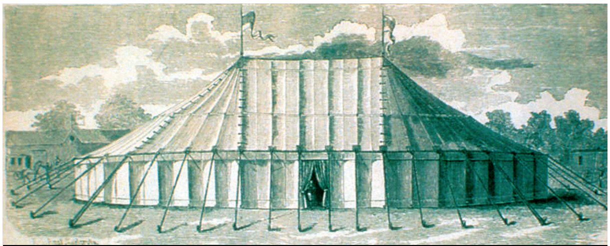

Fig. 2.1 Circus tent 'Chapiteau'

Whilst these were travelling structures, and therefore protected from exposure to the excesses of climatic loading, their design embodies two of the primary features of the modern fabric structure – a deformable surface shape and pretension.

For the Pan-Russian Exhibition of 1896 the eminent Russian engineer V. G. Suchov designed four exhibition halls of large clear span.[2] The roof construction was intriguing in that Suchov employed flexible 2-way networks of thin strip steel which in turn were clad in thin overlapping steel tiles. The system as a whole formed an unprestressed "warped" surface hanging in tension under its own weight. In effect it obtained its stiffness, stability and load carrying capacity from its surface shape, in conjunction with its self-weight.

After a 50 year interval long span "saddle" shaped roofs started to be built commencing with the Raleigh Livestock Arena in North Carolina, USA, designed by engineer Fred Severud and architect Matthew Nowicki and completed in 1952 (Figure 2.2). In essence the roof consists of a 2 – way network of cables spanning 95m between a pair of arches inclined away from one another at 20° to the horizontal.

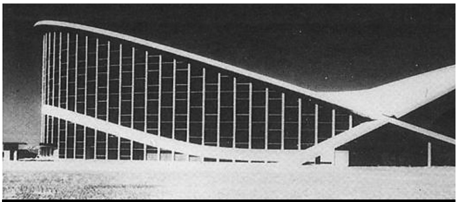

Fig. 2.2 Raleigh Livestock Arena in North Carolina, USA

The significance of the building is that it displays two primary features of the modern tension structure – the arch boundaries act together to “contain” the forces coming out of the cable network whilst the configuration of the arches enables a roof surface having double curvature of the “anticlastic” type to be formed.

The Raleigh Arena formed the archetype for a great number of cable roofs built throughout Europe, Russia, China as well as North and South America. Expos became the proving ground for new ideas and techniques. In Belgium for instance Rene Sarger engineered two pavilions at the Brussels Expo in 1958. The larger of these, the French National Pavilion, had spans of 100m. The other, The Marie Thumas Pavilion, had slightly more modest spans of 53m x 36m. Clever use of alternating ridge and valley cables helped to create a continuous envelope formed of warped planes for both roof and walls. The system was prestressed with levels and distribution monitored by ultrasonic means.

In the early 1960’s Robert Le Ricolais, when considering the design of a long span/ minimum weight “Sky-Rail” system, researched the possibilities of weaving cables into networks so as to form prestresed “funicular” surfaces of revolution.

In the 10 years following Raleigh the German architect Frei Otto developed his knowledge of tent design through a fruitful collaboration with the tent maker Peter Stromeyer. Between 1955 and 1965 many free-form, doubly curved tents were designed and made for Federal Garden Shows and other national exhibitions such as Lausanne in 1964[1]. Each one introduced new ideas about shape, erection and stressing technique, and experimented with different kinds of cloth and methods of jointing.

