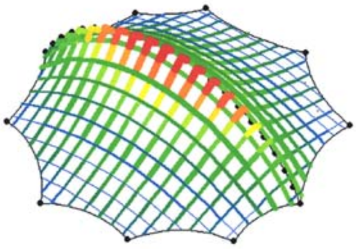

Textile Roofs 2016

The 21st International Workshop on the Design and Practical Realisation of Membrane Structures

www.textile-roofs.com

Archenhold Observatory, Berlin - May 2nd - 4th

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PATHOLOGY

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INTRODUCTION: learning from failures to prevent future troubles.

Failures in tensile structures can be due to the materials, design, installation, use or maintenance that correspond to the owner, designer, manufacturer, builder, supplier or users.

Material failures are usually due to an inadequate resolution of requirements and properties.

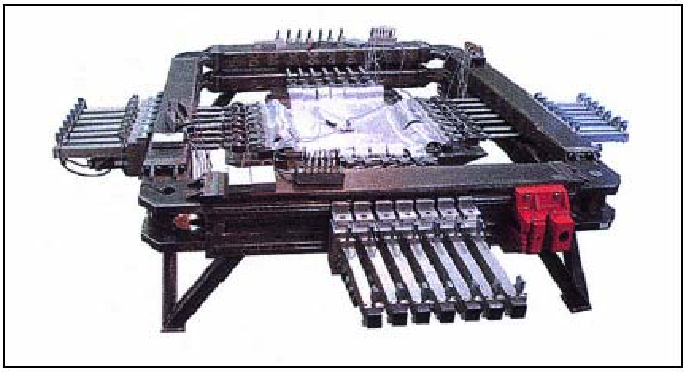
The **design** is responsible, for flatness, lack of pre-stress or an inadequate shape, resistance or detailing.

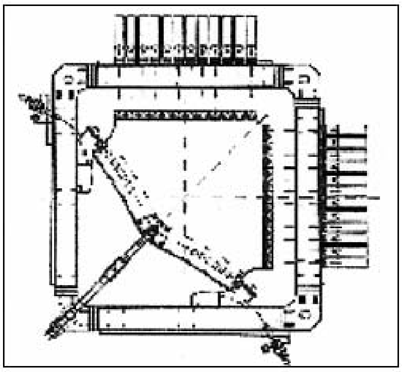
The **installation process** involves stability issues, provisional situations and final shape.

Final **use** does not always correspond to the design specifications.

Maintenance is necessary to keep the structure clean and to preserve the effects of pre-tensioning.

A list of cases and some examples are presented **to prevent future troubles and failures.** All phases and agents are involved.





1.- Materials

1.1. Resistance. The tension in the membrane depends on span, surface, curvature, pretension and loads, but the resistance does not always correspond to this requirements.

On the other hand, the uniaxial resistance is specified in most cases instead of the biaxial one, that represents much better the actual behaviour. Shear resistance is always unknown and never considered.

1.2.- UV radiation

UV radiation affects most artificial fibres used in textile membranes. It fragilises them and promotes failures depending on the solar exposure.. Protective coating is needed.

It was the case of the Highway Tall Station, roofed with unprotected material that broke after one year of exposure to solar radiation.

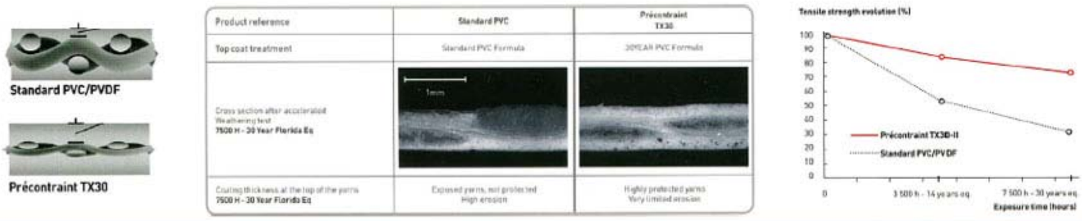
Some alteration agents affecting the evolution of features are: humidity, UV radiation, chemical aggressiveness of the surrounding environment, the state of tension and heat.

Examples of combinations of alteration agents:
• moisture under UV radiation
• chemical attack combined with heat

UV radiation affects also the protected fabrics if the coating is not thick enough. The protruding weft of the fabric is especially vulnerable, unless the “précontraint” procedure of tensioning is applied and the thickness on top of the weft increases.

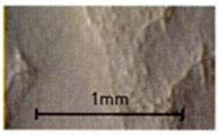
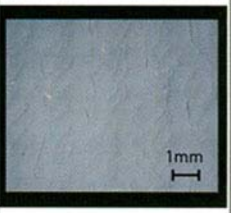
The mechanical strength evolution with ageing depends strongly on the thickness on top of the yarn. Measurements of residual characteristics were performed over the years.

Materials. Longevity (Serge Ferrari)



Project references	Date of installation	Time in use	Product	Residual tensile strength values
AIRBUS AIRCRAFT HANGAR BREMEN - GERMANY	1982	**22 Years**	**Précontraint® 1302**	Warp: 97% Weft: 84%
EXHIBITION HALL PORT GENTIL - GABON	1982	**18 Years**	**Précontraint® 1302**	Warp: 78% Weft: 76%
AIRPORT TERMINAL LYON - FRANCE	1989	**16 Years**	**Précontraint® 1202**	Warp: 78% Weft: 98%
PARKING GARAGE FACADE AVIGNON - FRANCE	1994	**12 Years**	**Précontraint® 392**	Warp: 90% Weft: 80%
WALKWAY COVER PARIS - FRANCE	1989	**11 Years**	**Précontraint® 1002**	Warp: 97% Weft: 86%
RADISSON HOTEL CAPE TOWN - SOUTH AFRICA	1996	**10 years**	**Précontraint® 1002 Fluotop**	Warp: 99% Weft: 100%
UNITED AIRLINES HANGAR MIAMI - USA	1999	**6 Years**	**Précontraint® 1002 Fluotop**	Warp: 97% Weft: 100%

Recent developments (Serge Ferrari)

Product reference	**Standard PVC**	**Précontraint S2**	**Précontraint T2**	**Précontraint TX30**
Top coat	PVDF weldable without abrasion	PVDF weldable without abrasion	Calibrated PVDF weldable after abrasion	CROSSLINK PVDF weldable after abrasion
Accelerated weathering **2.500 H - 10 year Florida Eq**				
Accelerated weathering **7.500 H - 30 year Florida Eq**				
LARGE SHOT Yarns protection 7.500 H – 30 year Florida Eq				
	Lots of micro cracks and exposed yarns – Irreversible degradation	*Lots of micro cracks and dirt build up*	*Limited micro cracks and dirt build up*	*No micro cracks, aesthetics is preserved, easy cleaning*

Microscopic observation of surface evolution after 30 years of accelerated weathering.

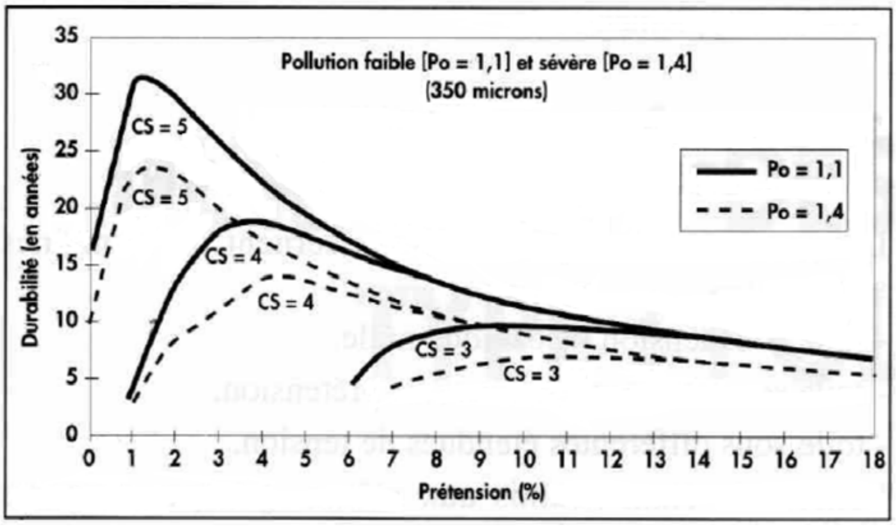
- Standard PVDF coated polyester weldable without abrasion: lots of micro cracks and exposed yarns. Irreversible degradation.

- Précontraint 52 PVDF coated polyester weldable without abrasion : lots of micro cracks and dirt build up.

- Précontraint T2 PVDF calibrated coated polyester weldable after abrasion: limited micro cracks and dirt build up.

- Précontaint TX30 Crosslink PVDF coated polyester weldable after abrasion: no micro cracks. Aesthetics is preserved. Easy cleaning.

