Membrane structures: understanding their forms.

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1 Introduction.
The oldest tents were made out of skins or woven fabrics. The fabric only resists tensioning and has almost no compression or bending stiffness. The material is flexible and can be folded or rolled up into a small parcel.

Also ropes and cables are flexible. If a rope hangs freely under its dead weight it takes the form of a catenary curve. The higher the curvature, the lower is the horizontal component of the reaction forces. The form changes for different point loads. A fabric that hangs freely under its dead weight also changes its shape if it is loaded, it could even reverse its form.
Tension implies an optimal use of the material, since the whole section is uniformly stressed. Moreover there is no buckling problem, like it is the case for compression. The form finding of fabric structures tries to take full advantage of the tensile strength of the material, while preventing negative stresses to occur. To withstand upward and downward loads, a cable has to be stabilised and pretensioned: compression in this case means a reduction of the initial pretension.

The same approach has to be considered for fabric roofs: due to their low dead weight, both upward and downward wind loads become important. The membrane needs to be pretensioned. Balloons resist external loads by means of an inner pressure. In circus tents internal poles and ropes are used to introduce the pretension in the membrane and to reduce deformations due to wind load.
To obtain a stable surface without an inner pressure, both an inward and an outward curvature need to be realised in each point of the surface.

2 **Basic form 1: the hypar or saddle shape.**

The first basic form is the saddle shape. It has a double curvature: the hanging curve can bear the downward load, the downward curve can bear the upward wind load.

The boundaries could be sloped arches (even forming a circle in plan view) or placed vertical.

The double curved membrane could be tensioned into a 3D curved ring or between two parallel circles (polygons).

3 **Combining saddle shapes.**

Individual saddles could be placed in a grid, in this case they act as structurally independent units.
Repetition of identical saddles: Yulara Resort and Olympic Games 2000 in Australia [9]

In the next canopies small slightly curved saddles are jointed in a larger net: they act all together.

Large saddle shapes built up from smaller parts: at the World Expo in Sevilla ‘96 and in Palma de Mallorca [10]

4 Other possibilities with saddle shapes.
The next example is the roof above the architecture office of Willy Van Der Meeren built in 1969. It was the first membrane roof, as far as I know, built in Belgium. Along its boundary it has several high and low points.

Smooth surface in an irregular boundary [11]

The following structure built by Tensoforma has 4 high and 4 low boundary points. It is a seasonal structure, the membrane is taken away during the winter.

Supporting structure with and without the fabric roof [12]
5 Basic form 2: the conical shape.

Another basic form is the conical one with an internal point out of the plane of the perimeter support. Again this shape has a double curvature. This time the horizontal rings bear the load from inside to outside and radial lines bear the load from outside to inside. The high point can be supported by inner or outer compression elements. The conical form can be placed in the upright position. In the umbrellas of the World Expo in Lisbon ‘98 an inner frame takes the pretension.

Frei Otto designed the following foldable umbrellas.

Conical shapes are characterised by large radial stresses near to the center, while there is less and less material to withstand the pretension and to transfer the forces to the supporting element.
In the Diplomatic Club of Ryadh (by Frei Otto) additional compression elements solve the problem. Steel cones reinforce the high points of the awnings for the Olympic Games 2000. Radial arches support the high points in the Schlumberger factory in Paris (by Renzo Piano).

6 Combining conical shapes.
Several forms can be combined: they either touch at fixed boundary elements (Yokohama Show ’89, Kurokawa, Hamautsu) - remaining structural independent - or they act as a unity.

The Palenque built in the Expo in Sevilla ‘96 (by IPL) consists of double modules supported by external compression elements and longitudinal cables. Along the boundary cable trusses ensure the pretension.
The roof of the Florida Festival Hall (by Berger) consists of four high point membranes with a square base: one larger and three smaller ones are arranged around one common corner point. This corner point is a low point. The roof is tensioned in between these internal points and a concrete ring beam. Around the roof the ground is sloped and covered with grass, which integrates the construction naturally in the landscape.

7 Surfaces with conical regions.
Several high and low points could be used in the same roof.

The canopy built in the Markies building in Brussels is an example of conical forms jointed together into one structure. Along its boundary it is fixed with cables to the second floor of the building. Cables fixed at the sixth floor pull up the high points. The structure takes full advantages of the heavy surrounding building.

The high points of the covering of the stand of Lord's cricket ground (by Hopkins) are alternately supported by masts and cables. Transverse pretension is introduced by compression elements connected to the masts.
The following open-air theatre at Bad Hersfeld (by Stromeyer) is a foldable roof: by means of cables, the corner points and top points can be pulled to the same position. This technique is still used for swimming pools and coverings for cultural events.

The overall shape of the roof can be synclastic (principle curvatures have the same direction) if the roof is supported by arches like the skating rink in Paris (by Blasco).

The roof over the swimming pool in Sevilla is supported by a scissors system (by Escrig). The supporting system can itself be folded together. The scissors are placed both in the x- and y-direction and form arches when unfolded. Diagonal elements are added to stiffen the unfolded shape.
The playground of the Colombo Shopping Centre in Lisbon is covered with a membrane roof. It contains 9 high points either supported by ‘A frames’ or by masts. A closer look to the cutting patterns shows that the roof has been considered as an assembly of saddle shapes rather than an assembly of conical units.