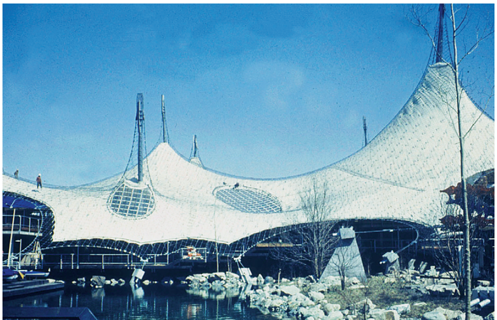

Fig. 2.3 German Pavilion at Montreal Expo 1967

Frei Otto had also been inspired by Nowicki and Severud’s cable net roof at Raleigh. His first major cable net, designed with fellow architect Rolf Gutbrod, was the German Pavilion for the Montreal Expo in 1967 (Figure 2.3). Both architecturally and structurally it was a radical departure in a number of ways. It had a very free-form plan which meandered around the edge of a lake, and the conventional distinction between building and landscape virtually disappeared – the building itself became landscape. As a result of the irregular plan, the net was hung from masts of varying heights and inclinations, with the concentration of forces at mast tops cleverly intercepted and carried by loop cables lying within the net surface. Ten thousand square metres of PVC coated polyester textile were suspended from the cable net and tensioned to form the enclosing skins. His method of design was an exploratory one working through a sequence of physical models which became progressively more refined and accurate. As the behaviour of surface structures is largely conditioned by their geometry, this approach enabled him to combine his architectural ambitions with a structural logic as well as a method of building. The process required painstaking care and time to build the final models accurately enough for them to be measured for the purpose of structural analysis and construction drawings. The engineering design of the Pavilion was led by the office of Leonhardt and Andra, who continued on with Günter Behnisch and Frei Otto to realise the astonishing cable net roofs for the 1972 Olympic Games in Munich. This project, because of its scale and importance, marked a shift away from physical model testing to computer methods for the justification of structural behaviour and capacity. Inevitably, non-linear engineering software has embraced the choice and optimisation of surface geometry and the conversion of this into cutting patterns and dimensions for fabrication.

A more extended historical discussion is to be found in [3].

The materials commonly used in fabric structures consist of a woven textile encapsulated in a polymeric coating. There are for instance different constructions of weave, different weaving techniques which can include control on yarn straightness and tension which affect the strain behaviour of the finished product. Such factors need to be understood and accommodated in the engineering design and specification processes for each project. Chapter 8 refers to numerical modelling techniques and Chapter 9 describes the formulation of the commonly used materials and their characteristics.

2.2 Form and Behaviour of Fabric Structures

The form and physical behaviour of fabric structures are very different to those of conventionally stiff “linear-elastic” framed structures used in most buildings.

Designers of fabric structures concern themselves with three primary structural factors – choice of surface shape, levels of prestress and surface deformability.

Consideration has also to be made regarding the internal climate of spaces enclosed by textile membranes as well as the choice of the particular type and grade of the membrane to be used.

2.2.1 SURFACE SHAPE

Most contemporary fabric structures have as their basis an “anticlastic” surface geometry. This is one in which a set of “arching” tensile elements act in opposition to a similar set of “hanging” elements (see Figure 2.4). Physically the two groups of elements represent the two directions of the textile yarns (warp and weft) within the membrane.

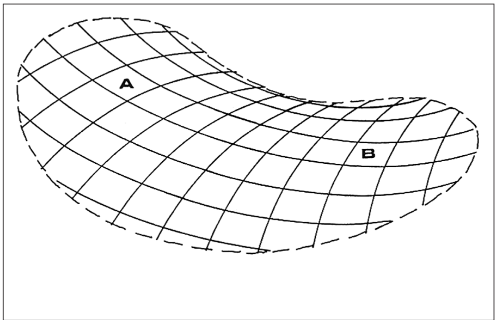

Fig. 2.4 Anti-clastic surface

This configuration has a valuable property in that the surface as a whole is prestressable without significant change occurring to its overall shape.

It also possesses clear and separate “load-paths” for inward and outward pressure. Downward pressure from snow is carried by the yarns in the “hanging” curvature and outward suction from windflow is carried by the yarns in the “arching” curvature.

There are four generic types of anticlastic surface in common use – the “cone”, the “saddle”, the “hypar” and “ridge and valley”. These are shown in Figures 2.5-2.8 and the essence of each is that they are constituted from four sided “warped” elements, with the degree of warp dependent on the choice of boundary conditions.

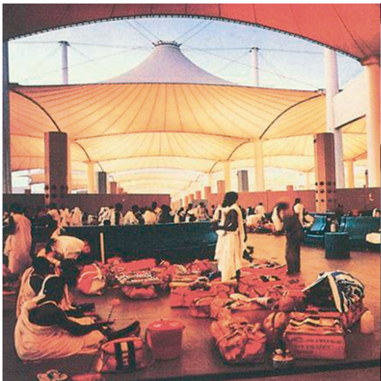
Fig. 2.5 Cone


Fig. 2.5 Saddle


Fig. 2.7 Hypar


Fig. 2.8 Ridge and valley

Furthermore the geometry of a membrane’s surface is not defined by imposing on it a mathematically based surface of revolution as in the case of shells, rather it needs to be defined by its “internal equilibrium of prestress” within a predetermined boundary system of support. The physical analogy of the soap film is useful here in that a film can only form within a boundary system whose geometry permits tensile equilibrium to exist between the film’s molecules. Therefore in terms of designing fabric structures the designer is essentially involved in choosing a set of “boundary conditions” in the process of defining the membrane’s shape. Boundary conditions are in effect the disposition of all elements that contact and provide support to the membrane, for instance, ridge and edge cables, masts, arches, beams etc.

