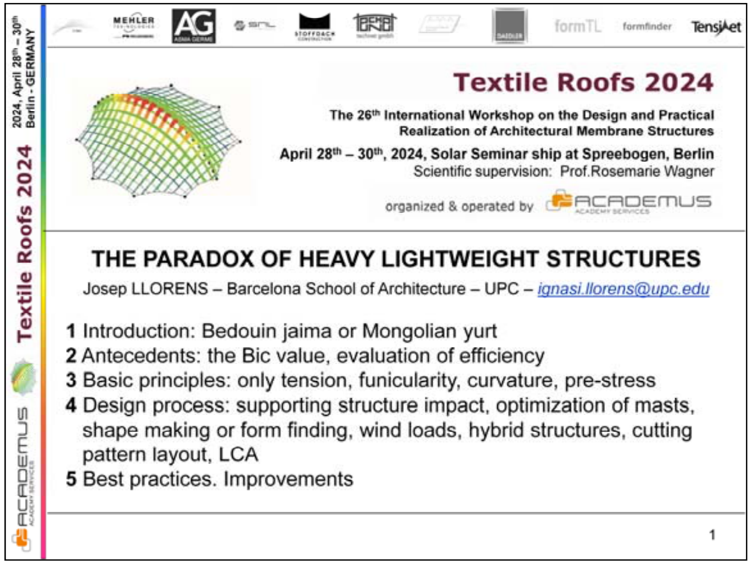


Summary

Progress is being made in the understanding of the appropriateness of membrane structures that are much more efficient than bending solutions based on trusses and cantilevers.

But some designs do not take it into account to the point that membrane structures frequently end up being covered conventional steel structures.

Attention to the structural characteristics of membranes and feasible improvements can reverse this situation.

Dissemination of best practices may also help.

The idea is introducing/remembering the principles and hints of design to prevent supposedly lightweight structures from turning out to be colossal.

A kind of response to Jürgen Hennicke's lapidary phrase: "*Structural membranes, if not designed as such, require an imposing steel structure".*

The growing concern for the environment and sustainability favours tensile architecture because it saves material, energy, emissions and waste. However, some designs do not take advantage of these benefits because they apply conventional methods suitable for concrete and steel, which are not appropriate for structural membranes. This leads to the paradox that supposed lightweight membrane structures end up being oversized cladded imposing steel structures.

It can be illustrated by comparing the main hall of the Denver airport with its car and bus access:

1 The primary structure of the main hall is reduced to the lateral masts and bending is avoided. The basic principles of structural membranes (only tension, funicularity, curvature and pre-tension) are satisfied.

2 In contrast, the access by road is a covered street that uses an imposing steel structure subjected to bending.

Another similar comparison:

3 Cardo e Decumano Streets. Milano

4 Imagine Clearwater Amphitheater

1 Municipal Stadium, Poznan, 2010 (43.269 52.000 m^2 and 45.830 spectators). Cladded steel structure.

2 Multifunctional sport court, Sevilla, 2010 (46x24 = 1.104 m^2).

3 German Pavilion, Expo Milano.

4 Football training centre, Wolverhampton.

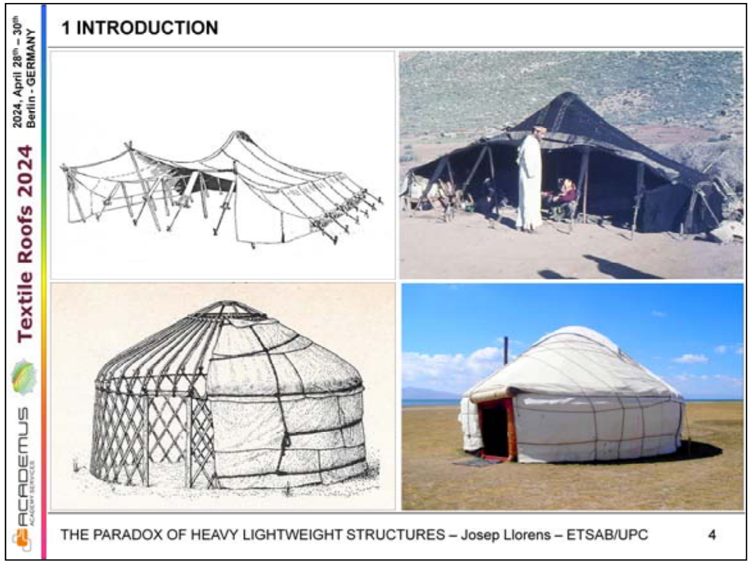
5 Oriam Scotland's Sports Performance Centre, 2016.

6 J-Village, Futaba-gun, Fukushima, 2018. Structure: frame and membrane. Membrane: PTFE coated glass fibre textile with TiO_2 coating.

7 Takanawa Gateway Station, Minato-ku, Tokyo, 2020. Frame membrane structure. Membrane: PTFE coated glass fibre textile with TiO_2 coating

8 Name: Nagasaki Station, Nagasaki, 2022 Structure: frame membrane structure. Membrane: PTFE coated glass fibre textile with TiO_2 coating on both sides.

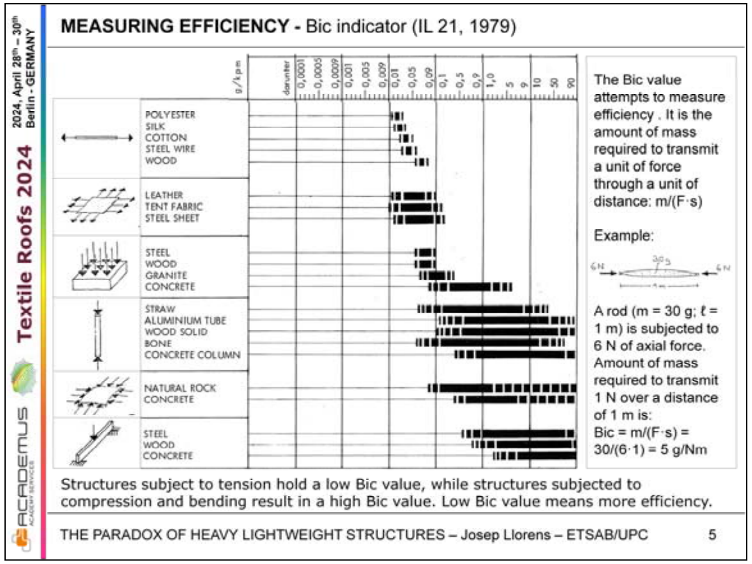
9 Makuhari Toyosuna Station, Mihama-ku, Chiba, 2023. Structure: frame membrane structure. Membrane: PTFE coated glass fibre textile.



This issue has emerged recently but it was already present since ancient times in the tents of the nomadic people.

The Bedouin "jaima" is a structural membrane with the primary structure reduced to a minimum.

Instead, the Mongolian yurt uses the fabric as a lining.



The structural efficiency can be evaluated using the values "**Tra**" and "**Bic**" in order to minimize material/energy input, as natural structures do. (I.Lochner, 2018 & F.Otto, 1979).

Tra = **F** · **s** (**Tra**: ability of transmitting forces; **F**: force; **s**: transmission distance or force path).

