Wire meshes may be used in applications such as aviaries, where openness to light and air is required in combination with the toughness of steel. Wire meshes include both grids of closely spaced interlocked wire rope similar to cable nets and heavy wires interwoven in the manner of chain link fence.

Cables and Fittings

Cables are key tension-carrying elements in fabric structures, critical to their stability, shape, and load resistance. Cables, like the fabric itself, are selected for their strength and durability characteristics. Their flexibility (in accommodating required bending radii) and appearance also play a role in the selection of cable materials.

The most commonly selected cables use high-strength steel wire rope, in which individual wires are wound into strands that are in turn wound into completed ropes. In typical configurations, 19 or 37 wires are wound into each of the seven strands that form a cable. Wire rope combines high strength (ultimate tensile strength of up to 1,900 Mpa) with relative flexibility and ease of handling. At connection points, the ropes can be shaped to radii of about 15 times cable diameter with no reduction in allowable stress (ASCE 1997). Their flexibility adapts to the tightest radii required at catenary, valley, ridge, or radial applications and accommodates reasonably sized saddles where the cable must bend around steel fittings. Wire rope can be rolled to package readily for shipment to the site, and it can be manipulated into position with relative ease in the field.

Where less flexibility is required, designers may select steel structural strand, in which larger diameter wires are wound into a single strand that forms the finished cable. In general, strands have slightly higher tensile strength and stiffness than wire rope of the same diameter, but they can only be bent to a minimum radius of about 20 times cable diameter without weakening. Their characteristics are well suited to uncurved guy or tie-back cables.

Tensioned fabric structures also provide limited applications for steel tensile rods, formed of a single round or rectangular cross section without individual wires. The use of tension rods is limited to applications where no curvature is required and where the inflexible length of the rod does not present an impediment to shipping and handling.

On smaller structures using vinyl-coated polyester fabrics, particularly those for temporary or demountable applications, polyester webbing may be used in lieu of steel cables both to reduce initial cost and to provide excellent flexibility for tight radii and ease of handling. The limited strength and stiffness of webbing restricts its use to applications with working loads of 80 kN or less, using currently available products, and assuming a webbing width of 100 cm.

Durability is a critical consideration in cable material selection. Steel cables, particularly in exterior applications, must have adequate protection from corrosion. This protection is critical to the durability of the cables, but it also serves to prevent staining of adjoining fabric material. This is most often provided through the use of galvanized wire. If manufactured to ASTM standards, ropes with "Class A" zinc coating on all wires are generally suitable for interior and most exterior applications, while severe exposures may employ Class B or C coatings on outside wires.

Stainless steel cable, although it has higher initial cost, may be used where a higher level of corrosion protection is required, or where the clean and high-tech look of the material's bright silvery finish is desired.

The use of webbing eliminates the corrosion danger associated with steel cable. Durability is limited by the effects of UV radiation on the polyester material, however, generally limiting its effective life span to 7 to 10 years.

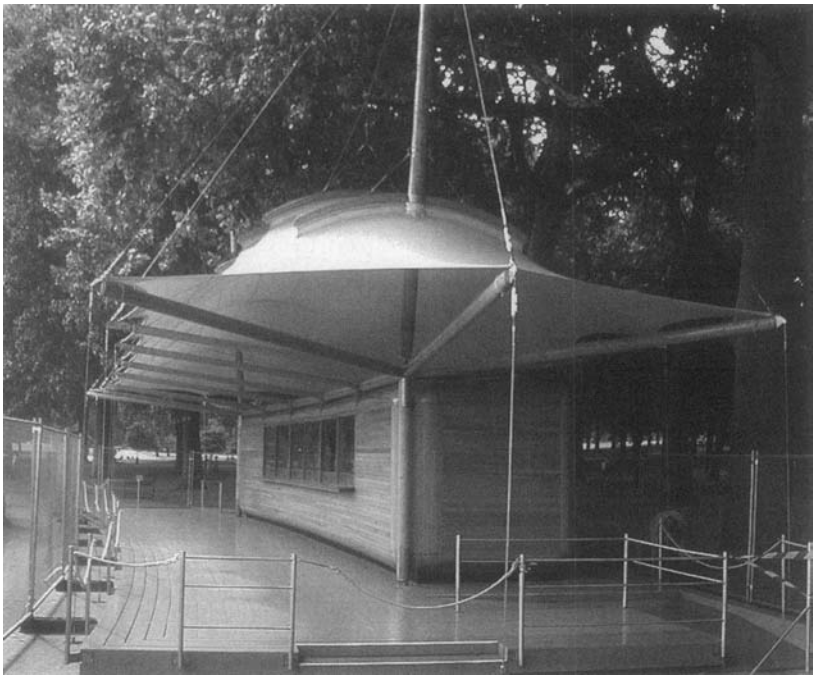
Cable fittings should be of a type as required to suit project detailing requirements (see Chapter 6), and fittings may be stainless steel, galvanized, or painted, as required to suit aesthetic, budgetary, and durability requirements.