Durability estimation (N.Stranghöner et al. 2016)



Durability-pretension-diagram. Low pollution Po = 1,1. Severe pollution = 1,4. CS: safety factor related to fracture. Level of pretension related to fracture.

It can be noted that the strong pretensions are harmful to durability, as well as pretensions less than 1% of the rupture. In general, it can be found that diagrams Po = 1.1 and Po = 1.4 are each tangent to a curve.

1.3.- Humidity

Dampness can affect the threads or the coating with formation of colonies of micro organisms. The edges of the cuts are especially vulnerable if left unprotected.

Mound Stand Lord's Cricket Ground textile roof. It has been replaced.

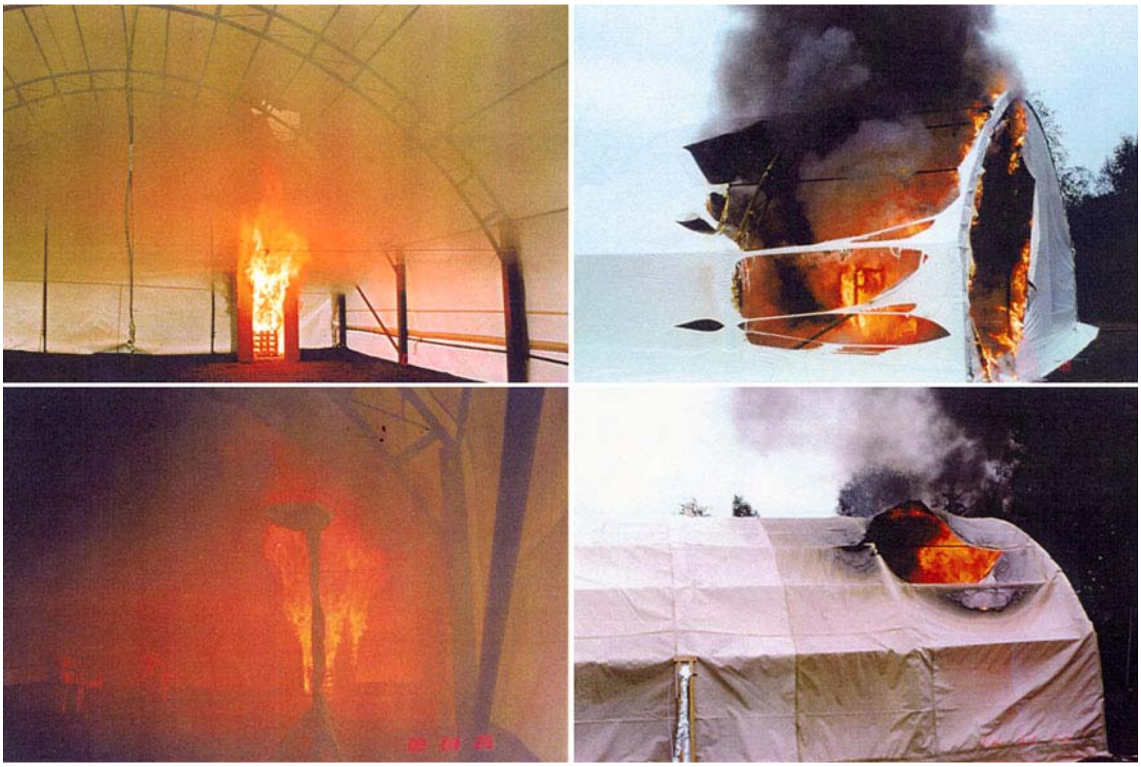
1.4.- Corrosion

Aerial and galvanic corrosions affect the metallic parts present in edges, corners, fittings and structure.

1.5. Fire resistance

In May 21, 1910 a spectacular fire destroyed the main tent of Barnum & Bailey Circus in Schenectady. The **Hartford circus fire**, which occurred on July 6, 1944, in Hartford, Connecticut, was one of the worst fire disasters in the history of the US. The fire occurred during an afternoon performance was attended by 6,000 to 8,000 people. 167 people died and more than 700 were injured. The tent's canvas had been coated with paraffin wax dissolved in gasoline, a common waterproofing method of the time.

Natural fibres are combustible and spread the fire. In Mecca 1997, 70.000 tents burnt, 340 pilgrims were killed and 2.000 injured.



Top: Polyester fibres limit the extent of damage because they are self-extinguishing: flaming stops if there is no fire reaching to them. Moreover, a hole is formed, smoke comes out and temperature decreases. Flaming in the membrane is limited. Extent of damage is limited. Bottom: Smoke pervades the entire volume before the membrane tears. The glass fibres are not combustible. They are charred. (Swedish National Testing Institute, 1998)