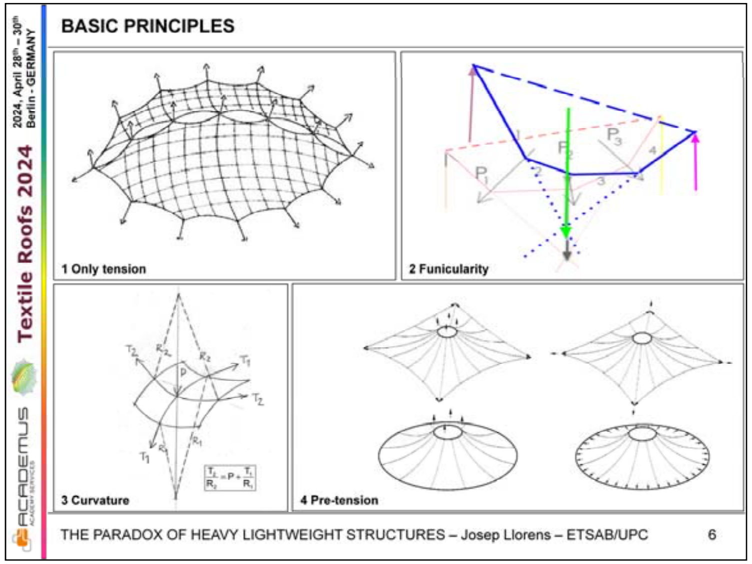
Given a load to be transferred, a low **Tra** value results in a more lightweight structure.

Bic = **m** / **Tra** = **m** /(**F** ·**s**)

Bic is the ratio of the mass of the structure to its capability to transmit forces, so it takes into account the mass **m** of the structure and illustrates the mass used in order to transfer a force **F** along a distance **s**.

It is a way to measure the amount of mass (expenditure) required under a given load condition to transmit a unit load over a unit distance.

(IL 21, 1979)



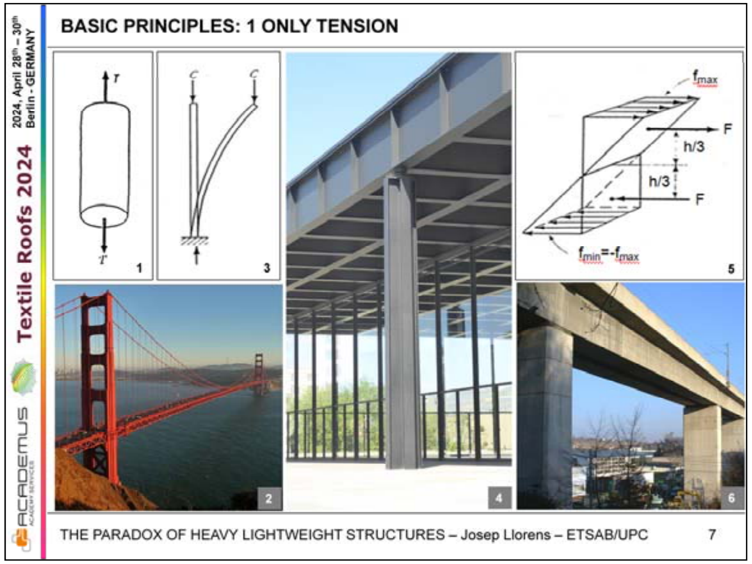
The way to take advantage of the benefits of membrane structures is to design and build them according to their basic principles:

1 Only tension

2 Funicularity

3 Curvature

4 Pre-tension



1 ONLY TENSION: membrane structures are loaded in tension.

The material strength is used optimally as the entire cross-section of the structure is completely stressed up to the breaking load. This material efficiency saves resources. And the possibilities of disassembling and recycling promote sustainability.

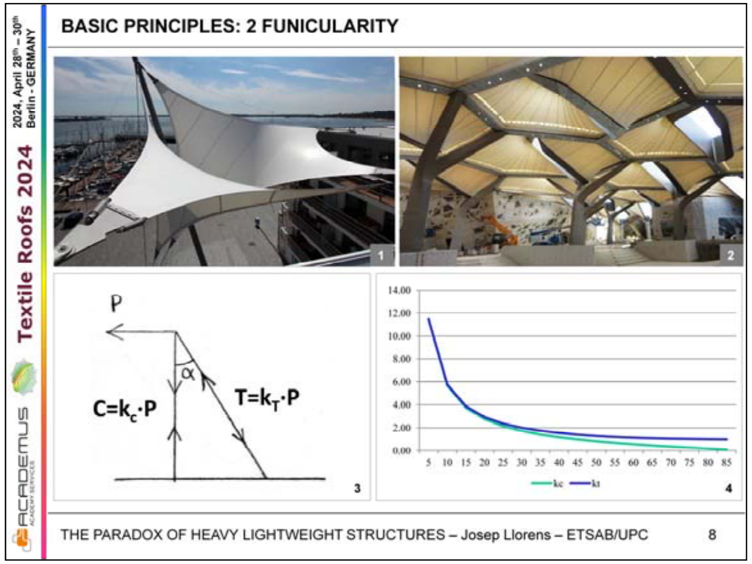
2 Joseph Strauss, 1937. Golden Gate Bridge.

3 Axial compression also mobilizes the entire cross-section, but depending on the slenderness, it is susceptible to buckling which forces over sizing and therefore decreases the efficiency.

4 Neue Nationalgalerie, Berlin

5 The most unfavorable stress state is bending. It is not efficient because it does not exhaust the resistant capacity of the material, as revealed by the cross section of a bar submitted to it. Observe that the material near the neutral axis of the section is not stressed to the limit of its capacity. Only those parts of the sectional area remote from the neutral axis are stressed to the effective limit set by the strength of the material.

6 Bending beam-bridge in concrete



Only tension means funicularity. The form has to follow the directions along which internal forces flow. Each load pattern determines a form-active shape containing axial internal forces only. This will be a fundamental condition of the form-finding process which will not allow the form to be free despite of what is often claimed regarding structural membranes.

1 The form of tensile structures is funicular.

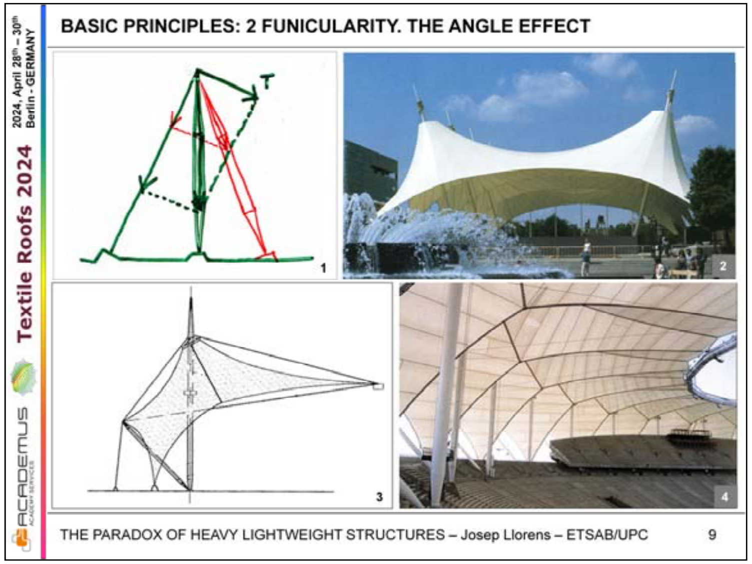
2 The shape of rigid structures can be arbitrary.