The process of determining the shape and form of the structure is commonly referred to as "form finding". It is an iterative process where changes and adjustments are made to the disposition of supporting elements such as edge and ridge cables and the relative heights of masts etc.

The geometry of a soap film's surface is unique to its given boundary and so changing the boundary, in whole or part, changes the film's surface geometry. It is useful therefore to think in terms of each surface being the outcome of choosing particular boundary conditions. Figure 2.9 shows a soap film by Frei Otto which will have been the result of several iterations in the choice of heights and spacing of the supports. This is in effect what designers do when working with either physical or computer models. An extended coverage is to be found in [4, 5].

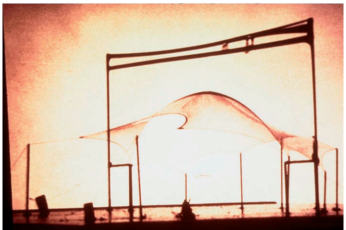

Fig. 2.9 Soap film model by Frei Otto

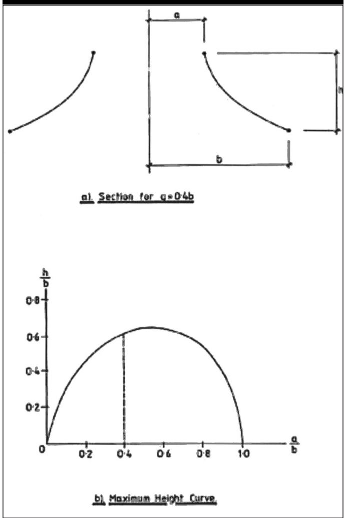

Fig. 2.10 Physical limits of soap films

It is also important to note that there are physical limits to the boundaries within which soap film and their numerical analogues can form. For instance there is a limit to which any pair of concentric circular rings can be drawn apart before the film "necks" and collapses. Limiting ratios have been established for soap films physically and numerically by Day[6]. These relate the ratio of ring diameters to their distance apart, see Figures 2.10 and 2.11.

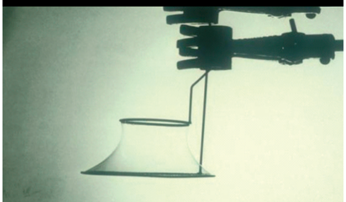

Fig. 2.11 Soap film model

However by introducing a sub-set of "boundaries" lying within the film, such as a series of "threads" running between the upper and lower rings, a soap film surface can then form beyond the limiting ratios quoted above.

In real life these "threads" can be a set of prestressed radial cables lying in contact with the membrane's surface, see Figure 2.12. Alternatively they can represent the presence of a non-uniform and varying stress field (i.e. not a soap film) within a slightly altered geometry with larger prestress forces put into the radial direction of the membrane's cloth than in its circumferential direction. See Figure 2.13.

This type of approach in defining surface shape permits the designer to step beyond the constraints of the equi-stressed soap film and so produce surfaces having less restrictive ratios of height and ring size whilst having smoothly changing prestress fields. See Figure 2.14. Thus surface shape can be the outcome of not just the choice of boundary conditions but also the choice of prestress ratios within those boundaries. Choice of boundary conditions is primary to the resulting surface shape since choice of a prestress ratio is not, in itself, a primary generator of shape, simply a modifier of it.

The shapes that are possible for fabric structures aren't simply limited to the 4 generic shapes illustrated in Figures 2.5-2.8. Indeed hybrid versions and combinations thereof increase the choice of forms considerably as can be seen in examples illustrated in Chapter 3.

Where very large areas have to be covered but with control on the internal height to be maintained then modular arrangements can be employed. The Haj Pilgrim Terminal at Jeddah Airport in Saudi Arabia (Figure 2.5) is one such example in which 45.75m x 45.75m square based conical units cover a total area of 440,000m² [9].

The physical and numerical methods commonly used for "form finding" are described in Chapter 8.

Fig. 2.12 Radial cables lying in contact with membrane's surface

2.2.2 PRESTRESS

Prestress contributes significantly to a membrane's stiffness due to its opposing curvature components interacting to constrain what would otherwise be severe deformations typical of flat or singly curved surfaces. For example in Figure 2.15 the deformation of the "hanging" curvature due to loading in zone A is constrained by the "arching" tensions in zone B. Actual values of prestress used in practice generally represent a small proportion of a membrane's ultimate strength.

Fig. 2.13 Non-uniform prestress field

The chosen level of prestress will normally be a compromise – low enough to reduce the work done during installation – whilst sufficiently high to maintain a sufficient prestress after losses due to 'creep' of the membrane material over time. Some typical values of prestress used in practice are given in Chapter 7 – Design Loading Conditions.