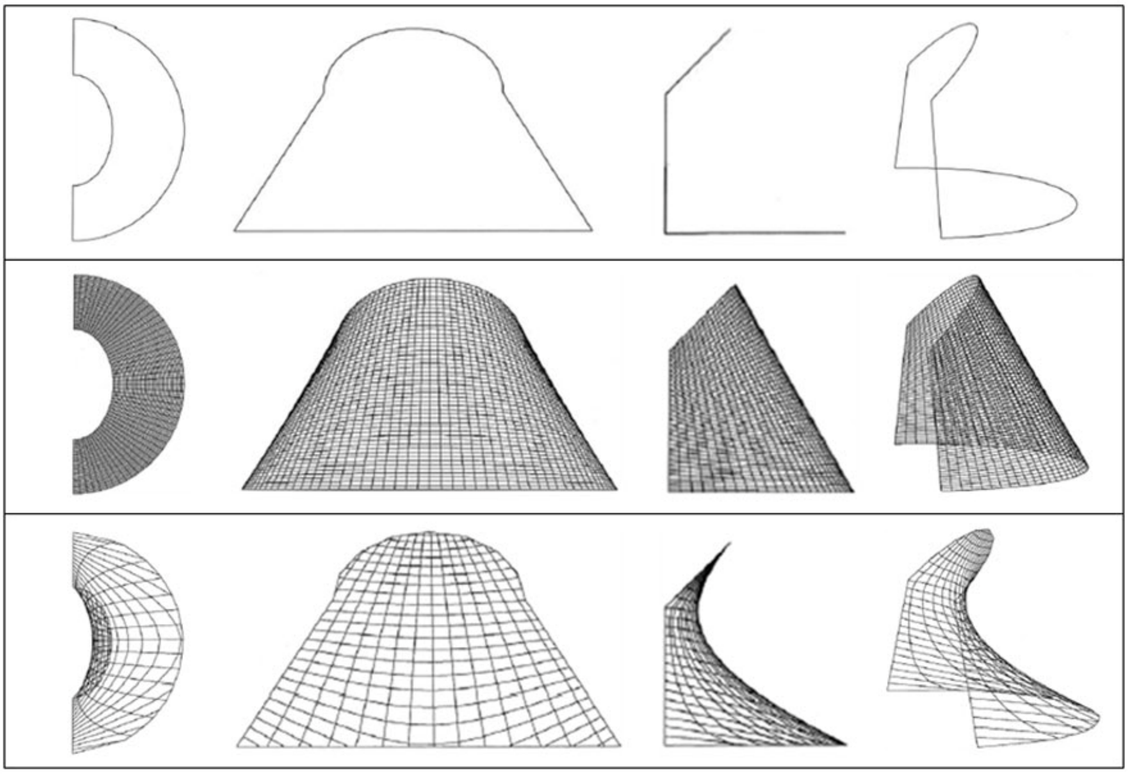
2 Design

2.1.- Funicularity

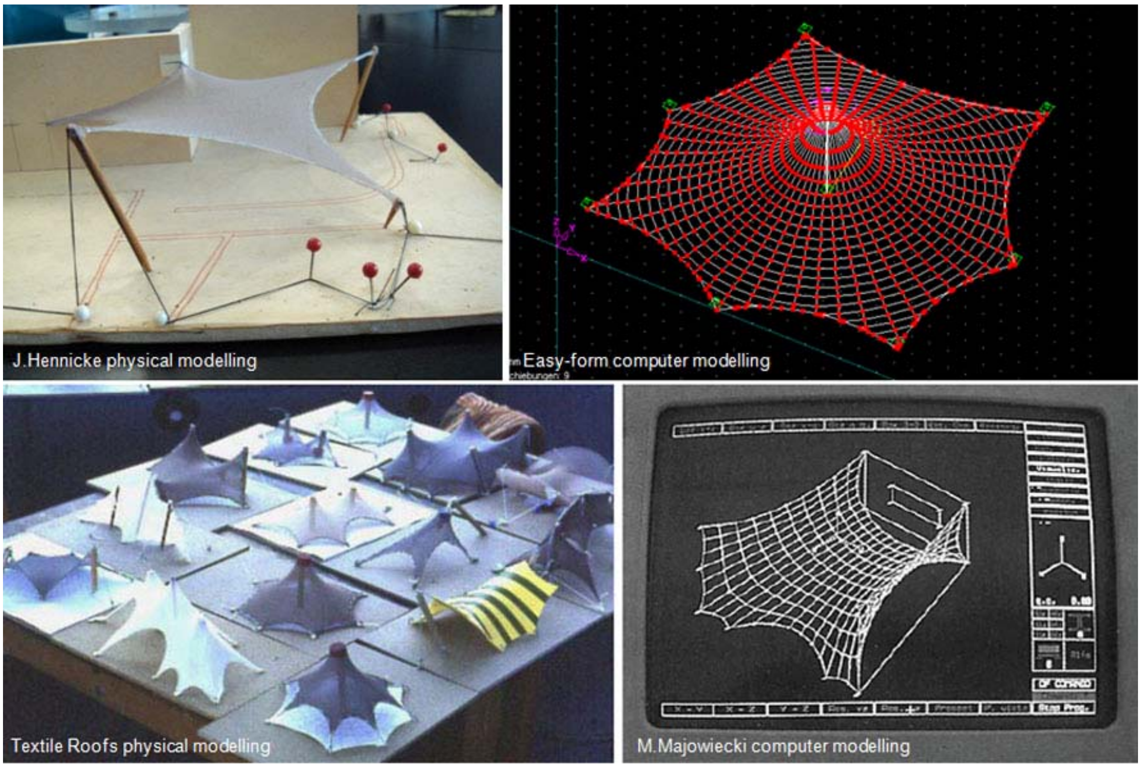
Textile roofs are not free forms. They work only in tension. Double curvature and pretension are needed.

The form is dependent on the membrane: threads, structure and coating (if any), orientation of warp and weft, geometry and flexibility of supports and boundaries, loads and pre-stress, temperature and humidity, creep and yielding. Equilibrium is achieved with a particular geometry, loads and reactions.

Such a combination of factors cannot be controlled by hand. 2D preliminary sketches and drawings can be misleading because either they do not address equilibrium or they simply represent non-feasible surfaces.



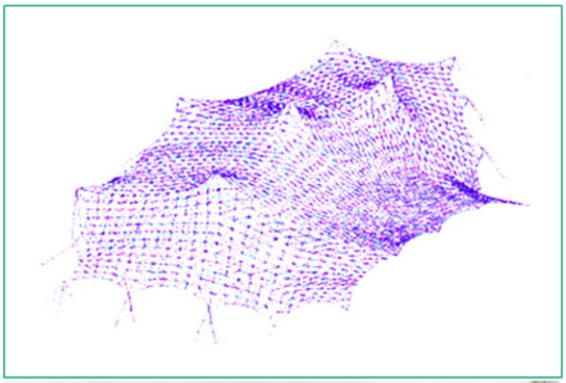
Top: Some computer programs, like AutoCad, build surfaces from closed perimeters. Middle: Equilibrium and feasibility are not checked. Bottom: The surface created inside the same closed perimeter in equilibrium.

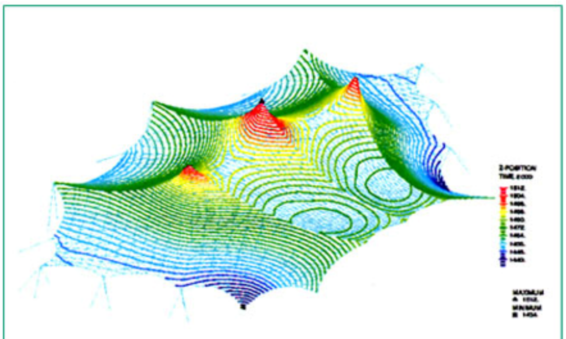


Two ways of approximating the form: physical modelling (left) and computer form-finding (right). In any case, tension, curvature and pre-stress must be kept in mind.

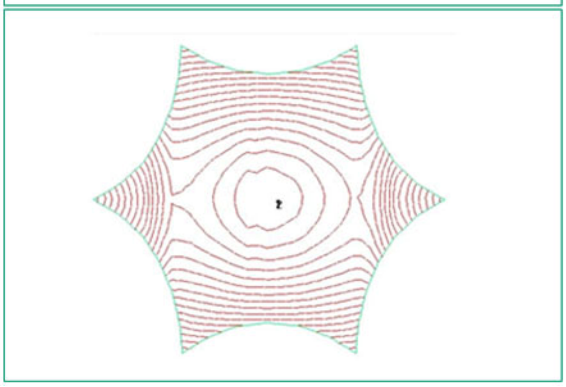
2.2.- Ponding

Water ponding is the result of horizontal flatness and lack of pre-stress. It has to be controlled within the form finding process and tested during the installation. The danger of shallow gradients is that accumulation of water can cause a depression in which rain can collect more water with the surface geometry having changed from “anticalstic” to “synclastic”. This in turn increases 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. 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.

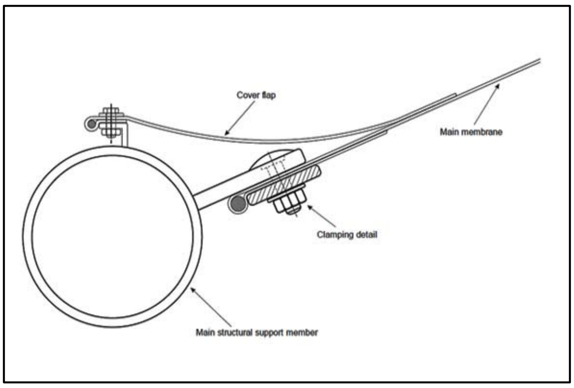




J.Tritthardt, Büro für Leichtbau, Radolfzell, Germany, 2007.



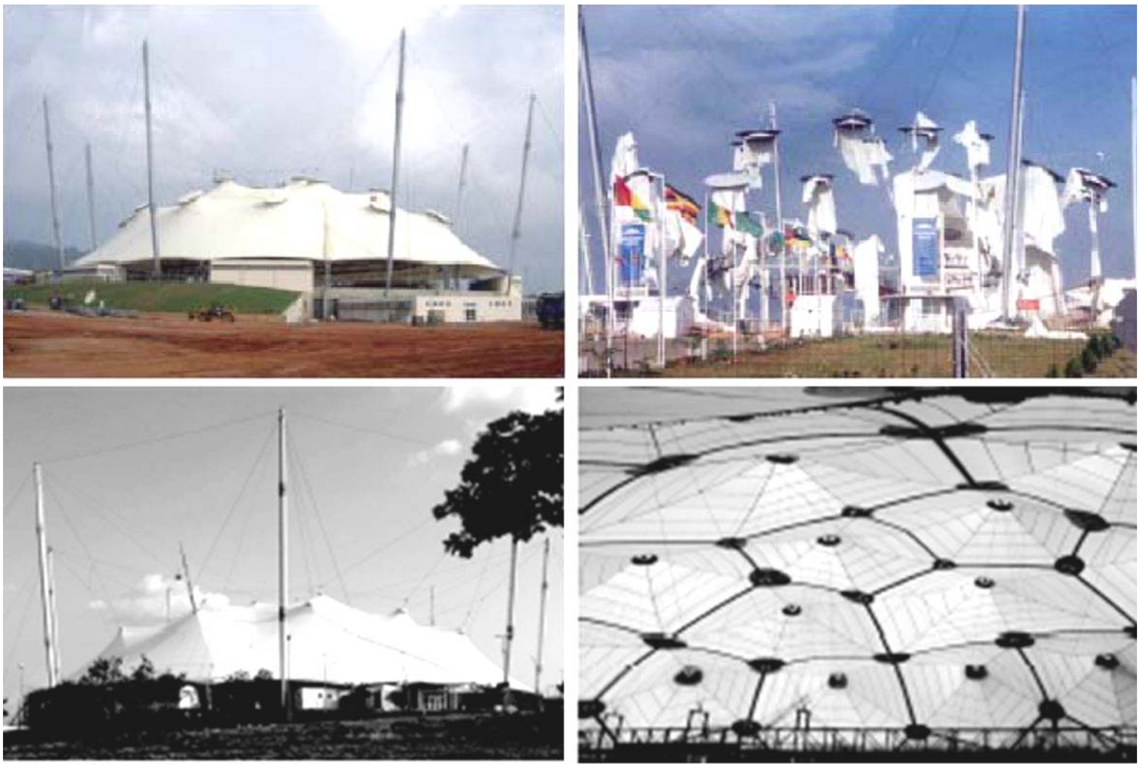
Some ways to prevent it are: a) careful observation of the contour lines, b) running cork balls on the physical model; c) watering the roof before delivery



Left: Besides the checks on the main membrane (which are usually done by using the global structural model) special attention should be paid to potential local ponds at connection details. This is especially the case for cover flaps that can compromise the natural drainage path from the membrane surface.

Right: A flat membrane prone to ponding.