Supporting Elements

Fabric roofs, like all tension-based structural elements, require compression and bending elements to support them and bring their forces down to grade. Supports often provide, as well, a means of applying tension to the fabric. Reinforced concrete, wood, and metals all have the ability to provide tension and bending resistance economically, and each has found applications in fabric roof support (see the photographs on page 84).

However, the majority of fabric roofs rely for their support on structural steel, a material that is readily and economically available in cross sections of high bending and compression resistance and that is readily transportable and easily erected in the form of overhead arches or tall ground-supported masts. Another factor weighing in favor of the use of steel is the precision with which it can be shop fabricated and therefore interfaced accurately with a carefully patterned and fabricated fabric membrane. Steel provides, as well, an appropriate visual marriage to fabric, with smoothly textured surfaces and slender cross sections that use the material's high strength to advantage.

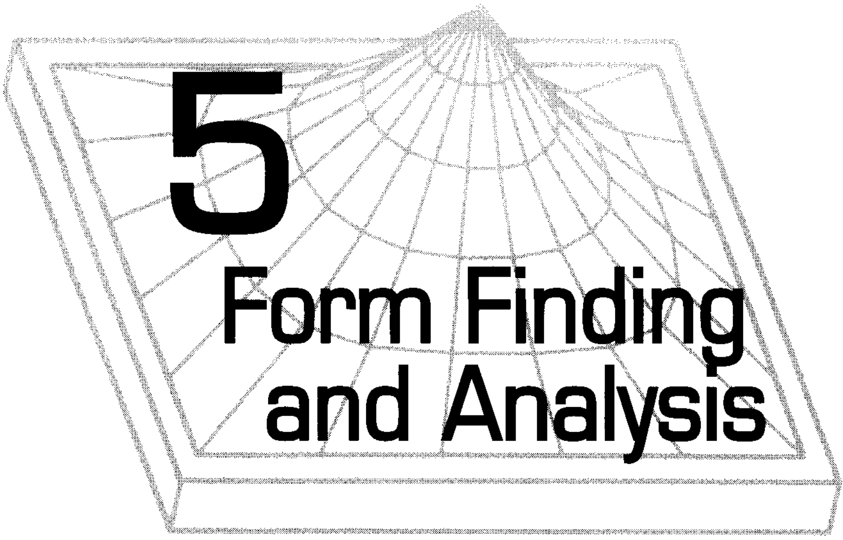
One of the defining characteristics of tensioned fabric roofs is the number and complexity of their connections: fabric, multiple cables, and supporting elements are often joined at a single point. Steel, as a material that can readily be formed in varying cross sec-



The Buckingham Palace Ticket Office uses straight and curved timber elements to gracefully support the roof canopy of this seasonally erected structure.

tions, or cast, cut, bent, rolled, punched, welded, or bolted, is above all else a material that facilitates the complex demands of connections. It may be this feature that provides the most compelling rationale for the merging of steel with fabric.

The nature of tensioned fabric roofs does not generally create a demand for steels other than the mild carbon steel most common to construction. Finishing of the material can be critical to its success, however, particularly in applications where the supporting structure is exposed to the weather or in unusually damp interior environments. Galvanizing generally does not provide an appropriate appearance, so painting must be done using materials and processes that ensure adequate corrosion resistance, and field workers must use special care in avoiding impact or other damage to finishes. Where steel interfaces with other materials, such as aluminum clamp bars, special care must be taken to isolate the two materials against the effects of bi-metallic corrosion. In addition to potential long-term effects on the strength of the structure, corrosion presents the danger of unsightly staining on light-colored fabrics and must be carefully guarded against in design.