![Saddle shapes tensioned between high points](image)

### 8 Arch supported shapes.
The following basic unit is supported by an arch. The built roof is constructed for the Olympic Games 2000 in Sydney.

![Membrane tensioned by a compression arch](image)

Also the Diadema for the Expo in Sevilla ‘96 (by IPL) can be considered to be supported by an arch. Due to the fact that this is a high structure, special wind tunnel tests have been performed to be sure to dimension this structure properly.

![Boundary and internal arch](image)

In the Milan Fairgrounds cover the main arch is supported by a hanging cable. The hanging cable supports a row of high points in the Misano cover.
9 Combining arch supported shapes.
The Zenith in Paris and in Montpellier (by Chaix, Morel) are covered by square modules each one tensioned by a diagonal arch.

10 More possibilities for arch supported shapes.
Arches could be placed parallel.

The Fina Service Station in Wanlin was designed by Samyn & Partners.
The equilibrium calculations were performed with EASY. The structure stands upon 6 concrete columns. They hold 3 planar arches in the transverse direction. Compression elements transmit the compression from one end to the other. The curvature for the upward wind (which could be high for an open structure) is quite small and for that reason cable trusses were added under the roof. They only act for upward wind.

Continuous arches hang on high poles in the Bigo in Genua (by Renzo Piano). The anchoring occurs at both sides of the arches by cables connected to the appropriate weights in the water. Special attention has been paid to the possibility to adjust and refine the pretension.

The structure in Venafro designed by Samyn & Partners and IPL is supported by triangulated arches.

Their slope slightly increases towards the end creating a radial and more appropriate reaction to the tension forces. The building is in fact a second skin for the office buildings inside but is the only protection for the research installations. The boundary cables form 3D curves.

Arches can be placed one against the other like in the Momi tent. The arches are reinforced by fine bars and cables to create a very light structure.

Steel arches hang on high masts [32]

Sloped arches [33]

Tensegrity compression elements to make the arches stiffer [34]
A structure could be tensioned by complete rings, like the EDF Tower in Bouchain or the sculpture by Aleksandra Kasuba.

A square membrane could be tensioned by 4 arches along its sides, which creates the possibility to place several units one beside the other.

Much lower arches are used in the Parasol Dome. To ensure form stability extra cables pull the midpoint of each module downwards to the corner points.
In the Nihon University the supporting arches are placed on the midpoints of the larger arches and create triangular units.
The membrane could be held by diagonal arches supported by floating masts like in the HST Station in Nantes.

**11 Wave forms.**
Another type of structure is the wave form, based on a two-dimensional system with a load bearing cable, a tensioning cable and connecting cable elements. If the load bearing cables and tensioning cables are placed in parallel planes a wave form is obtained.
For the structure used in the World Expo in Brisbane ‘88 (by IPL) a similar principle was arranged radially. Extra cables pull the structure downward to withstand the large wind loads on this high construction.

The Akita Sky Dome is supported by a double arch in one direction and a single arch in the other. Between the double arches a cable tensions the membrane covering downward creating a wave in the membrane.

12 Tensegrity.

The possibility to support structures by means of floating masts has already been mentioned. Sculptures have been made which consists of bars and cable elements in such a way that an endpoint of a bar only touches cable elements. They are called tensegrity structures.
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Membrane elements can be combined with this type of structure.

The Georgia Dome with a span of 200m is completely supported by floating masts. In the middle they are aligned, up to the boundary they form ellipses. The mast tops are held in position by the membrane covering, the base points are supported by two upward and outward cable elements (to the tops of the masts on the next ring) and two inward cable elements (forming a horizontal hoop).
13 Design rules.
It is sometimes mentioned that membrane structures (tensile architecture) allow creating free forms. But because membrane roofs are pretensioned specific rules should be respected.
Membrane structures are more flexible than we generally accept for steel or concrete frames. They need curvature to bring the deformations up to an acceptable level. It is not the best solution to add cables afterwards to prevent the inversion of the form.

The less the curvature, the larger the risk for inversion [44]

Too much curvature could give rise to high buildings, which implies very important wind loads and requires reinforcements for the structure. A good compromise is necessary.

Also the boundary cables should have enough curvature.

Curvature in the boundary cables of the Aviary in Stuttgart (by Auer, Weber) and the awning in Zeebrugge (by Tentech) [45]

High and low points need special attention. The structure could be reinforced or the membrane could be replaced by cables in a radial pattern or forming a loop.

Solutions for low or high internal points [46]

Complex shapes can have locations where one or two principle curvatures become zero. Large deformations could occur in such area. If it is functionally possible the corresponding area can be left open.
The coated fabric itself is a very light material but one always has to verify the layout of the boundaries to make sure that the foundations become not the very heavy part of the so-called lightweight structure.

Since every detail is visible all connections should be conceived properly and be well dimensioned.

If the rules to create beauty are respected in every detail membranes provide good solutions to cover both small entities and large free spans.
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