2.3 Wind and snow load underestimation



Top left: before the storm. Top right: after the storm. Bottom: redesign. The roof of the Velodrome was replaced by a more redundant system, with the same appearance and avoiding any modification on the main masts. A circumferential ring cable was added to minimize the asymmetric loads on the tie-down cables. (B.Stimpfle, 2008)

Estimating wind and snow loads on double curved surfaces is not easy and building regulations provide little help. Wind tunnel tests and computational fluid dynamics can help. Wind coefficients for typical tensile shapes and open stadium roofs are available. In addition, unexpected high wind and snow loads act as a full scale test of the whole structure reducing the safety factor and highlighting shortcomings.


Saturday, February 16, 2008: The Liverpool arts company Brouhaha International has finally been charged, along with artist Maurice Agis, two years after their inflatable sculpture *Dreamspace* broke its moorings killing two people and injuring 13 others.

1 November 2013: The Museum of Moving Image in Croydon was ravaged due to 145 km/h wind.

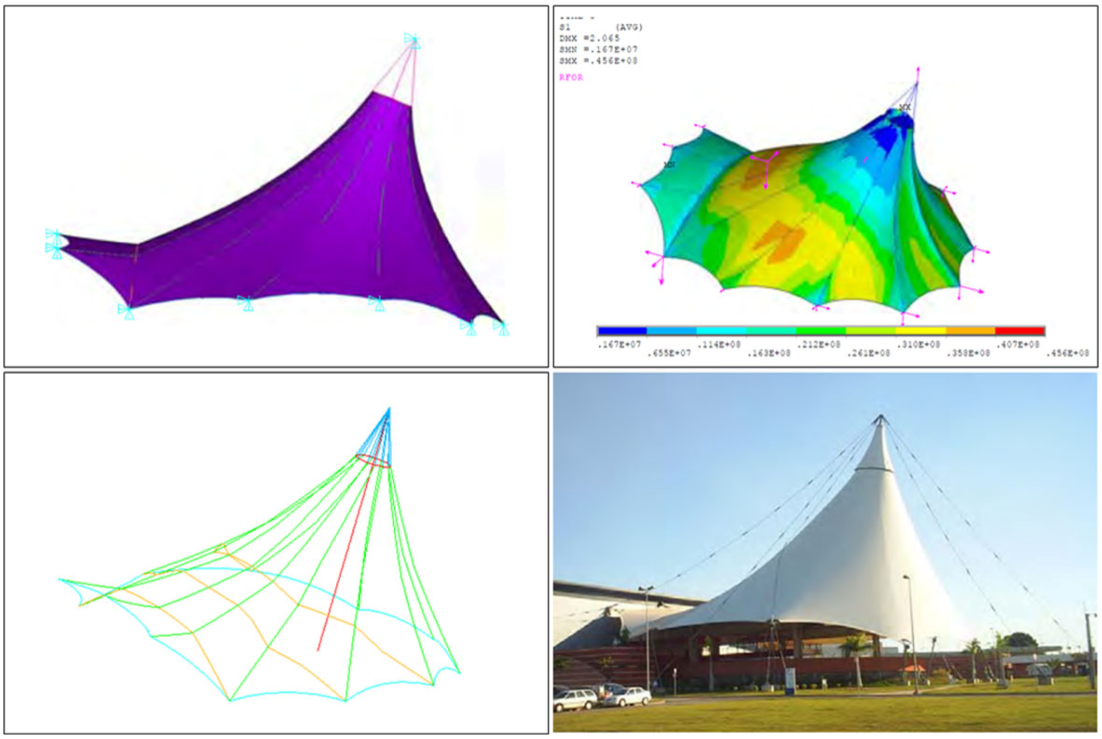
Kumagaya Dome under the snow.


The Giant of the Seven Seas show. Barcelona Forum of the Cultures, 2004.

A 230 m^2 textile roof was designed for the "Giant of the Seven Seas" show to protect the performers from direct sunlight at noon. It did not survive the first storm under the east 100 km/h (28 m/s) speed wind. The membrane began to flutter and continued to flap until it tore. This was due to the installation of additional oblique cables for the tackles of the trapeziums that hurt the membrane during its displacements under the violent storm (N.Pauli, 2005).

Another wind-induced trouble was that of the "Centro Cultural" of Paulinia. It was an asymmetrical conical tent built in 2004. It covered an area of 2.200 m^2 with a total surface of 3.700 m^2 with a central mast 42 m high, inclined 13º with respect to the vertical (R.M.O.Pauletti et al.2007). It collapsed in 2005. An analysis was developed to infer the possible causes of the failure.

The collapse occurred for a 100 km/h wind speed, corresponding to a dynamic pressure of 480 N/m^2 and maximum traction value of 26 kN/m, below the 100 kN/m informed by the supplier. Tests extracted from the collapsed membrane indicated 20% to 40% reduced values. Localized tears were detected previous to general collapse. They propagated easily because the tear strength is considerably lower than the tensile strength.

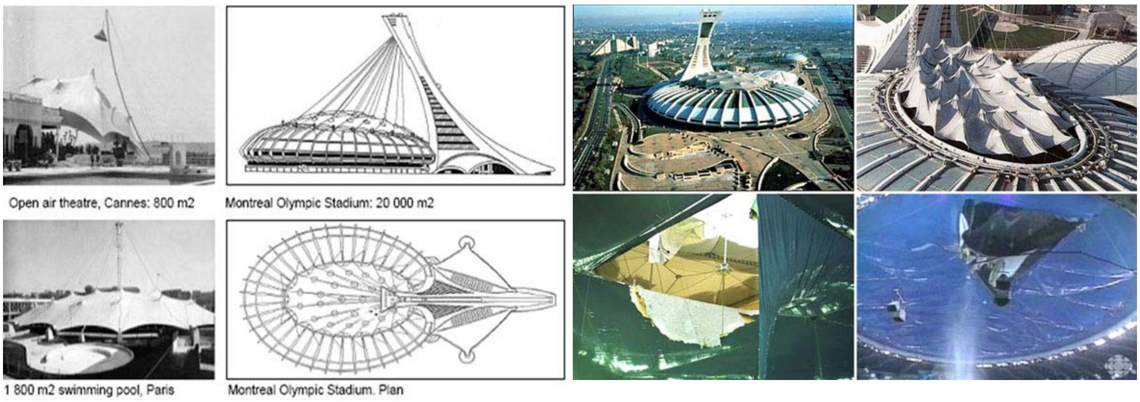


To rebuild the tent much higher loads were considered: 168 km/h wind speed corresponding to a dynamic pressure of 1.340 N/m^2. The original geometry and level of prestress were also improved to avoid ponding and reduce displacements by means of a set of 3 transversal steel cables combined with 11 radial cables that also alleviated stresses in the membrane.

2.4 Scale effect

The effect of scale is also significant. **Changing the scale of a structure has a much greater effect than changing its size**. One must also take into account the structure's self-weight, the rigidity of its materials, the geometry of its connections and the multiplication factor of its loads due to full size deformations and temperature.

Multiplying the dimensions by factor K means multiplying the surfaces by K^2 and the volumes and weights by K^3. This means that doubling the length multiplies the weight by 2^3 = 8 times.

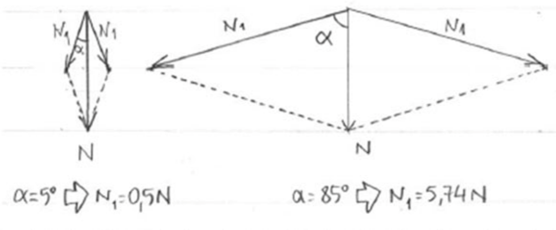


The same solution for 800 m^2, 1.800 m^2 and 20.000 m^2.

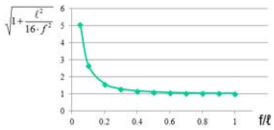
The 800 m^2 roof of the open air theatre in Cannes, 1965, was a convertible with an exterior slanting mast and a centrally bunched roof skin. In the Boulevard Carnot swimming pool, 1966, the same solution was adopted for 1.800 m^2. The operation was very difficult and restricted twice a year (open position in summer and closed position in winter). The 20.000 m^2 roof of the Olympic Stadium, Montreal, envisaged for the 1976 games but installed in 1987, tore due to snow accumulation and deformation. It was substituted by a non retractable textile roof that also tore. Major effects produced by the excessively enlarged scale were uncontrolled snowdrifts and increased deformations that reduced substantially angles and curvatures with amplifying catastrophic effects.