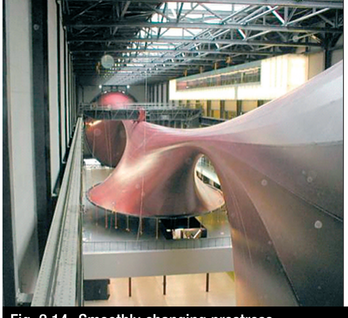

Fig. 2.14 Smoothly changing prestress fields

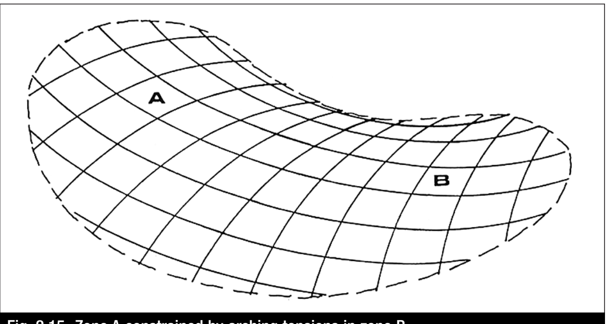

Fig. 2.15 Zone A constrained by arching tensions in zone B

The choice of the initial boundary conditions for an anticlastic surface can often be guided by the use of the relationship T= p x R where T = membrane tension, p = pressure applied normal to the surface, and R = radius of curvature of the surface. This relationship has particular relevance to the 'saddle' and 'hypar' shapes. Thus by knowing what the applied pressures are likely to be as well as what the membrane tensions should be limited to, then the radius/radii or curvature can easily be found. This can then be fed back into the initial assumptions made about the geometry of the boundary conditions.

In doing this a number of simplifying assumptions are being made, such as that the pressures are 'normal' to the deflected surface and are uniformly distributed. Nevertheless it can be a useful starting point for design as well as a simple means of checking the output of more elaborate computations.

Where geometric constraints are placed upon a design – such as to require the use of flatter and therefore larger radii of curvature – then larger values of prestress will be required to control the size of the membrane's deflections. There are practical limits to what can be safely applied and remain in the long term. In the limit where the surface becomes flat (radius = ∞) then prestress and the material's stiffness (EA) are the only parameters controlling deflection.

For many structures the same quantity of prestress is applied to both directions of the textile's weave. However in cases where the magnitude of the inward and outward applied loads are markedly different to one another then it can be economically advantageous to determine the membrane's shape such that a smaller (tighter) radius of curvature is subjected to the higher external pressure and vice-versa a larger (flatter) radius of curvature carries the lower external pressure. In this way the resulting maximum membrane tensions will be of a similar size.

The level of prestress may also be set so as to avoid loss of stress in both directions in a particular zone of the surface under applied load. The setting of such values is generally made in combination with the selection of shape.

2.2.3 DEFORMABILITY

Unlike in more conventional forms of building construction deformability is seen as a useful and important characteristic of a fabric structure. Indeed due to its relatively low surface stiffness (both in-plane and out-of-plane), changes in geometry/surface shape are a fabric structure's primary response to externally applied load coupled with changes in stress distribution throughout its surface. In addition the strains developing within membrane material are several orders of magnitude larger than those in steel for instance. Consequently fabric structures exhibit very much larger deflections and geometric changes under load than orthodox framed construction. Flexibility in the supports of a membrane also add to its deformability providing of course that overall stability is assured.

All this has the beneficial effect of stresses not rising linearly with applied loads due to the geometric changes that occur in the surface as a whole.

For instance wind flowing around a conical membrane causes a "pin-ended" mast to lean into the wind allowing changes to surface curvature on the windward face to attenuate the rise in membrane stresses in that zone, but also with membrane curvatures on the leeward side acting to stabilise the mast.

Heavy localised loading such as wind pressure on eaves and ridges is in effect supported by a much larger area than simply the contact area of the pressure due to changes in surface geometry within the membrane.

Encouraging deformation of the membrane's surface is beneficial provided that the deformed surface under load remains with positive inclinations throughout. The inherent danger of shallow gradients is that an accumulation of snow/ice can cause a depression into which meltwater and rain can collect ("ponding") with the surface geometry having changed from "anticlastic" to "synclastic" (Figure 2.16). This in turn can increase the depth of the depression allowing more water to pond and hence creating a larger depression and so on. It may remain as water or convert to ice according to weather conditions. The effect however is for snow loads to progressively increase far beyond those applicable to a more rigid structure[7]. The objective must be the achievement of a form which as it deflects maintains positive gradients under the effect of the worst credible loading conditions.