5 Form Finding and Analysis

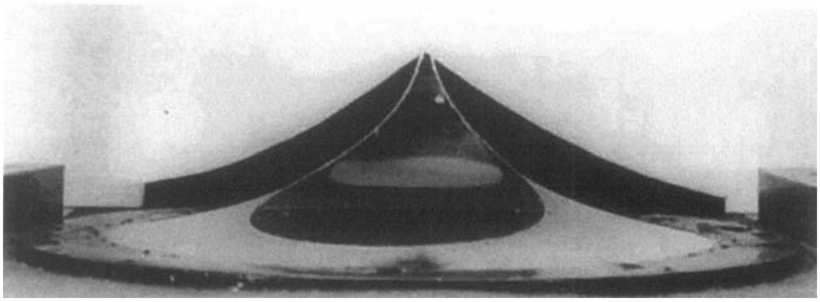
Contemporary tensioned fabric roof structures are successors to a tradition of tent building that dates back to prehistoric times and includes more recent tents for circus and military applications. Emerging technologies, however, make these contemporary structures fundamentally different from those created as recently as 30 years ago. Newer materials ensure fabric life spans in excess of 20 years, even in harsh environments, while meeting strict fire safety standards. High light reflectivity and natural daylighting provide energy efficiency in warm and bright climates, while evolutions in translucent and flexible insulation provide the opportunity for improved energy performance in cold climates, as well. Recent designs have provided R values of 12 or greater while maintaining sufficient translucency to eliminate artificial lighting under full daylight conditions. These developments have given tensioned fabric roofs application in permanent, high-occupancy, enclosed structures, and in buildings where energy-efficient, conditioned spaces are required.

While materials advances have improved many measures of fabric roof performance, it is newer structural design methodologies that have been instrumental in the evolution of traditional tents into high-grade works of architecture. With these methodologies, a construction genre that was once restricted to conventional tent shapes and hampered by wrinkled forms and unreliable behavior has evolved to one of porcelain smooth surfaces of wildly divergent shape with predictable performance under all environmental conditions.

This chapter provides an overview of the shaping and analysis of tensioned fabric membranes using methods that include hand computation and physical and computer modeling. The mathematical complexities of these methods are of limited interest to most readers and are well documented elsewhere; therefore, they are not included here.

By measuring the forms of soap films stretched between fixed boundaries, designers learned to model the shapes of uniformly tensioned membranes.

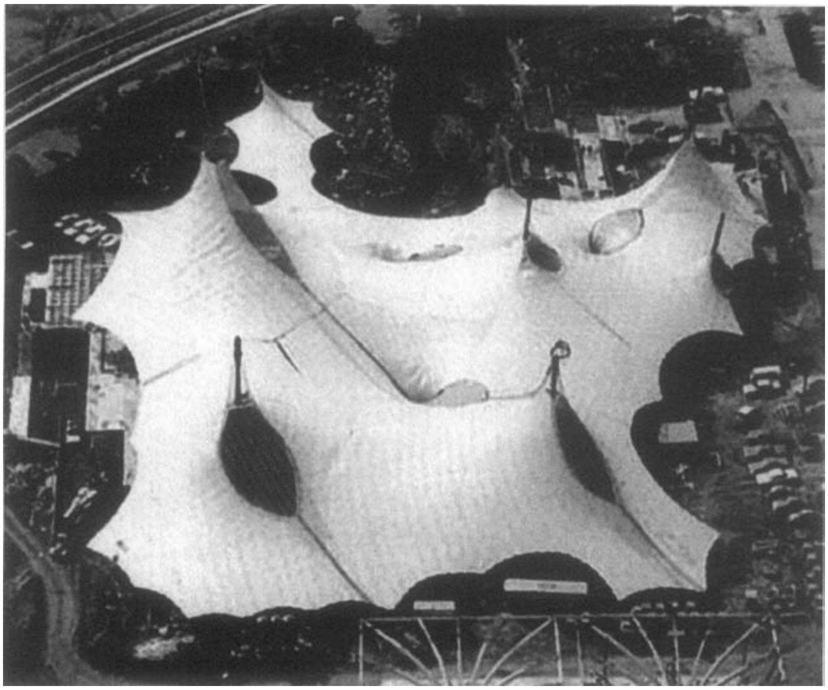
Source: Larry Medlin; used with permission.