This makes a big difference with rigid structures that admit a wide range of shapes, as Professor Pauletti pointed out in SM 2015.

Therefore funicularity imposes conditions to the geometry, that greatly influences the distribution of loads, as can be seen for example with the angle effect.

3 A tied lateral mast receives a horizontal load **P**. As a result, a compression **C** is mobilized in the mast and a tension **T** in the stay. They depend heavily on the angle **α**.

4 Observe that a deviation **α** less than 30 degrees greatly increases the components **C** and **T**, so it can be said that small angles are inefficient.



On the other hand, it should be remembered that when several forces meet, equilibrium requires that each force be the resultant of the others.

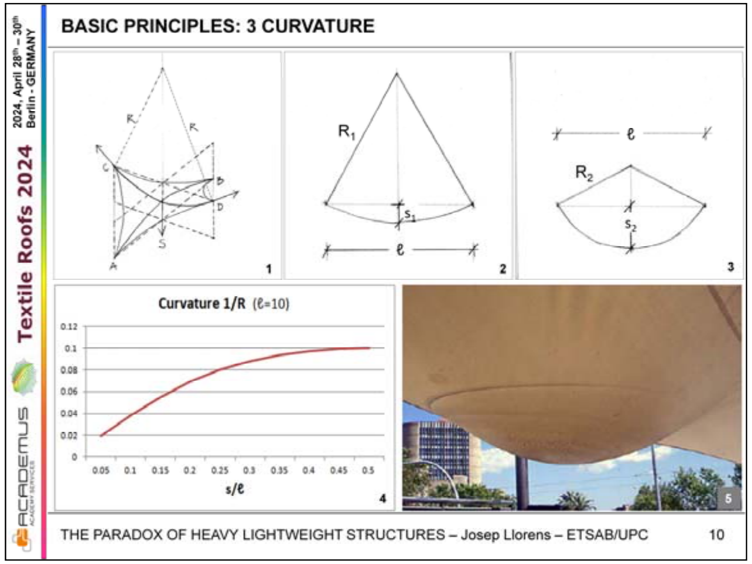
It can be illustrated with the inclination of the masts. The optimal position corresponds to the resultant. Otherwise, the loads increase considerably both on the mast and on the stays, and the amount of material increases with loss of efficiency.

1 The mast misaligned (green) needs much more resistance and material than the one that is oriented according to the resultant (red).

In addition, the position corresponding to the resultant not only reduces the loads but also expresses equilibrium. Visual expression is ore than visual.

2 At the Independence Mall Pavilion, Philadelphia, the masts are balanced with the fabric because they are sloped outward bisecting the angle of the cone.

3, 4 Instead, at the Riyadh Stadium the masts 58 m high are vertical and *do not bisect the angle of the stays* in order to satisfy non-structural considerations. They are misaligned with the resultant of the fabric form and the external guy cables must perform the additional function of resisting the horizontal resultant force at the top of the mast.



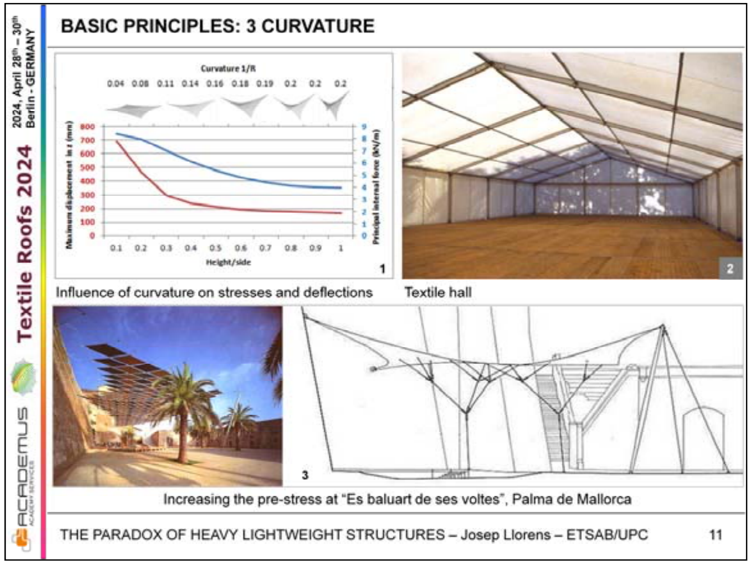
Transmission of loads with tension only and funicularity are achieved by curvature to resist any load.

1 It is measured by the inverse of the radius of curvature **R** that depends on the ratio sag/span (**4**).

2,3 As the sag increases in relation to the span, the curvature **1/R** increases, tensions relax and drainage is improved, but in doing so the height and surface of the membrane increases while the covered area is reduced.

On the contrary, a reduction of the curvature **1/R** implies a reduction in the sag/span ratio, an increase in the radius of curvature **R** and the formation of flatness, to be avoided as much as possible

5 because flatness is prone to lack of drainage, ponding and greatly increases internal forces of the membrane.



1 Influence of curvature on the values of stresses and deflections in a 10 x 10 m hypar submitted to 1kN/m^2 of wind suction and 1kN/m of pre-stress.

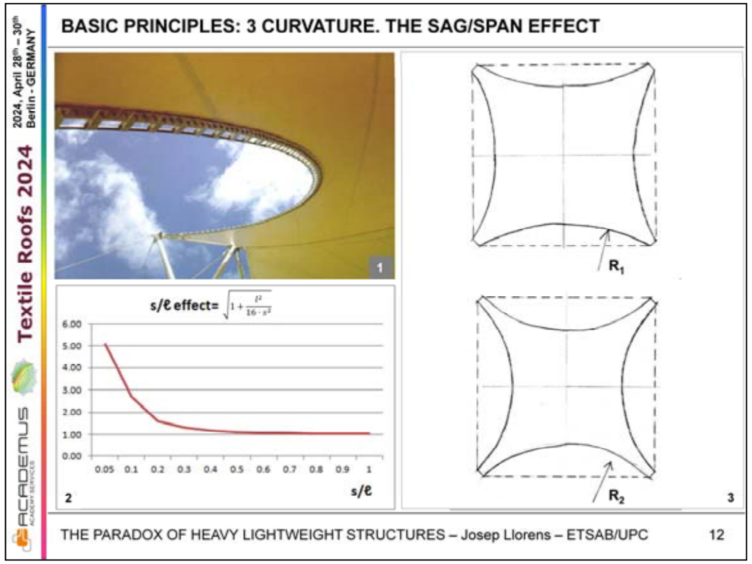
Flat hypars with minimal curvature the structure must deform to enable the applied loading to be resisted, that is why

2 flat surfaces are feasible (although they are not recommended) because the strain of the material provides curvature.

It is the case of the panels that enclose textile halls but they have to reduce the spans considerably.

3 Another way of resorting to (almost) flat surfaces is to increase the pre-stress such as in the open-air theatre "Es Baluart de ses Voltes" in Palma de Mallorca.