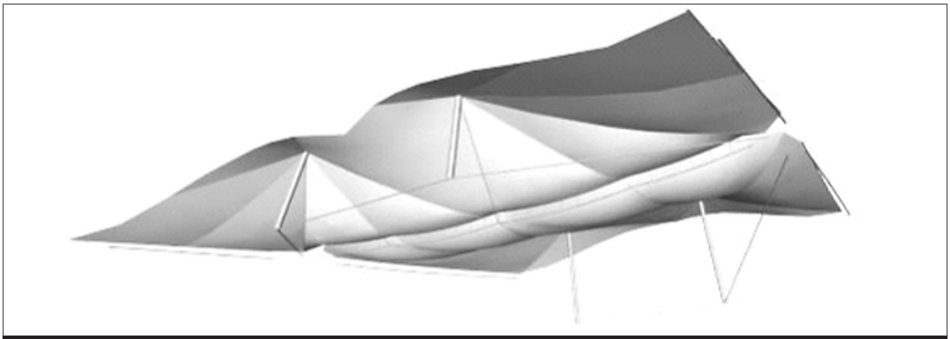

Fig. 2.16 Ponding

Fig. 2.17 Akita Skydome

The deformation of each structure under snow loading must therefore be investigated and tested carefully in the design stage. The choices made for boundary geometry are high influential as well as the realistic assessment of the flexibility (i.e. spring stiffness) of all supporting elements in the system.

In areas of the world with high snowfall such as Canada, USA and Japan, designs based on both inclined "ridge and valley" and "arch and valley" systems have been successfully employed for covering large buildings (Figure 2.17). Ishii [8, 9] provides many examples.

Fig. 2.18 Cargolifter Airship Hangar

Fig. 2.19 Inland Revenue Centre Sunshading as climate control

The major spanning loads are carried by the deflected curvature of the ridge and valley cables with the membrane panel acting as a prestressed web spanning between them. The panels are slightly warped but because of their length to width aspect ratio the ± applied pressures of snow and wind will both largely be carried in the short direction of the panel as a result of 'form inversion', regardless of whether it is pressure or suction loading. A further example is the Cargolifter Airship Hangar in Germany shown in Figure 2.18.

The deformability of the surfaces comes into play where snow builds up but "ponding" of rainwater and melting snow is avoided by the deflected membrane surfaces remaining positive in inclination due in effect to the initial choice of boundary support stiffness and geometry.

The engineering techniques for modelling large deformations are described in Chapter 8.

2.2.4 INTERNAL CLIMATE

Fabric structures are to be found in almost all of the world's climatic zones and serving a range of different functions.

The commonly used membrane materials, such as PVC coated Polyester and PTFE coated glass, typically reflect circa 75% of incident solar energy, absorb 17%, whilst transmitting 13% of incident sunlight (Figures 2.5, 2.6, 2.7). This makes them very effective as sunshading in the arid temperate and tropical zones.

They have also been used with success in temperate zones for enclosed large volume/low occupancy spaces such as sport and recreational buildings where a combination of underfloor heating and wall-mounted radiant heating can provide satisfactory comfort levels during the winter months.

The cost of such heating can be offset by the savings made through reduced costs of artificial lighting. (Figure 2.19).

Examples are the Saga Amenity Building at Folkestone, UK and The Inland Revenue Centre at Nottingham, UK. The internal behaviour of the latter example has been monitored[10].

Other strategies can involve trapping air between multiple layers of membrane such as in the Cargolifter Airship Hanger. In this project there are 4 layers of PVC coated polyester assembled so as to create 2 sealed volumes of air. This results in a thermal transmission thought to be comparable with a U-value of 0.95W/m²K and a light transmission of 1.5%. (Figure 2.20). Extra membrane layers of course erode the % of natural light transmitted.

The roofs over the Museum of Science and Industry at La Villette in Paris (completed 1986) and the Lindsay Park Aquatic Centre in Calgary (completed 1984), both involve the use of a 400mm thickness of translucent glass filament insulation and transparent vapour barriers placed between an outer and an inner layer of PTFE coated glass. This gives each roof a thermal transmission thought to be comparable to a U-value of 0.4W/m² and a light transmission of 3.5%.

A discussion of environmental behaviour and the parameters influencing it is provided in Chapter 4.