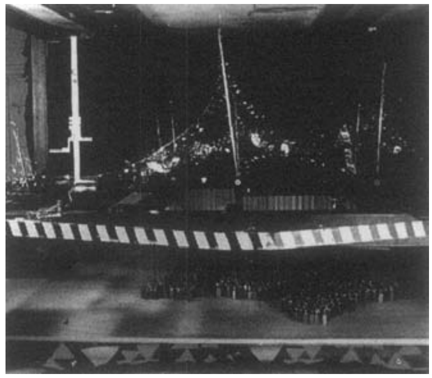


Non-numerical Shaping Techniques

Up to the 1960s, tent shapes emerged from the gradual evolution of previously realized forms, with model studies and simple hand calculations used to evaluate shapes and structural adequacy. The German designer Frei Otto developed the use of physical modeling in membrane roof design. His best-known models were those made using soap bubbles (shown above). Soap film models have several defining properties. First, in stretching themselves between any rigid edges or supports (analogous to the cables, arches, or masts in a roof), they always form the shape having the least potential energy. In essence, the soap film relaxes, finding the shape that minimizes the overall tension in the soap membrane. These "minimum-energy" surfaces have two other interesting properties: (1) they provide tension stresses in the surface that are equal at all points and in all directions, and (2) they have the minimum surface area that will join the film to its edges and supports. By stretching thin soap films between any desired edge condition and graphically recording the resulting shapes, Otto found that he could replicate the shape that a fabric membrane or cable network would take in order to be stable and uniformly prestressed over any proposed system of mast or arch supports.

Soap film models continue to provide a valuable tool for conceiving and visualizing tension structure forms, but their usefulness in design is limited by the difficulty of measuring their shapes accurately. Techniques also were developed using heat-shrink polyvinylchloride (PVC) foil that cools to a fairly rigid model form from which paper-cutting patterns can be taken. Otto developed the technique of using fine wire and small cable clamps to develop tension structure shapes. The latter method was used to obtain cable net and cladding





The innovations of Frei Otto's West German Pavilion for Expo '67 were made possible, in part, by the use of wire models with suspended loads.

Source: Larry Medlin; used with permission.

[LEFT] Exterior view.

[ABOVE] Wire model.

geometry, forces, and deflections for both the West German Pavilion (shown above) and for the swimming pool roof at the Munich Olympic Park (Liddell 1989).

Elementary Analytical Procedures

Analysis of the forms developed through wire models or other techniques was carried out using simple hand calculation on two-dimensional forms. These calculation techniques also illustrate the basic principles of fabric membrane load carrying that form the basis of the complex computer software used in contemporary design.

Under vertical loads, a cable or other tension element assumes a catenary shape akin to that of a suspension bridge cable (see [a] in the drawing on the next page). When these loads are uniform, like most design live loads, the catenary shape is coincident with a parabola, and the reactions at the ends of the cable are calculated according to the following formulas:

$$V = \frac{wl}{2}$$

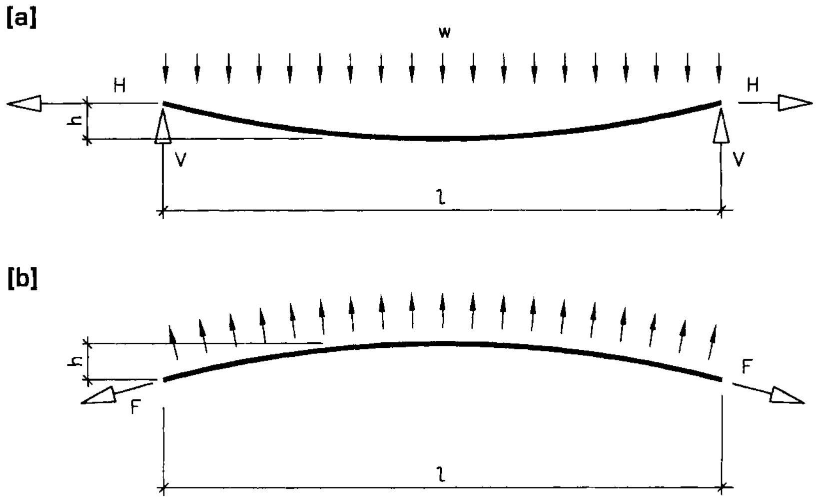
and

$$H = \frac{wl^2}{8h}$$

The resultant force, F, in the cable is given by the formula

$$F = (V^2 + H^2)^{1/2}$$

For cables loaded perpendicular to the line joining their end points and with sag ratios (h/l) of 0.2 or less, the tension force may be approximated by the value of H.