Considering its low curvature, to keep the awning as rigid as possible, it is pre-stressed to the ground via tree-like cables that can be adjusted by means of turnbuckles.



1 The sag/span ratio effect is also essential for edge cables.

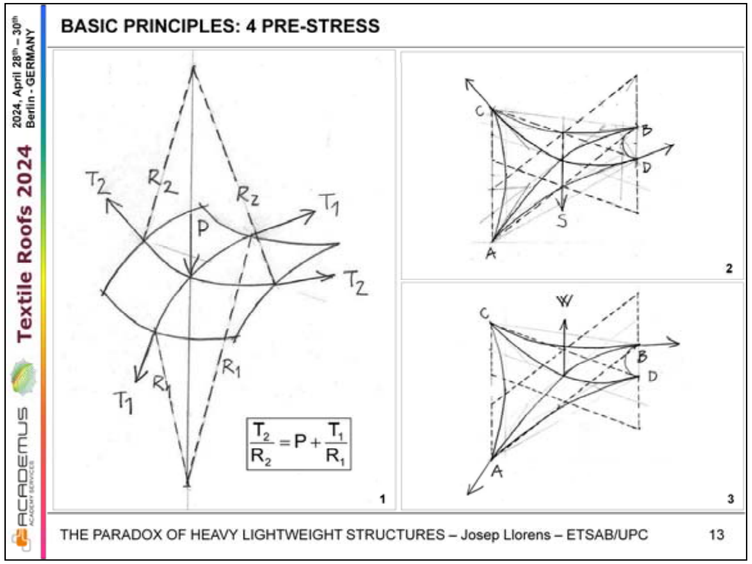
2 Assuming that span = ℓ, sag = **s** and uniform applied load = **q**, the cable tension **T** is subjected to an amplifying effect depending on the ratio sag/span = **s**/ℓ.

Note that the sag being equivalent to 30% of the span amplifies the load by 1,30, while the sag being equivalent to 5% of the span amplifies the load by 5,10.

Therefore, a sag to span ratio less than 0,05 should clearly be avoided as the cable force increases dramatically.

3 The interval between 0,05 to 0,1 may be desirable to provide protected area since by raising the curvature **1 / R** and diminishing the radius **R**, one can relax tensions, but in doing so reduces the area covered.

A sag to span ratio greater than 0,1 ensures low cable force that result in smaller diameter cable , smaller end fittings and consequently more elegant connections details and supporting steelwork.



1 Double curvature provides resistance to any load because, at any point of the membrane, two intersecting lines pull in opposite directions**.**

2 Snow load **S** is resisted by stretching in direction **CD**

3 Wind uplift **W** is resisted by stretching in direction **AB**.

But stretching in one direction means compression in the other, which is not allowable.

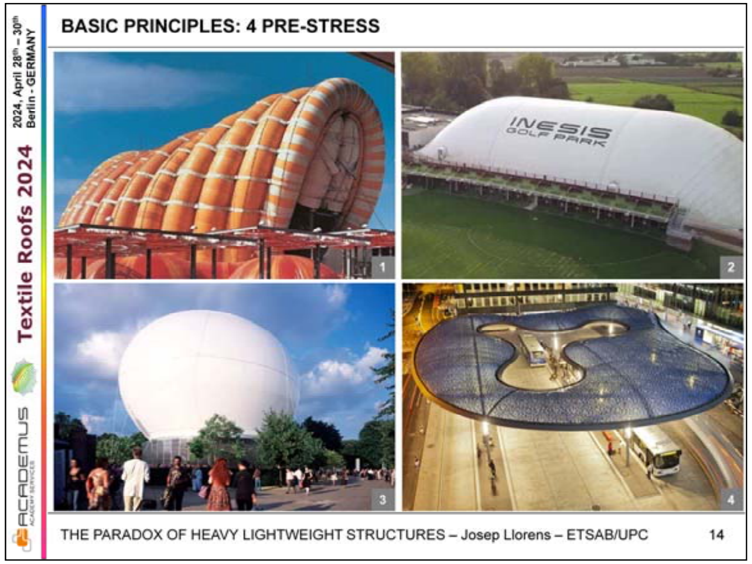
The structure works only in tension.

Under compression its stability is lost.

The most practical way to ensure that the fabric remains in tension (and therefore stable) is by pre-stressing it because pre-stressing transforms compression into a reduction of tension.

Any two directions exert tension against each other.

The higher the initial tension, the more stable and stiff the membrane will become.



The pre-stressing described above is mechanically implemented on surfaces with double negative curvature, that is, they have the radius of curvature on both sides of the membrane as represented.

An alternative to mechanical pre-stressing is inflation applied to positive double curvature surfaces, that is, they have the radius of curvature on the same side of the membrane.

Several examples are represented:

1 Yutaka Murata with Mamoru Kawaguchi and MakMax, 1970: Fuji Pavilion, Osaka.

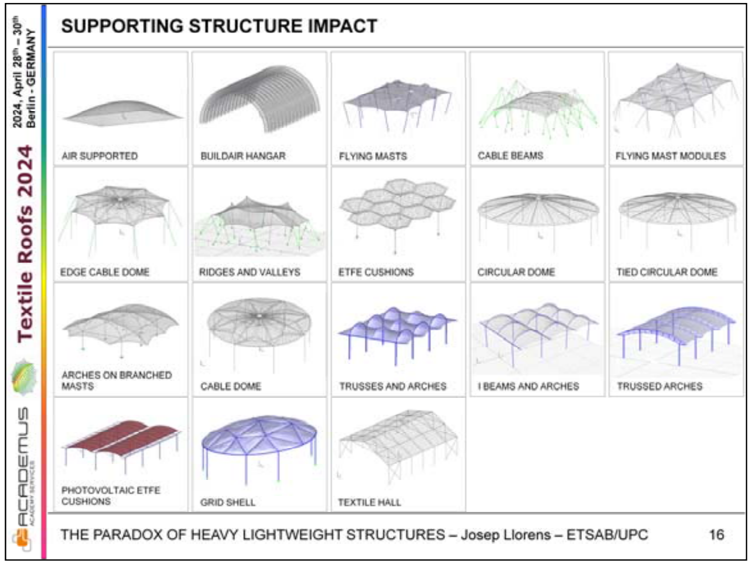
2 Canobbio Textile Engineering, 2006: 40 x 80 m air hall for the Inesis Golf Park, Marcq-en-Barœul.

3 Rem Koolhaas with Arup (Cecil Balmond), 2006: Serpentine Pavilion, London.

4 Vehovar & Jauslin with form TL and Vector Foiltec, 2014: Bus Station, Aarau.

In addition to the basic principles, some design steps that also contribute significantly on efficiency are:

- the primary structure impact,
- the shape making or form finding process,
- the structural analysis with special mention to wind loads and hybrid structures,
- the cutting pattern generation and layout
- the life cycle analysis to optimize energy and material consumption, waste production and gas emissions.



Membranes need primary structures that require more material, weigh more and have more environmental impact than the membrane itself.