Fig. 2.20 Extra membrane layers


Fig. 2.21 Open sided canopy

2.3 Design Sequence

2.3.1 CONCEPTUAL DEVELOPMENT


Fig. 2.22 Folding mechanism mock-up

The Client's brief and the nature and configuration of the site need to be fully considered and understood. Within the brief there may be space and climate requirements which could be fulfilled by being enclosed with a fabric structure and the architectural form of such a roof may respond harmoniously with the topographical qualities of the surrounding terrain. Can the Client's brief be met satisfactorily by an open-sided canopy or is an enclosed building required? Open sided canopies provide much more freedom in choice of shape and configuration, and they can be built to less exacting tolerances of final position. (Figure 2.21 plus examples in Chapter 3). Bringing an enclosing wall up to such a canopy needs to accommodate quite large displacements of the roof which, according to circumstances could be as large as ± 500mm due to wind or snow loading. A variety of folding mechanisms made from membrane material have been employed to effect such closure. They need to be lightly tensioned for reasons of appearance and stability. (Figures 2.22, 2.23 and Chapter 3).

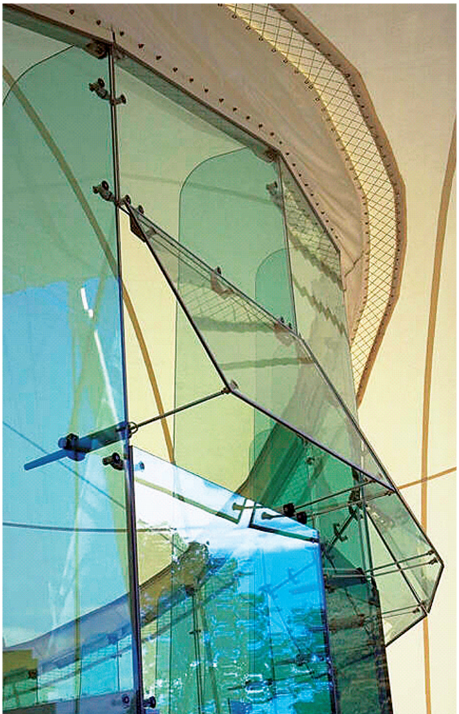
Fig. 2.23 Dynamic Earth Centre, Interface of wall and membrane roof


Fig. 2.24 Saga Headquarters Building


Fig. 2.25 Munich Airport Centre

On the other hand if a fabric structure is to form part of the enclosing skin of a building the opportunity may exist to geometrically integrate the two so that, like the Raleigh Arena and others such as the Saga building, the membrane's tensile forces are largely and economically absorbed within the building's framework (as opposed to heavy ground anchorages) and sealing between wall and roof is relative simple (Figure 2.24). Other examples are the Munich Airport Centre (Figure 2.25), the Sony Center Forum roof in Berlin (Figure 2.26) and Thomson LGT at Conflans St. Honorine. Figure 2.27.

Geographical location has a very direct bearing on the type and magnitude of loading which a fixed non-retractable roof must support. Design values for wind and snow have to be derived via National Standards, the meteorological records of the site, and where necessary through wind tunnel model testing. For structures of significant size model testing should be an essential requirement. Refer to Chapter 7 for expanded discussion on the choice of suitable loading patterns and loading intensity.

Membrane materials are easy to cut with a sharp knife and are therefore susceptible to accidental damage from vandalism and flying objects. As with conventional structures the accidental removal of individual members or membrane panels needs investigation to demonstrate the inherent damage limitation of the whole system. Whilst such accidental damage is quite rare, a sound and regular system of inspection should be implemented by owners so as to pre-empt the occurrence of serious damage. Designers therefore need to anticipate the need for access. Chapter 10 provides further information.

A fabric structure is composed entirely of prefabricated elements which once assembled forms a prestressed system with its own particular geometry and prestress distribution.

The fabric and cable elements therefore have to be made to smaller dimensions than those finally intended so as to allow for the development of appropriate strains during the process of assembling the whole structure.

Generally elements are loosely assembled on a suitably level plane. A set of displacements are then required to draw the membrane towards its various points of support so as to induce the desired prestress. Figure 2.28. The designer needs to anticipate this and must ensure that throughout the design's development there are embodied within it practical and effective means by which the desired prestress configuration can be achieved.

In some cases this may require discrete elements to be included in the design whose lengths can be changed significantly during the stressing process but remain in the system as permanent elements, such as masts that are jacked (Figure 2.29) and aerial ties that are shortened as in Figure 2.30. The designer also needs to anticipate the scale and direction of displacements and rotations that are likely during installation (Figure 2.31) as well as thereafter in service so that appropriate articulation is provided between elements and at support points. The design process can therefore involve a number of "feedback loops" which may require revision to element lengths, topology and coordinates.