A cable or fabric membrane will assume [a] a catenary curve under vertical loads (dead or live load) and [b] a circular curve under loads perpendicular to the surface (wind).

Under loads perpendicular to the cable, such as wind, the element assumes a circular curve (see [b] in the drawing above). The cable tension is calculated according to the formula

$$F = \frac{w(l^2 + 4h)}{8h}$$

where w is the applied force per unit of length along the circular arc.

Returning to the parabolic element, the original arc length of the cable can be approximated by the formula

$$A = 2\left[\frac{l^2}{4} + \frac{4}{3}h^2\right]^{1/2}$$

and the change in its arc length under load (δA) can be calculated by the formula

$$\delta A = \frac{FA}{E}$$

where E is the modulus of elasticity of the cable, calculated as the ratio of stress to strain (σ/ε) under load. Modulus of elasticity is the property most commonly used to define the stiffness of materials of all types.

The new arc length, then, is

$$A' = A + \delta A$$

Transposing the above formula for A, the sag of the membrane can be recalculated by the formula

$$h' = \frac{\sqrt{3}}{4}\sqrt{A'^2 - l^2}$$

The revised sag is then input to the original formula for F to compute a revised tension force. Because of the increase in sag due to the change in arc length, the tension force will be less than computed originally, and all of the formulas can be cycled through in iterative fashion until the final geometry and forces are approximated. The changes in geometry that occur under load can have a dramatic effect on the final stresses in a cable, and calculation of these nonlinear effects is an important part of the analysis process. If a fabric membrane can be viewed as a network of intersecting cables, we see that the deformation of a fabric roof under load has a significant impact on its internal stresses.

Prior to the availability of membrane analysis software, the simple analytical techniques described above were applied using geometry measured from physical models. The computer automates what is a laborious process of hand calculation, and accurately models the effects of three-dimensional behavior, which is far more complex than the two-dimensional model developed above.

A simple example illustrates the methodology and the effect of geometry changes on internal forces. Consider a parabolically curved membrane segment with the following input parameters:

l = 10.0 m
h = 0.5 m
w = 0.8 kN/m
E = 1,200 kN/m

The initial iteration yields the following results:

F = 20 kN
A = 10.067 m
δA = 0.168 m
A' = 10.235 m
h' = 0.944 m

Following through with successive iterations, the shape converges to one having a rise (h') of 0.805 meters and a tension force (F') of 12.4 kN. In the example, then, using span-to-sag ratios, loads, and stiffness that are realistic for a tensioned fabric structure, consideration of nonlinear effects changes the resultant tension in the membrane from 20 kN to 12.4 kN, a 38-percent reduction.

Computerized Techniques

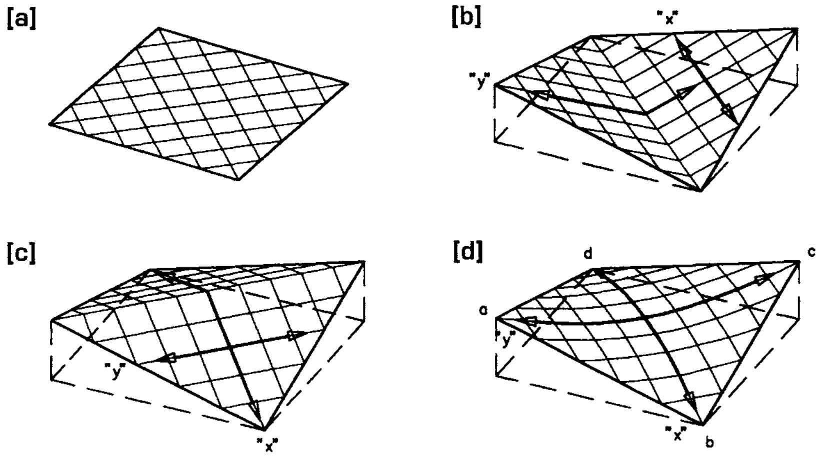
The Munich Olympic Park design represented the pinnacle of tension structure design based on physical modeling. It also provided a bridge to the modern era of computerized shaping, analysis, and patterning. As the elongation under prestress of a 25-m-long cable may be only 15 mm, a length error of 5 mm (very reasonable for geometry derived from a carefully constructed wire model) results in a prestress error of more than 30 percent. Noting this, the Olympic Park engineers began to seek greater accuracy through purely analytical solutions, and they developed software in time to be successfully used in the design of the Sports Hall portion of the Munich complex (Holgate 1997).