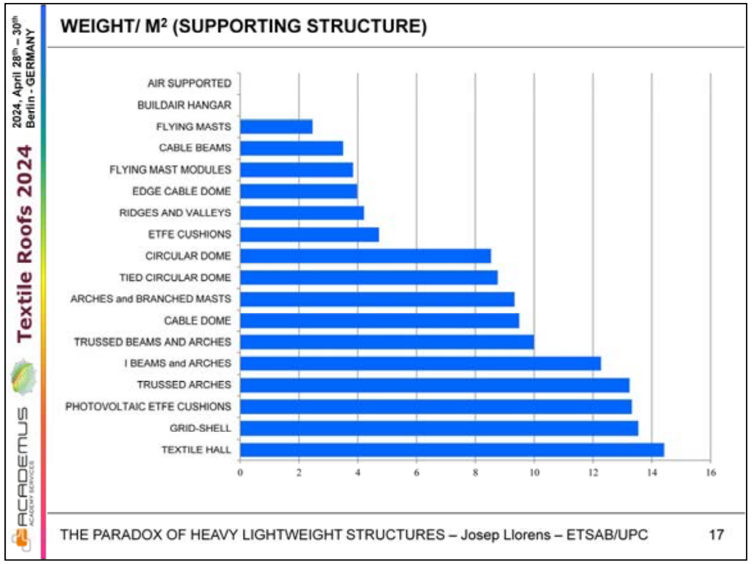
It is convenient to design them so that they do not contradict lightness and sustainability.

To get an idea of their impact, a comparative study has been carried out including commonly used arrangements varying from 642 m^2 to 1.149 m^2 which has provided practical design recommendations.

The compared values have been

- the surfaces (covered floor area and membrane),
- their ratio,
- the weights (supporting structure and membrane).
- curvature (by the relation sag/span),
- maximal internal forces,
- total wind action (per square meter) and
- displacements.

The analysis has been carried out using the software RFEM and RWIND, considering a wind speed of 26 m/s in zone IV.



The range of covered surfaces varies from 642 m² to 1.149 m², the weight of the primary structure from 0 to 14,42 kg/m², the maximum internal force from 2,45 kN/m to 30 kN/m and the wind action from 23 N/m² to 508,4 N/m².

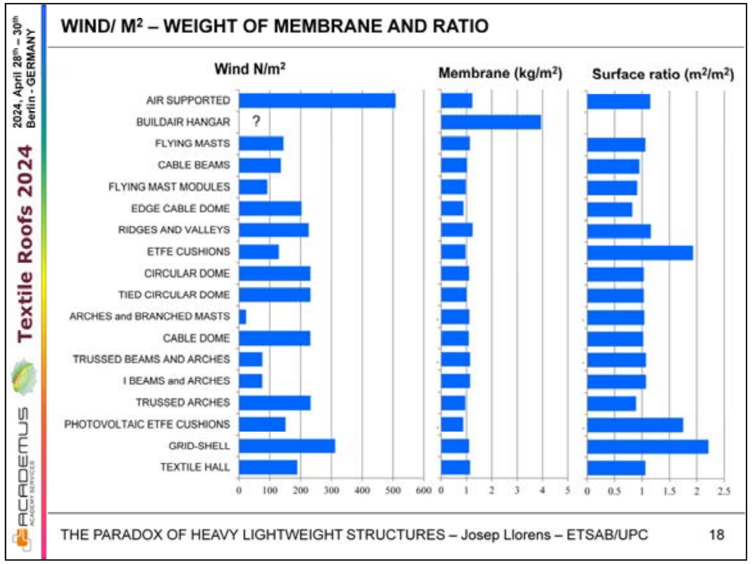
This are values sufficiently different to make them worth taking into account.

Note that the lightest structures are those that avoid bending: AIR SUPPORTED, BUILDAIR HANGAR, FLYING MASTS, CABLE BEAMS, FLYING MAST MODULES, EDGE CABLE DOME and RIDGES AND VALLEYS.

The structure that weighs the most is the TEXTILE HALL, the one that does not have the structural action of the membrane.

The structure that weighs the least is the one with flying masts (apart from the pressurized).

The suspended roofs (cable beams, cable domes and ridges and valleys) are also favourable but weigh more due to the height of the masts.



The total wind action can be measured to assess how aerodynamic is the roof by adding up the reactions it mobilizes.

The maximum value corresponds to the AIR SUPPORTED because of the lateral enclosure.

The less value (most aerodynamic) are the ARCHES AND BRANCHED MASTS.

Note that wind pressure values may be oversized in CFD analysis that does not consider deformations.

On the other hand, the ratios of surfaces and the weight of the membrane vary very little except in the cases of ETFE cushions because of the double layer.

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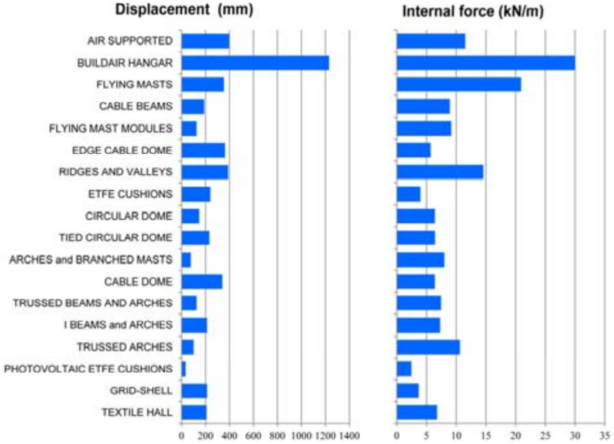
DISPLACEMENTS AND INTERNAL FORCES



Attention has to be paid to deformations that depend on some particularities such as spans, cantilevers and the dimensioning.

Minor displacements correspond to TRUSSED BEAMS AND ARCHES, TRUSSED ARCHES and PHOTOVOLTAIC ETFE CUSHIONS because trussed beams and arches deform less.

Referring to internal forces, membrane stresses are higher in pneumatic structures as they rely on internal pressure only for stability.

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OPTIMIZATION OF MASTS

If bending is dispensed with, the masts become the main elements of the primary structure.

Different types of masts can be used: hollow sections, trussed, tapered, subdivided, branched, coupled, clustered, flying and tied.

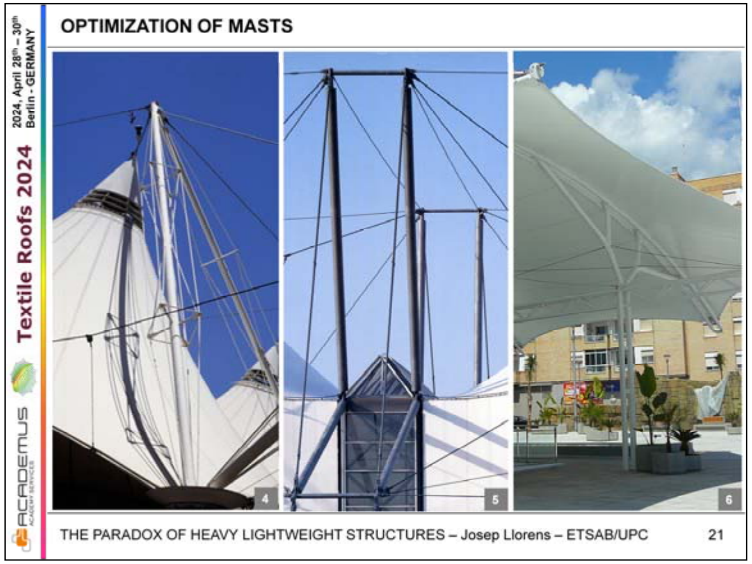
There are different strategies to cope with over dimensioning imposed by buckling on such long elements.