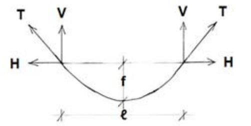
2.5 Multipliers

$$N_1 = \frac{N}{2\cos\alpha}$$



α	10	20	30	40	50	60	70	80	85	86	87	88	89	90
$\frac{N_1}{N}$	0,51	0,53	0,58	0,65	0,78	1	1,46	2,88	5,74	7,17	9,55	14,33	28,65	∞





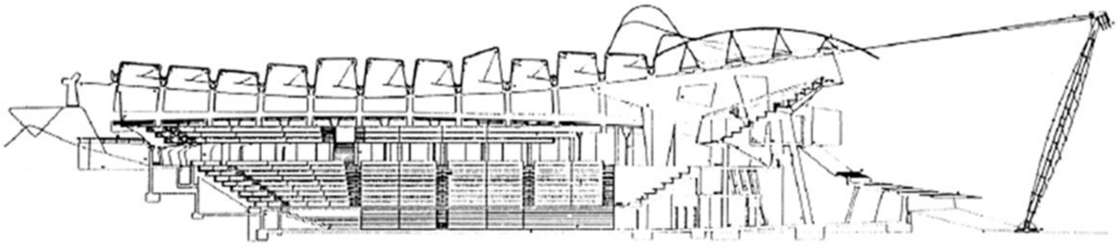
$$T = \frac{q \cdot \ell}{2} \cdot \sqrt{1 + \frac{\ell^2}{16 \cdot f^2}}$$

T: tension in the cable; **V**: vertical component; **H**: horizontal component; **q**: uniformly distributed load; **ℓ**: span; **f**: sag

f/ℓ	0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
$\sqrt{1+\frac{\ell^2}{16 \cdot f^2}}$	5.10	2.69	1.60	1.30	1.18	1.12	1.08	1.06	1.05	1.04	1.03
$\frac{T}{0,5 \cdot q \cdot l}$	5.10	2.69	1.60	1.30	1.18	1.12	1.08	1.06	1.05	1.04	1.03
$\frac{V}{0,5 \cdot q \cdot l}$	1	1	1	1	1	1	1	1	1	1	1
$\frac{H}{0,5 \cdot q \cdot l}$	5.00	2.50	1.25	0.83	0.63	0.50	0.42	0.36	0.31	0.28	0.25

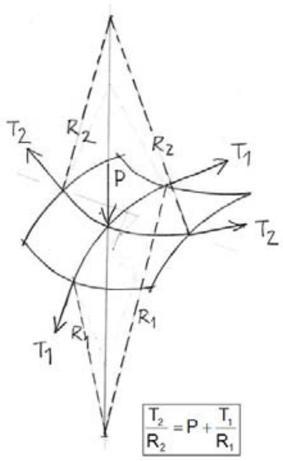
Left: **The angle multiplying effect**: three or more forces come into play at a corner. Equilibrium requires that each force be the resultant of the others. **The best way to save energy and material is by directly following the path of the loads.** When derivations are needed, the influence of angles is significant. Being able to divide a force into two components is highly dependent upon the angle of projection.

Right: The sag being equivalent to 30% of the span amplifies the load by 1,30. The sag being equivalent to 5% of the span amplifies the load by 5,10.



A Sports Hall designed with a ratio sag/span = 5 m / 125 m = 0,04 < 5% collapsed before completion.

Multiplier effect of the sag/span relation: $\sqrt{1+\frac{125^2}{16\cdot 5^2}} = 6{,}33$

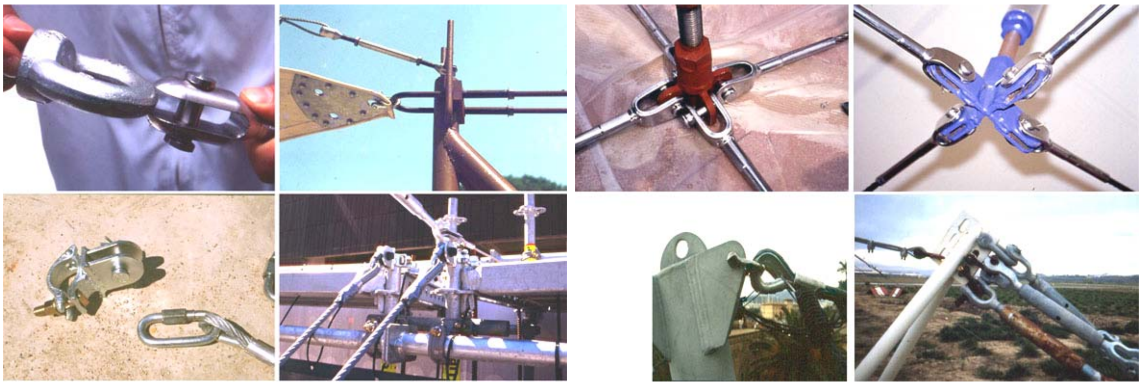


About the flatness effect

Equilibrium of a piece of membrane shows that radius of curvature are denominators, so tensions increase proportionally to them. According to the formulation: R = 0 (flatness) means T = ∞. In other words, equilibrium is not possible between tension stresses and external loads acting perpendicular to the membrane. But what happens is that equilibrium is possible because of the elastic strain, not taken into account in the above formulation. In fact, flat and curved membranes deform till equilibrium is reached. Taking into account the elastic strain of the material, the membranes deforms till equilibrium is reached between the tension stress and external loads acting perpendicular to the membrane surface (R.Wagner, 2008).

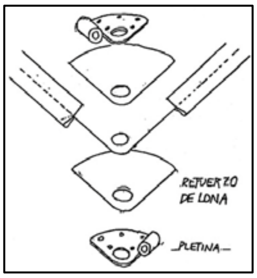
Nevertheless, the pitfalls of building flat surfaces are fluttering, ponding and high stresses.

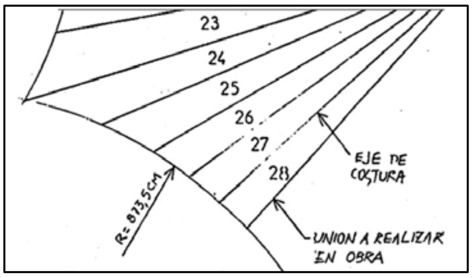
2.6 Detailing



Details are not an addition to the overall design. The strength, shape, behaviour, size, prestressing, assembly, maintenance, adjustability and appearance of the details are dependent on the complete arrangement and vice versa. Choosing, designing and evaluating connections and joints are integral to the overall concept of the structure and its results.

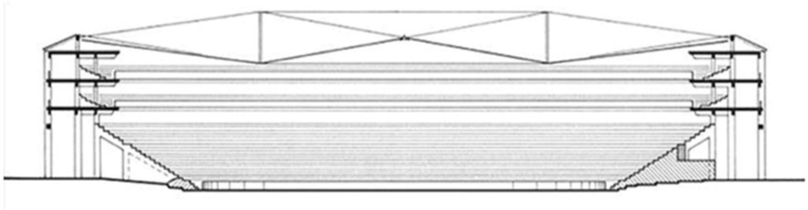
Coordination: the elements that meet at any given point must be coordinated. The choice of cable termination must be coordinated with how the elements to which the cable attaches are designed. (Closed eyes need a pair of plates, jaw ends connect to a single plate etc.). On the other hand, lack of proportion reveals over sizing or underestimation.



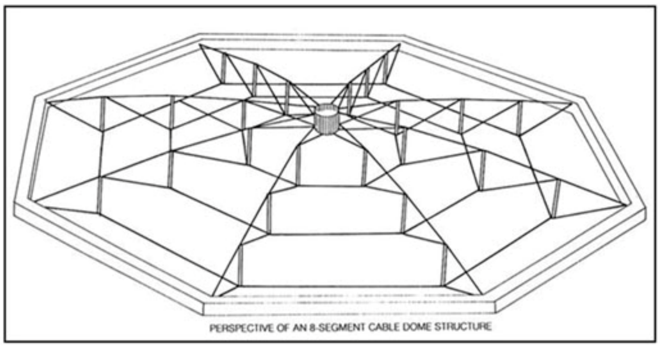


The elements that meet at any given point must be coordinated. The swaged cable end doesn’t fit into the CHS welded to the corner plate.

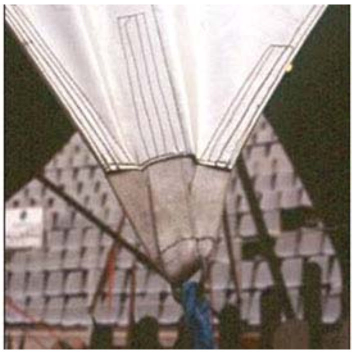
Space is needed where cables meet and loads pass from fabric to steel. **Preliminary designs and computer models tend to underestimate the dimensions of connections and joints**. Moreover, impermeability, drainage and ventilation also require space → points are not points, lines are not lines, lines become strips.




Convertible roof over the Arena, Zaragoza. The central "point" is 3 m in diameter.