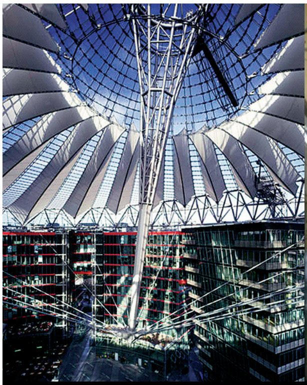
Fig. 2.26 Sony Center Forum


Fig. 2.27 Thomson LGT Conflans Ste Honorine


Fig. 2.28 Inducing the desired prestress


Fig. 2.29 Jacked flying mast


Fig. 2.30 Shortening of aerial ties


Fig. 2.31 Installation process

According to circumstances the designer may explore these issues in the first instance with scale physical models (Figure 2.32). Analytical modelling can provide confirmation of the forces applied to the elements in the system at various stages during erection and prestressing.

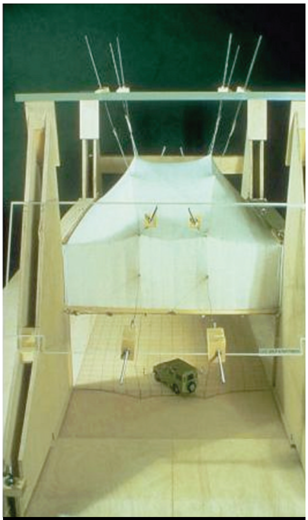

Fig. 2.32 Scale model

2.3.2 DETAILED DESIGN

The detailed design process involves several stages, and is invariably based around the use of geometrically non-linear analysis software. This process can be summarised in the following three steps:

a) Developing the design concept. This involves defining a physical configuration of elements, defining materials and their strength and stiffness properties, element sizes; defining the connections between all elements. An “equilibrium form” needs to be established using zero-stiffness finite elements representing the membrane and cables each of which have specified tensions. By changing the relative values of tensions and the relative geometry of the supports, different surface geometries result. This can be advantageous in accommodating, for instance, the dominance of a particular service load, and in improving areas that may be prone to ponding or inversion.

   In the structural analysis that follows the form finding stage, cable and membrane elements with real stiffness values are used; particular elements whose tensions go to zero are automatically switched out during the analysis to simulate a slack cable or buckled membrane. The element meshes used in the computer model are aligned with the directions of weave and anticipate the position and direction of the seams between the individual panels of fabric that will make up the whole surface.

   It is important to note that the positioning and direction of seams over the membrane’s surface is never arbitrary or merely a matter of taste, except in the most lightly loaded structures.

   The seams are an indication of the direction of the warp yarns. Since in most cloths the warp direction is stronger than the weft, the warp would be placed to follow the higher stresses for reasons of economy (Figure 2.19).

   In regions of significant snow loading the warp would generally be chosen to follow the sagging curvature so that its greater stiffness can limit snow load deflections in the medium to long term.

   Where wind loads are significantly higher than snow loads then it can make sense to the place the seams in the arching direction. (Figures 2.19, 2.23).

Some PTFE coated glass materials are woven with a high crimp in the weft direction and consequently with fairly straight warp yarns. This allows the introduction of a biaxial prestress by simply extending the weft yarns whilst holding the warp steady. This was achieved in Figure 2.12 by jacking the mast and in Figures 2.29 and 2.30 by shortening the aerial ties. This is therefore another factor which engineers take into account in planning both the erection strategy system and layout of seams.

The membrane's stiffness properties used in the above analysis need to be determined via biaxial testing of the material to be employed on the project. Chapters 8, 9, 10 provide extended coverage of this topic.

Appropriate pressure distributions representing wind and snow loads are applied to the surface of the analysis model in appropriate directions. Load vectors are applied to the element surface geometry in its deformed state. The deformed surface under self weight and snowloading needs to be examined for the possibility of ponding and load accumulation. In this respect a rigorous examination of potential loading patterns and intensities must be undertaken.

b) Determining how it is to be built. This involves developing a sequence of assembly and the step by step means of obtaining the desired prestress distribution in advance of fabrication.

The purpose of this is to confirm the viability of a particular sequence and, where necessary, to determine individual component forces and movements during the construction process. Such information must feed into the detailing of connections etc. It can also assist in establishing the best "starting position" of the primary elements. This can be simulated numerically by modelling step by step the removal of prestress from the structure [11, 12, 13]. It involves presupposing a series of discrete steps which should of course be practicable. The chosen strategy and techniques for installing element prestresses on site need of course to be as insensitive as possible to fabrication and construction tolerances.