Circular hollow steel sections are efficient in compression and torsion, with minimal surface area to be protected, minimal wind resistance and availability.

1 To simplify the transport, the poles may be subdivided and assembled onsite through bolted connections not protruding from the profile of the section.

2 Tapering is a strategy to prevent from looking oversized compared to the whole structure and the site.

3 Trussed masts are common in travelling circuses to reduce weight, facilitate assembly and lifting from the ground.



4 Cross-trees and ties lighten the mast by reducing the buckling length.

It is a way to save steel and to prevent the mast from looking oversized.

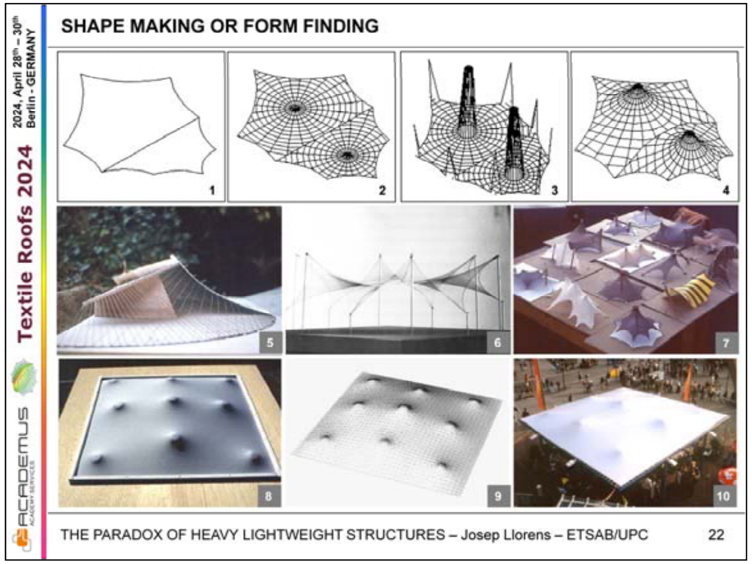
5 Coupling or clustering the masts make them thinner.

Slim tubes look more elegant than a single bulky cylinder.

6 Branching reduce spans and buckling lengths.

It is also worth remembering that mast sizing must provide sufficient cross-section to resist compressive loading and stiffness enough to prevent buckling.

The parameters to be considered are: load, height, constraints, stiffness, dimensions and shape.



The shape cannot be arbitrarily determined. Geometry and forces interact.

They have to be in equilibrium at any point.

It results from:

- boundary conditions and supports
- applied loading
- material mechanical properties
- curvatures and distribution of pre-tension.

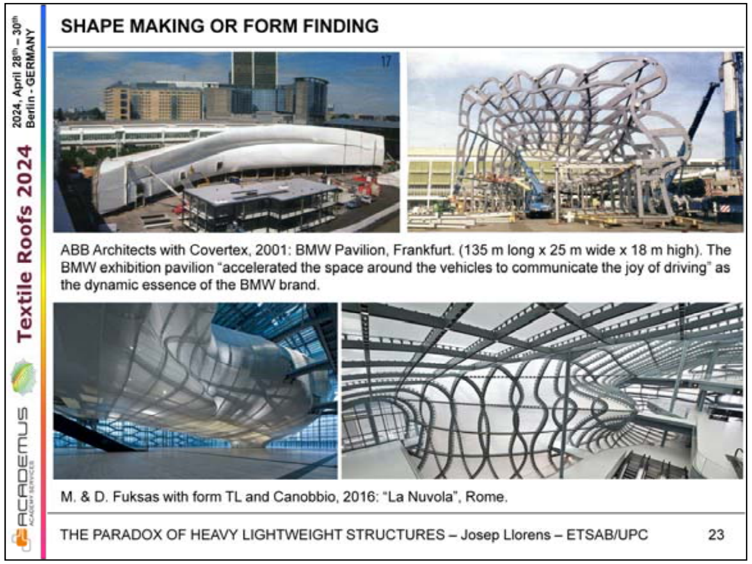
It can be predicted by:

1-4: computer assisted analytical form-finding. Boundaries, net, fixed points and the surface of equilibrium at each point.

5-7: physical modelling rubber mats, elastic threads, lycra fabric or soap bubbles

Example of physical and computer form finding: the Venezuela Pavilion Cafeteria, Hanover 2000:

8 Physical model
9 Computer model
10 As built.



Free-forms require a steel framework and may be cladded with fabric.

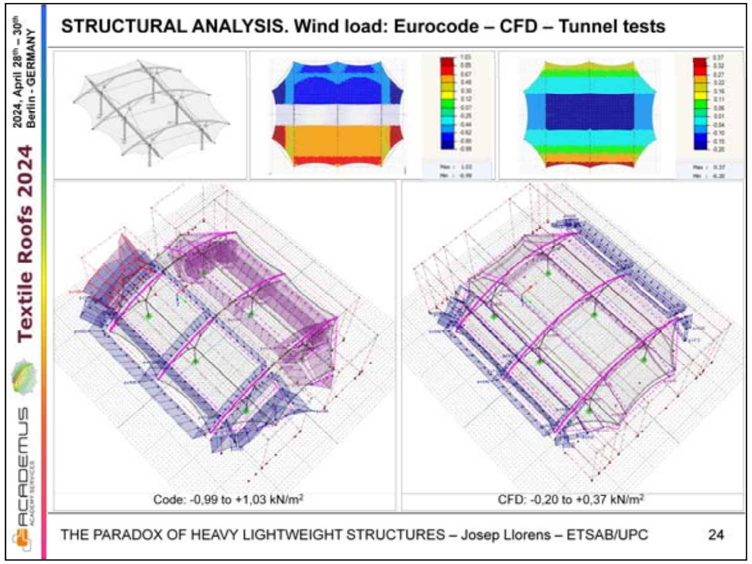
It is the case of the BMW exhibition pavilion. Its free “dynamic” form was made with 15 different double-curved welded hollow beam Vierendeel girders every 8 m covered with a 7.190 m^2 membrane.

The frames comprised more than 600 individual parts, each of them unique. In the longitudinal direction, rigid round pipes provide lateral stability together with the rigid frames at both ends and the ceiling grids.

For “La Nuvola”, a cloud (a true free form suspended in the air), a curved steel framework has been defined and enveloped by silicone coated glass-fibre fabric with an acoustic punch pattern to improve the sound absorption.

The way to materialize the arbitrary shape consisted of slicing the cloud and define buildable sections in the yz, xz and xy planes.

The final result has been described as "*a cloud in prison*".



Regarding the structural analysis, there is a concern with the wind load.

Codes are unfavourable and lead to over sizing and cost increase.

On the other hand, most approaches are not accurate because the deflections, that are not taken into account, modify considerably the pressure/suction distribution.

It was verified applying the code and a CFD analysis to the structure illustrated above.