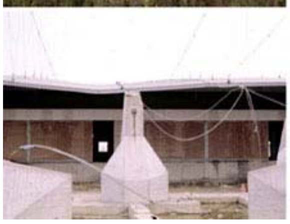
The ridge cables of the cable-dome become strips because the fabric cladding was installed by attaching it to aluminium castings that cover them.

Adjustable devices: the initial pre-tension of the membrane, together with the losses of pre-stress due to temperature, wind effect, creep and yielding, should be recovered with adjustable devices such as threaded bars and turnbuckles. The membrane is more deformable than the structural supports. The joints and ends need adjustable fittings for pre-stress to recover elongations and to compensate for the differences of deformability. Such devices must be visible and accessible.

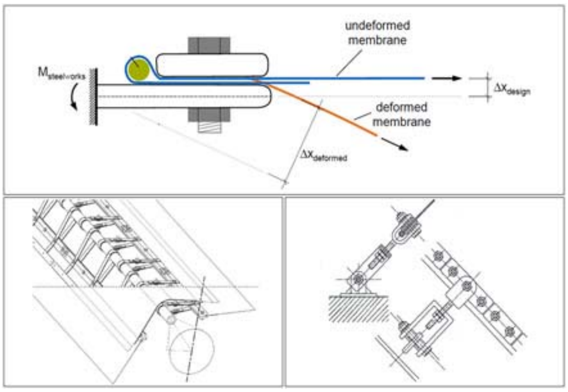






The Jawerth cable trusses are pre-stressed against cable ties down to the foundations. If the total length of the ties exceeds the manufactured or transported length, joints are needed, that may be also used to adjust the length and tension.

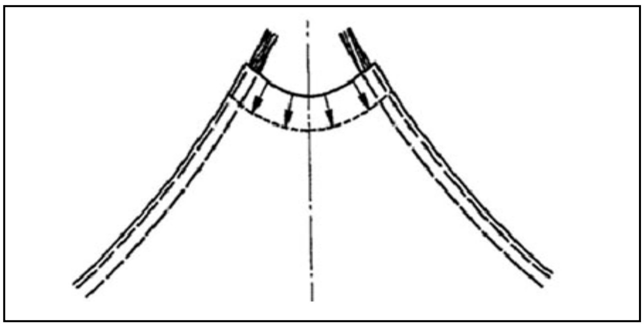
A blind sleeve is not advisable because the hidden part may become insufficient easily. It is much better to use a visible, accessible, manoeuvrable and safe mechanism.



Left: **Following the load paths**. The funicularity is not only a requirement of the surface, it is also needed in edges, corners, cables, ties, fittings, adjustable devices and all elements involved with the tensioned parts of the roof.

Right: **Impact of membrane deformation on eccentricities**. In the deformed state of the membrane the eccentricity increases the moment. Eccentricity deformed >> eccentricity designed. Other connections admit adjustments to the membrane slope by means of rotating, if tangential forces are not significant (N.Stranghöner et al.2016).

The canopy for the Restaurant of the Yachting Club was made of rectangles. Two opposite edges were free and two were continuous, connected to aluminium sections. The double curvature and pretension were introduced hoisting the central point and forming conoids with a rectangular perimeter. As the direction of the roof starting from the slot was not horizontal, the membrane was cut. Possible solutions were: changing the direction of the slot, softening the edge of the slot or/and reinforcing the membrane.

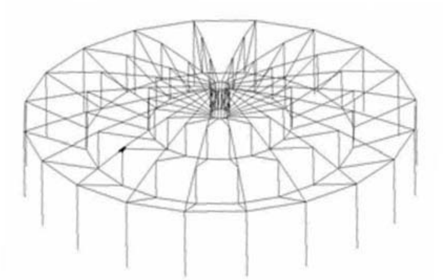


Wrinkles due to the gliding of the fabric.

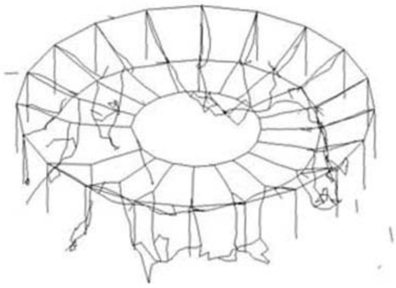
Corners of flexible edges are created by a spandrel. The spandrel region is very critical to overstresses since the short distance between the edges neither allow an elongation of the membrane nor an angular displacement of the fabric in order to reduce overstresses. In addition to that, the membrane has the tendency to glide off the spandrel under pretension which might lead to an overloading of the membrane. However, looking at the tension in a membrane spandrel between two flexible edges, it cannot be assumed that the membrane overstresses in the region are compensated by the “flexibility” of the edges. Edge cable, edge fitting and corner support or foundation together form a relatively stiff building member in this region. Here the term “flexible” is not an appropriate description when compared with the flexibility of the membrane. (N.Stranghöner et al. 2016).

Collapse assessment

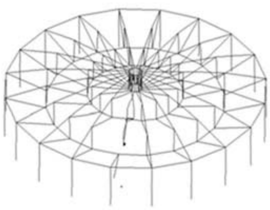
The progressive collapse-resisting capacity of the structure can be checked at design level considering the resistance to progressive collapse when a primary load-bearing member is removed.



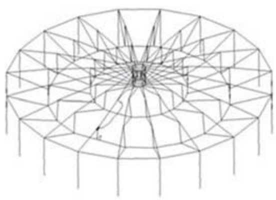
The cable-dome investigated (Ø = 71,2 m)



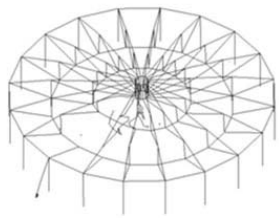
Ring cable removal



Radial cable removal



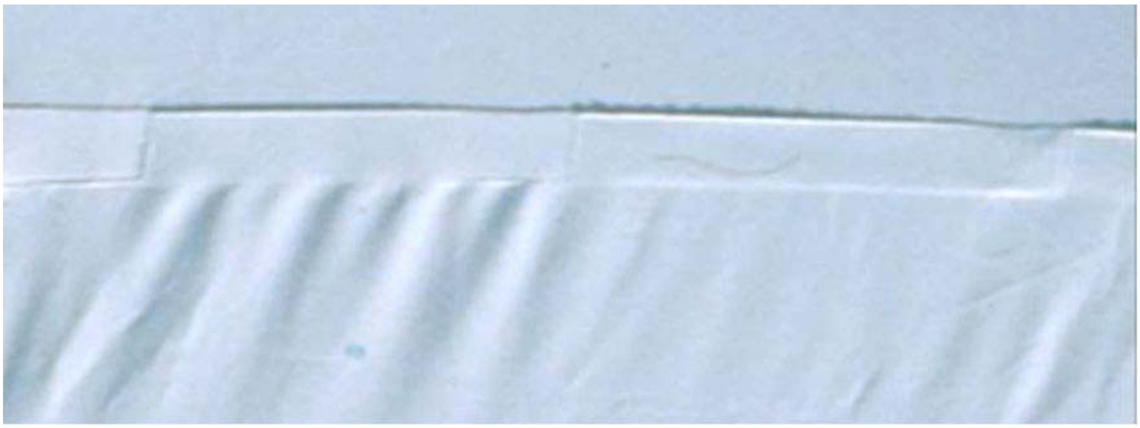
Diagonal cable removal



Strut removal

In this example a cable dome structure is investigated (W.J.Zhang et al.2013). A nonlinear dynamic progressive collapse analysis was carried out by removing one or two different types of members in various locations. The results of the analysis showed that the ring cables are the key members of the cable dome structure because their removal lead to progressive collapse. The loss of one or two other members would not result in structural progressive collapse.

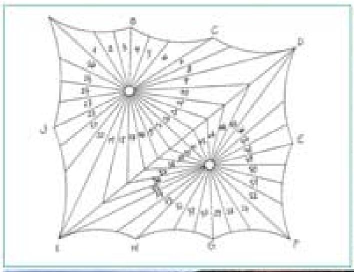
3 Manufacture

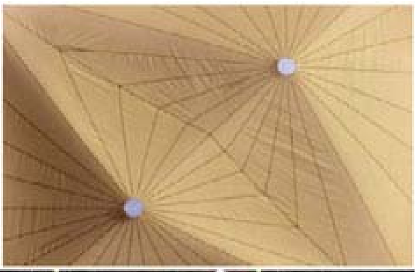


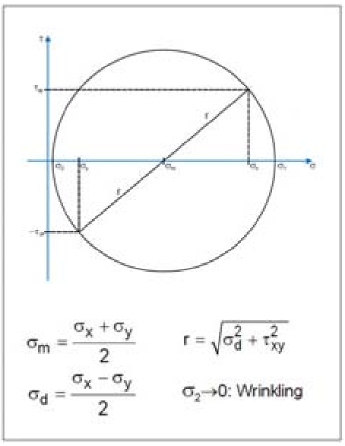
Sewing and welding may affect the resistance, waterproofing or the properties associated to the coating. Moreover, a manufacture defect appears when the patterns are joined with different stresses. The one less stressed wrinkles.