2.3.3 FABRICATION INFORMATION

Accurate fabrication dimensions are essential to the successful construction of fabric structures. This requires membrane cutting patterns to be taken out of the “at prestress” model of the structure. Seam lines between panels of cloth are defined by geodesic lines for efficiency in material use. Patterns have to be “compensated”, that is shrunk by percentage values in both warp and weft directions so as to allow for the development of strains necessary to give prestress. Batch testing of the fabric to be used in the work has to be carried out to determine these values. Local adjustments to edge lengths (“decompensation”) are often made at some boundaries, e.g. continuous beam edges, to facilitate safe installation. Chapters 8 and 9 describe this process in more detail[13].

In addition to the fabric related items, schedules will also be required for accurately dimensioning cables, taking into account stretch compensations and adjustment details. The shop drawings for metalwork items including membrane plates and support masts and frames have to be developed, and these should take into account final form geometry and angles.

Accuracy in both the dimensioning and the cutting out of individual fabric panels is important since gross errors will prevent the development of the intended strains and therefore the required prestress. In addition the membrane’s finished appearance may be impaired by the formation of folds and wrinkles.

Accuracy is important as it is generally not possible to correct errors on site.

Further description of how designers move from outline ideas to construction drawings is given in Chapters 3 and 5.

2.4 References

(1) IL16, "Zelte-Tents", Institut fur Leichte Flachentragwerke, University of Stuttgart 1976.

(2) I. G. Liudkovsky "On the choice of optimum types of suspended roofs....." IASS Colloquium, Paris 1962.

(3) B. Forster "Cable and Membrane Roofs – A Historical Survey" Structural Engineering Review Vol. 6 No. 3-5 1994.

(4) F. Otto and R. Trostel, "Tensile Structures" Vol 2, MIT Press, 1967.

(5) IL18 Seifenblasen – Forming Bubbles, Institut fur Leichte Flachentragwerke, University of Stuttgart 1976.

(6) A. S. Day "A general computer technique for form finding for tension structures, IASS Conference, Shells and Spatial Structures, the Development of Form, Morgantown, USA, 1978.

(7) W. I. Liddell, "Minnesota Metrodome. A Study of the Behaviour of Air Supported Roofs under Environmental Loads", Structural Engineering Review Vol. 6, no. 3-4.

(8) K. Ishii, "Membrane Structures in Japan" SPS Publishing Tokyo, 1995.

(9) K. Ishii, "Membrane Designs and Structures in the World" Shinkenchiku-sha Tokyo, 1999.

(10) J. C. Chilton, D. Devulder, "Environmental Monitoring at the Inland Revenue Amenity Building, Nottingham" – Designing Tensile Architecture – Tensinet Symposium, VUB Brussels 2003.

(11) M. L. Brown, "Denver International Airport Tensile Roof Case Study – The Fabrication and Construction Process" – Proceedings of IASS-ASCE Symposium 1994.

(12) B. Forster, "The Integration of Large Fabric Structures within Building Projects including the Significance of Design and Procurement Methods" – Proceedings of IASS – LSAA Symposium 1998.

(13) D. Campbell, "The Unique Role of Computing in the Design and Construction of Tensile Membrane Structures", Proceedings of ASCE Second Civil Engineering Automation Conference, New York, 1991.

(14) D. Wakefield, A Bown, "Marsyas – A Large Fabric Sculpture : Construction Engineering and Installation" – Proceedings of Textile Composites and Deflatable Structures Conference, Ed. E. Onate, B. Kroplin CIMNE, Barcelona 2003.

2.5 Picture Credits

Figure 2.1	I. L. Archiv
Figure 2.2	The Architectural Association, London
Figures 2.3, 2.4	M. R. Barnes
Figure 2.5	Owens Corning Corp.
Figures 2.6, 2.7	Arup
Figure 2.8	Arup SA
Figure 2.9	I. L. Archiv
Figure 2.10	Arup
Figure 2.11	Brian Forster
Figure 2.12	Birdair
Figures 2.13, 2.14	Arup
Figure 2.15	M. R. Barnes
Figure 2.16	Arup
Figure 2.17	Kajima
Figure 2.18	SIAT
Figure 2.19	Arup
Figure 2.20	SIAT
Figure 2.21	Arup
Figure 2.22	Birdair
Figure 2.23	Arup
Figure 2.24	Arup
Figure 2.25	Jens Willebrand
Figure 2.26	Ralph Richter/architectur photo
Figure 2.27	Arup
Figure 2.28	Arup
Figure 2.29	Tony Smith
Figures 2.30, 2.31, 2.32	Arup