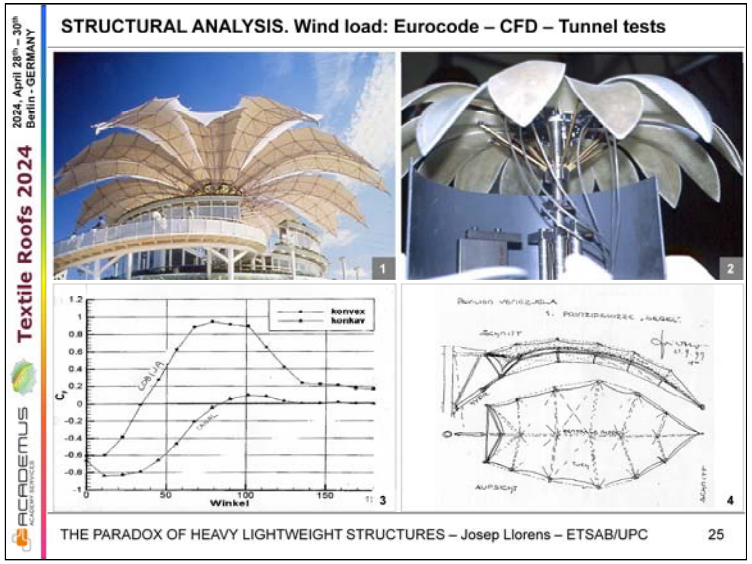
According to the Eurocode (left), values of -0.99 kN/m^2 (suction), to +1.03 kN/m^2 (pressure) were obtained.

According to the digital wind tunnel RWIND (right) the values were -0,20 kN/m^2 (suction) to +0,37 kN/m^2 (pressure).

Therefore the wind load is highly dependent on the method used to determine it.

Wind tunnel tests could be more reliable.

When deformations are significant, additional tests may determine the deflected shape, or theoretical estimations and numerical calculations may be performed.



Studying the action of the wind may greatly influence the design.

1 The Venezuela Pavilion in Hannover was designed as a giant flower with petals that could be opened and closed according to the weather conditions.

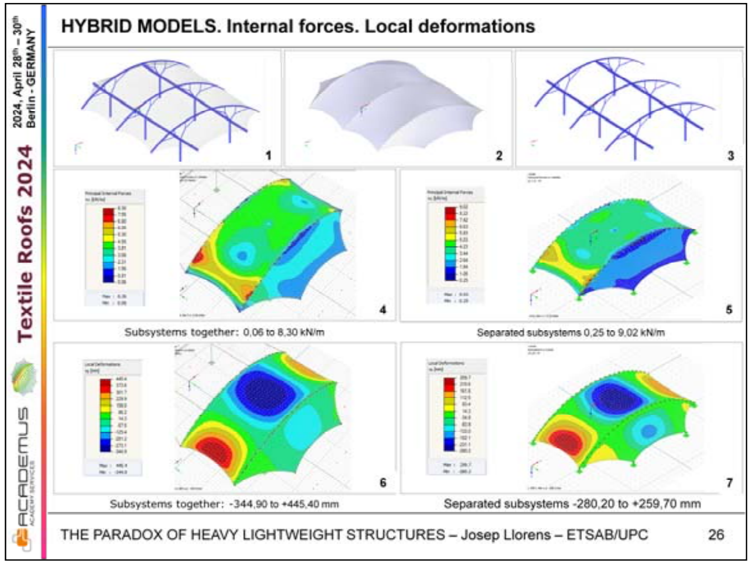
2 A wind tunnel test was required to measure the wind effects on the petals in different positions. They were initially designed convex and concave.

3 The test revealed that concave surfaces produce better aerodynamic behaviour than convex ones.

Hence, all the petals were designed as concave.

4 The petal of the Venezuelan Pavilion was one of Frei Otto's last designs.

Note that the edges are flexible. The petal is not enclosed in a rigid perimeter.



The membrane itself carries the external loads to the supporting structure. So the design model has to be hybrid and the subsystems should be analyzed together, but they are often analyzed separately.

The comparison of the results obtained with both procedures demonstrates that the separation is expensive because the interactions, especially the deformations, are favourable.

1,**2**,**3** A textile roof supported on steel arches made of tubular steel sections has been analyzed with both procedures.

4 The membrane, arches, branches and columns interact. Curvatures are increased and internal forces relaxed.

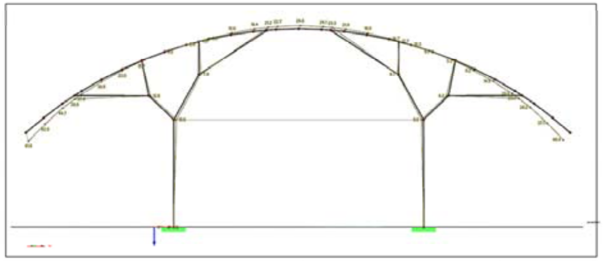
5 All the nodes are fixed. The steel part doesn’t deform. The panels are independent. They do not interact. As a result, curvatures are less and internal forces higher. So, the supporting structure ends up oversized.

6 The membrane, arches, branches and columns interact.

Deformations and curvatures are increased and internal forces relaxed.

7 All the nodes are fixed. Deformations are smaller.

HYBRID MODELS



CASE	1	2	3	4
Weight (kg)	1.659	1.658	3.272	9.967
Max. stress ratio	0,94	3,86	0,98	0,27
Max. deformation (mm)	61,6	795,3	318,1	62
Arch	2Ø120x5	2Ø120x5	2Ø150x8	2Ø200x20
Upper branches	Ø150x6	Ø150x6	Ø200x6	2Ø200x20
Lower branches	Ø200x7	Ø200x7	Ø200x8	2Ø200x20
Columns	4Ø100x3	4Ø100x3	4Ø120x10	4Ø200x20

Looking at the primary structure, the difference is even more noticeable. A frame composed by the arch, its branches and masts has been analysed

1 as a part of the complete system considered together with the membrane The sections have been sized so that all stress ratios are ≤ 1. Maximum stress ratio: 0,94. Maximum deformation: 61,6 mm. Weight 1.659 kg.

2 considered alone with the loads transmitted by the membrane (same sections as 1), Maximum stress ratio: 3,86 > 0,94. Maximum deformation: 795,3 mm > 61,6 mm. Weight: 1.658 kg. Stresses and deformations increase considerably. They are not allowable.

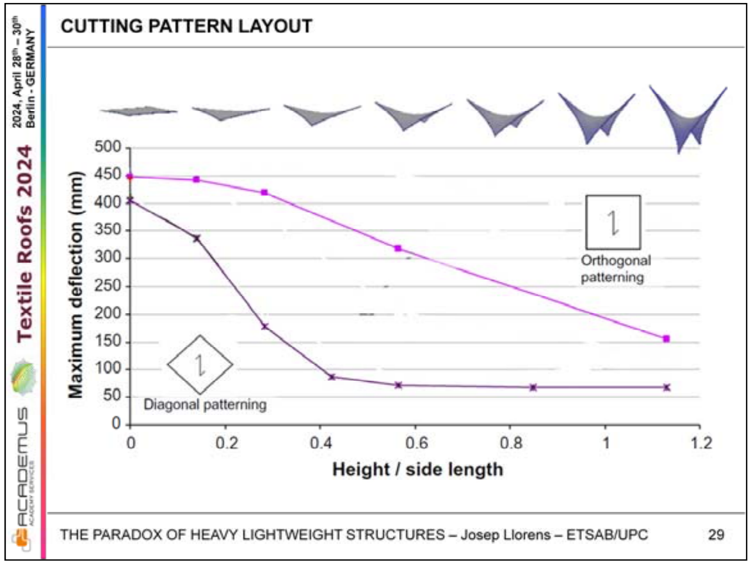
3 considered alone with the loads transmitted by the membrane with the sections resized so that stresses are allowable, The weight increases 97%.