4 Installation

As the behaviour of textile roofs is dependent on the form, the installation process becomes crucial to reach the expected position of every part and to provide the required level of pretension, not surpassing it. In addition, stability will not be reached until the end of the assembly, meaning that it is also a requirement of the installation process.

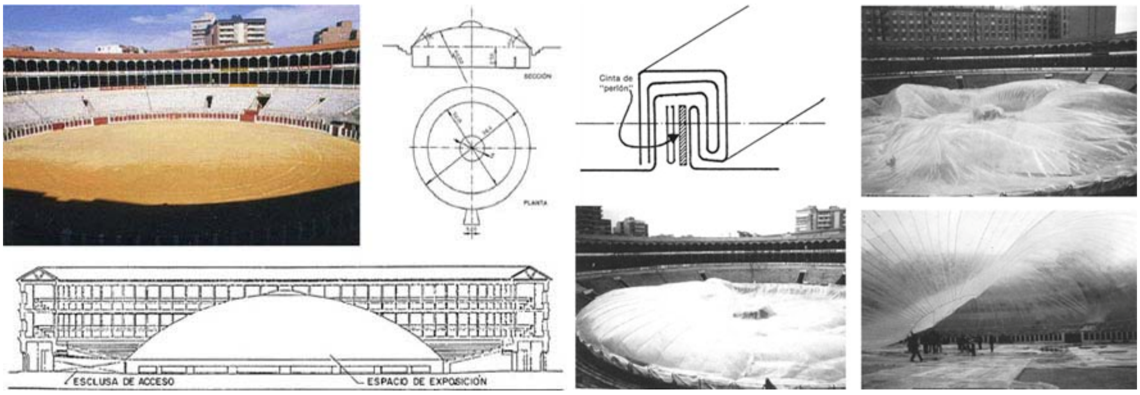




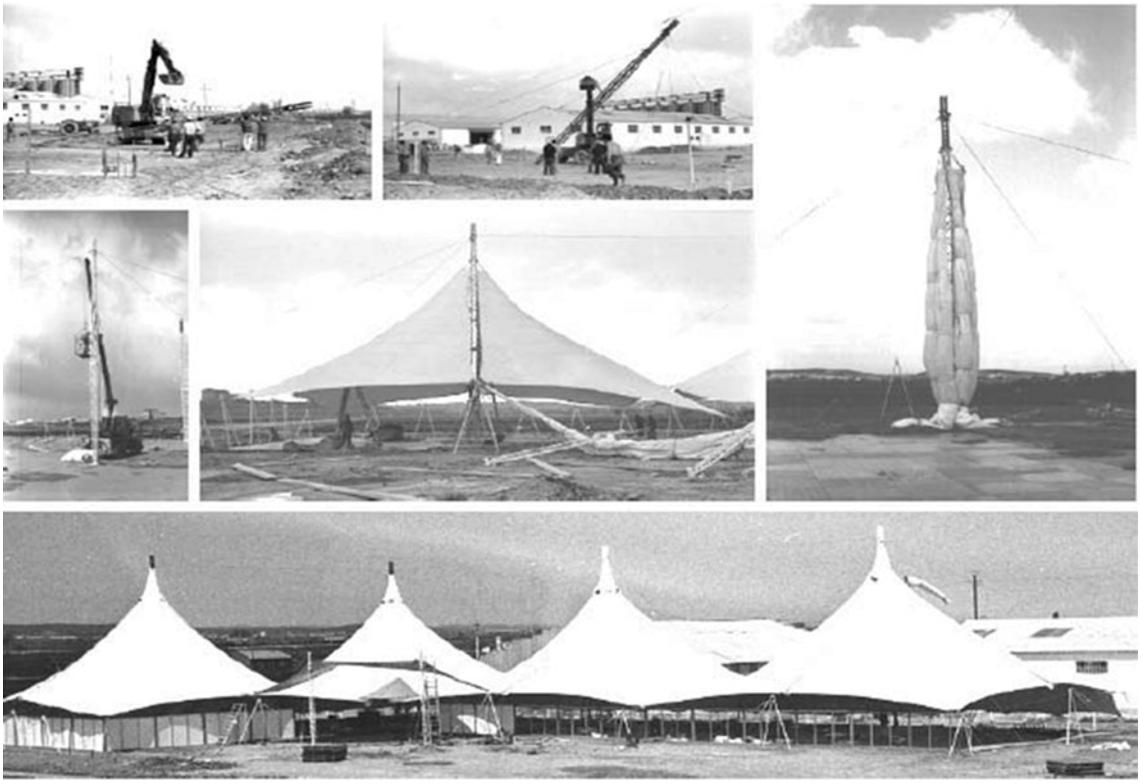


It is difficult to avoid wrinkles but they do not mean necessarily damage to the membrane unless they occur repeatedly. For aesthetic reasons the aim should be to avoid them.

The appropriate indicator for the risk of wrinkling is the smaller principal stress σ_2, linked to the increasing of shear stress. *The objective of the design should be the limitation of wrinkles to a minimum.High differential membrane stress should be avoided in the prestress state as well as under external loading. Deviations should be limited to areas that are not statically relevant.* (N.Stranghöner et al. 2016)



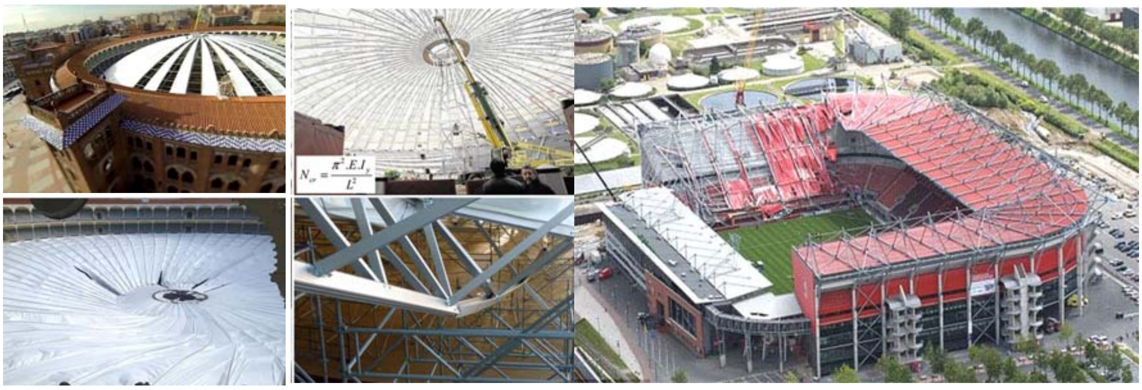
Weather conditions also affect. It is usual to specify a maximum wind speed of 10 km/h, but it is usual to surpass it because of timing requirements. A pneumatic dome was envisaged for a 56,45 m in diameter bull fight arena. The strong wind induced movements before completion and the membrane broke.



The design may take into account severe conditions of the installation process. A 1.600 m^2 pavilion was designed to be installed without interruption over a 24-hour period during the windy season in La Cogullada, Zaragoza.

Designing the roof as a single extension of fabric was not considered affordable and a fragmentation of the roof was envisaged. A series of 10 x 10 m^2 hyperbolic paraboloids were adopted in groups of four pseudoconoids, that created closed and stable shapes. Each of the groups of our paraboloids was assembled around a mast, all of which were stabilized by ties that were independent of the roof.

In order to minimize the wind pressure, the paraboloids were initially rolled up like sails, and were unfolded after being lifted into their final position. Handling the sixteen 10 x 10 m^2 elements separately proved to be feasible and safe.



Left: To enable events to take place outside of the bull fighting season, a roof was designed for Las Ventas bullring, Madrid, 2003, costing a reported 4 million Euros. It collapsed before its inauguration to the public under a 47 km/h speed wind. The structure has been designed in aluminium to affect as little as possible the existing building, but the values adopted by the computer program were those of steel. The consequences were twofold:

1 Buckling: the critical load (or length) was lower than expected. Modulus of elasticity of aluminium = 0.354 x modulus of elasticity of steel. In addition, if wind suction overcame the self weight, stresses were reversed: tension elements went into compression and buckling.

2 Instability: Lack of temporary bracing during installation favoured the instability. (In the final position, the membrane under tension was supposed to stabilize the trusses).

Right: During the construction, temporary bracing, in the form of steel cables, were being used to provide stability to the roof structure. As the project progressed, the temporary stabilizing cables were removed, requiring the permanent bracing components of the structure to engage and support the loads and forces acting on the roof. Upon removing the final temporary stabilizing cable, the partial collapse of the stadium roof was triggered.
Upon investigation, it was determined that the temporary bracing was removed before adequate permanent bracing was erected. The absence of coupling pipes at the back ends of the roof beams as well as stabilizing connections in the roof structure contributed to the partial collapse of the roof structure.