Computers had been used for the analysis of fabric roofs before this pioneering German work, but the engineers using them generally relied on adaptations of general-purpose structural analysis software that did not address certain key aspects of fabric structures. Most important, they assumed that the shape of the fabric was the same before and after loading, when actual deformations were often large. The new software, though, had the ability to apply loads in small increments and recompute the structure's shape after each load application to provide an accurate determination of the final shape and stresses.

While the Munich structures had acrylic roof surfaces supported on steel cable networks, the technology was adopted and further developed by engineers in the Geiger Berger office in New York City for use in designing fabric membranes without cable nets. They learned that, by modeling a strip of fabric as if it were a cable having equivalent axial stiffness, a good approximation of the proper shaping and stress under load of the fabric membrane could be realized.

By the mid-1970s, these computer programs were as amazing for their relative accuracy and analytical power as they were stupefying in their cumbersome methods of data input and interpretation. The programs were used in the late 1970s to design the Hajj Terminal, soon to become the largest fabric roof in the world; and analytical results about the forces in various members in the structure were validated within a few percent by test results on a prototype constructed later. As part of the team of engineers preparing that analysis, however, I spent many sleepless nights preparing input data for computer runs that cost $5,000 to $10,000 each on the first Cray supercomputers. The programs were limited in their means for automating the generation of geometric data, and each of several thousand "nodes" defining the shape of the fabric membrane was defined and input by hand. The graphic interface to plot this input geometry and assist the engineers in verifying its numerical accuracy was primitive.

The refinement of computing technology increased rapidly thereafter, however, until by the mid-1980s, engineers had automated the input of most data and could instantly generate plots that showed the structure's geometry and deformation under load. Engineers at Birdair, America's largest fabric structure contractor, could sit at the computer with the owner or architect of a proposed building and "walk him around" the structure—observing an isometric plot of the



A cable net modeled by the force density method yields the characteristic anticlastic tension structure form (d).

shape from any location, even moving inside the building in order to get a sense of its interior volume (Huntington 1994).

There are several methodologies for finding or modifying shapes on the computer in common use today. One, derived from the original German method used at Munich and elsewhere, determines minimum energy/minimum surface shapes analogous to the Otto soap films. The technique belies its roots in cable net structures by modeling the fabric as a gridwork of cables, each representing the stiffness of a narrow strip of fabric (shown above). If such a cable network is used to represent the membrane inside a square, flat perimeter, all of the cables will run in straight lines from side to side (see [a] above). A fabric roof that is flat like this will be subject to large deflections under load, like a trampoline, unless it is highly tensioned in the manner of a drumhead.

If two corners of the perimeter are lifted so that the edge no longer lies in a plane, it is no longer possible for all of the cables to pass from side to side in straight lines. Two extremes of shape are possible with the revised support configuration shown. In the first (see [b] above), cables in direction "x" remain straight, as if they were of infinite stiffness, while those in direction "y" kink at mid-length to accommodate the imposed geometry of the perimeter supports and "x" cables. In the second (see [c] above), the "y" cables remain straight, as if *their* stiffness were infinite. The real structure will find a shape intermediate between these two extremes (see [d] above), with both "x" and "y" cables deformed such that there is a constant "density" of force (the ratio between the load in a member and its length) throughout the structure. The elegantly curved shape that results from this "force density" method is that which stores the minimum total potential energy in the cables and has the minimum total cable length. The form is analogous to one of Otto's minimum-