Dirty execution. Protection from the soil was needed because of muddy conditions.

5 Misuse

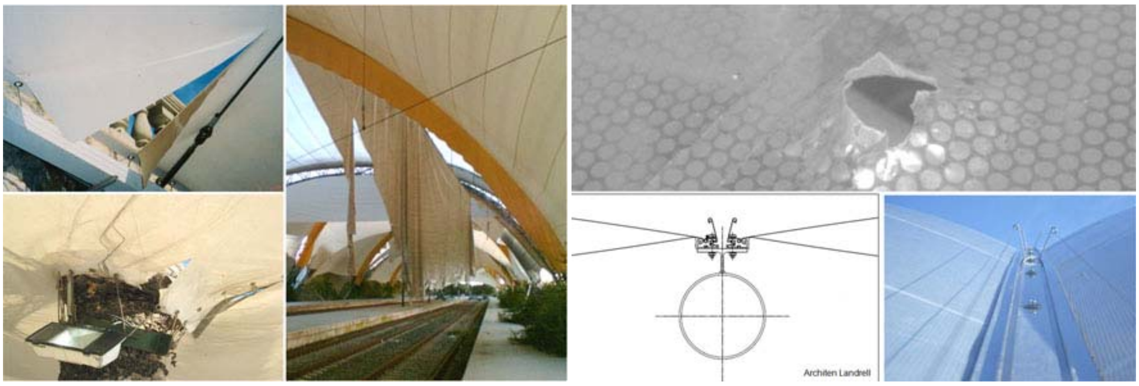
Left: Membrane materials are easy to cut with a sharp knife and are therefore susceptible to accidental damage from vandalism and flying objects. It usually occurs in the lower parts that can be easily accessed voluntarily or accidentally. They also occur on top of the roof due to falling objects, firecrackers or birds.

Right: Direct access to the fabric may be prevented in order to avoid vandalism. This measure can be taken in two ways:
1) introducing elements of separation between users and the membrane such as vegetation or street furniture or decorative elements.
2) the membrane is set above the reach of users.

Textile roofs are sometimes asked for retractability, that conditions the design and materials. It was the case of the Retractable Roof of the Zaragoza Bullfight Arena. 10 Years after completion a repair was needed because coating against UV radiation was ineffective, folded lines and suspended points tore and flexibility was lost. Opening and closing the fabric may end up causing the breakage of the fibres at points where the folding occurs persistently. The breakage of these fibres can facilitate initiation of the tearing of the fabric.

Left: For fabric folding and unfolding, the type of material needed is a flexible fabric. The border reinforcements must also be flexible, especially when the folds are very close. Polyester strings are preferred to steel cables. Parallel folding produces longitudinal folds not so aggressive than radial folding towards a point that produces point folds.

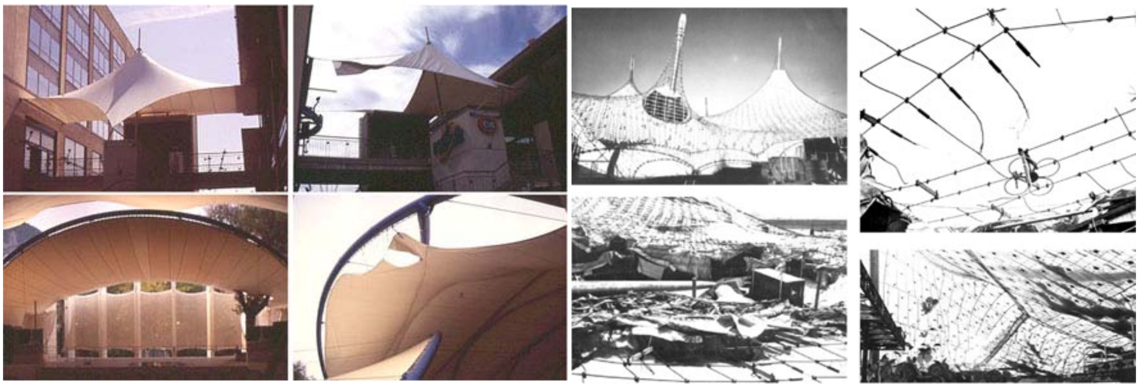
Right: An alternative solution for retractability is a more flexible fabric. In the Prophet's Holy Mosque umbrellas, white PTFE fabric integrated with strengthening belts was used. Movement is another alternative solution to retractability. Instead of folding the membrane, the whole structure is displaced. It is illustrated by the Vista Alegre Bullfight Arena Roof, Madrid.



Left: Tears cannot always be completely avoided in membrane structures. There are different reasons for tears in structural membranes: production unhomogeneities, knots, little cracks or similar in the fabric itself, points of sharp folding, pre-damages and damages caused by handling during production, fabrication, installation, misuse or abandonment. On the other hand, the deformed membrane must not hit the primary structure or any other objects. A tear does not grow unless the membrane stress near the tear exceeds the tear resistance. Once a tear appears, tear propagation has to be avoided in order to prevent a significant strength degradation of the membrane panel.

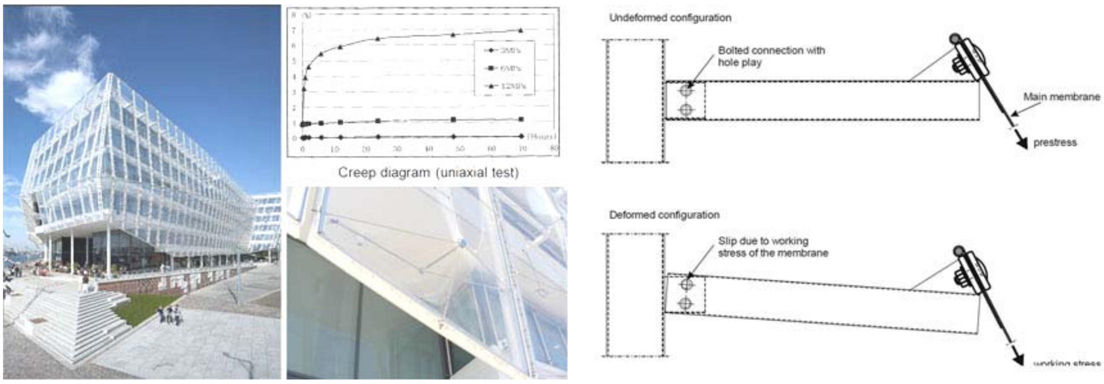
Right: Excessive bird pecking can cause small punctures in the ETFE cushions. This poses no threat to the stability of the cushion as a whole provided that will automatically adjust to compensate for the slight drop in pressure. Bird wire deterrents to stop bird perching are recommended.

6 Maintenance



Left: Most common defects of maintenance are loss of prestress and dirt. Loss of prestress produces ponding and flutter that go into soiling and tearing. Ponding reverses one curvature resulting in instability. The dirt degrades the aspect and ages the materials prematurely. Against these effects protective coatings and self-cleaning finishes are available.

Right: Maintenance and heating of the Pavilion were interrupted. Snow stayed on the roof and the permissible loads of 100 kp/m^2 were exceeded by a factor of 2 to 3. As a result, the cable net broke. Nevertheless, the collapse area was local and the cable net structure remained entire with a slightly changed geometry and a new state of equilibrium.



Left: The loss of prestress due to relaxation and creep has to be considered. Under constant load, ETFE foil creeps. The magnitude of the creep depends on the level of stress. Up to 3 N/mm^2 the impact of creep is negligible. For a stress of 6 N/mm^2 it stabilises at ~ 1%. With a permanent stress of 12 N/mm^2 the material creeps uni-axially towards a value of 7% to 8% after 70 hours, but has still not stabilised. Creeping requires limited values of pretension and adjustability: Unilever Building, Hamburg.

Right: Irreversible deformation of the primary structure results in a considerable permanent decrease of prestress. In this case a membrane is attached to the tip of a cantilever and the cantilever is attached by a bolted connection which contains hole play. A small rotation in the bolted connection leads to a large displacement of the cantilever tip that will not be reset. This mechanism is linked to a permanent decrease of prestress in the membrane.

Abandonment. Left: No maintenance means degradation. Right: Railway halt, Sevilla after Expo 92. Some administrations and firms do not think or do not provide for the maintenance or dismantling after the event that caused the construction. When the prestress relaxes, the wind causes fluttering, a significant movement of the fabric in the direction perpendicular to its surface, due to the alternating pressure and suction. This repeated action causes fatigue on the fabric and ends up tearing it. This occurs mainly in the free boundary of the cover, more affected by the wind.

Conclusion

Failures in textile roofs can proceed from the material, design, manufacture, installation, use and maintenance. All the agents are involved: owner, designer, manufacturer, builder and user.

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