4 considered alone with the loads transmitted by the membrane with the sections resized to maintain the deformations of case 1 (hybrid system). The required steel increases fivefold!

HYBRID MODELS

Consequently, the membrane restrains the structure and replaces the ties that come loose.

The panels interact, redistribute and balance internal forces.

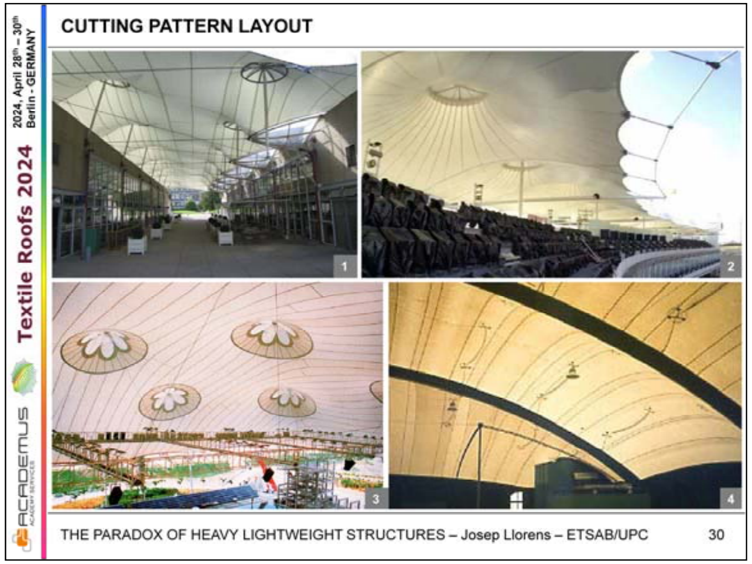


The shape of membrane structures has to be manufactured from flat panels of limited width.

The common way of patterning consists of cutting onto strips the shape of equilibrium using geodesic lines, flattening the strips trying to minimize the unavoidable distortion and applying a compensation to obtain the initial pre-stress.

The orientation of the fabric, its shear deformation, the stiffness of the seams and the process of pretension influence the result, but they are not always taken into account causing differences in geometry and stress between the shape of equilibrium and the built structure leading to wrinkles and measured stresses higher than expected.

Bridgens & Birchall showed that the orientation of the fabric parallel to main curvatures (diagonally patterned) leads to smaller shear stresses and deflections, for a 7.07 x 7.07 m hypar subjected to 3 kN/m of uniform pre-stress and 1 kN/m^2 of wind uplift. (From Bridgens, B. & Birchall, M., 2012: "Form and function: The significance of material properties in the design of tensile fabric structures". *Engineering Structures*, 44, 1–12. *https://doi.org/10.1016/j.engstruct.2012.05.044*)



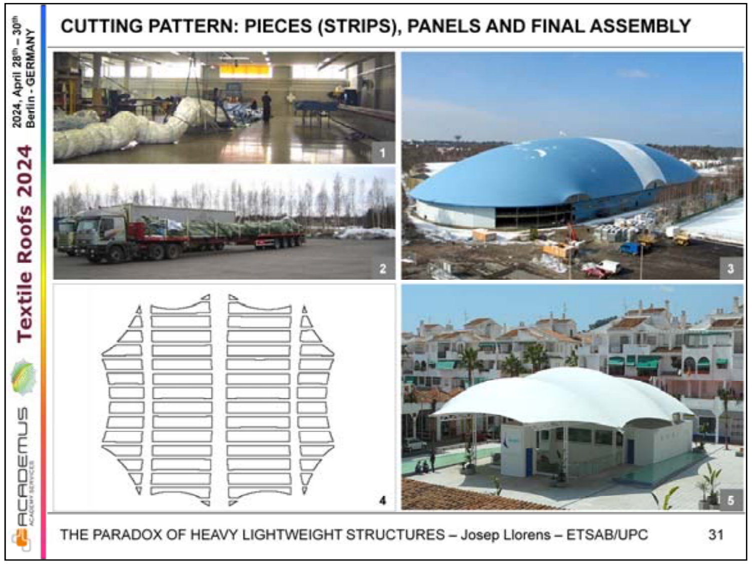
The layout of the seams is not only a technical problem. Since membranes are translucent, even transparent, the shape can be understood from the cutting pattern due to the seams that are visible against the light. Care must be given so that the perception of the overall surface is consistent with the spatial configuration. The figures show four cases in which the cutting pattern layout is significant.

1 The longitudinal cutting pattern forms continuous strips to maintain the sense of longitudinal continuity.

2 The radial pattern emphasizes a sense of individual space underneath each canopy.

3 The parallel membrane strips running towards the edge reflect the distributed stress caused by wind suction. The radial pattern of the high points reflect the concentration of loads due to snow.

4 The layout of the patterns minimizes the waste but the result is messy and confusing.



Size and number of panels are significant.

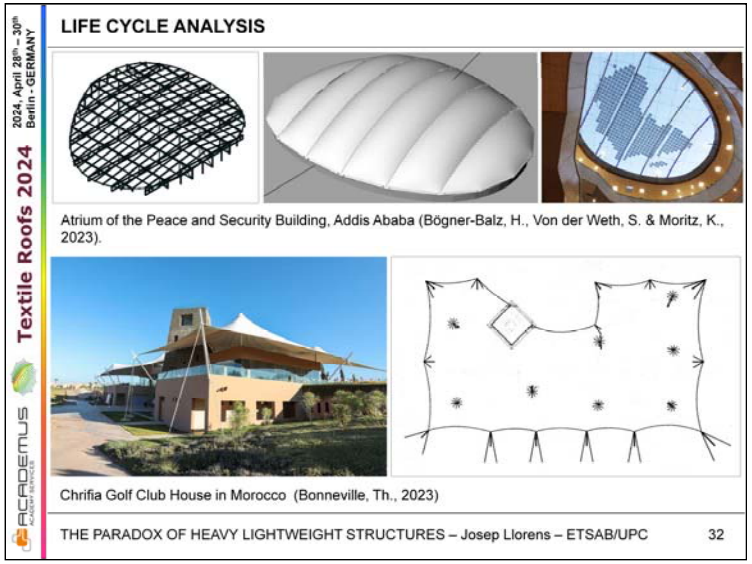
There is a tendency to manufacture only one (or just a few) panel(s) to reduce the membrane connections on site, saving labour and shortening the delivery time in exchange for complicating the handling.

In addition, fewer panels entails the continuity of the membrane, which is favourable because it balances tensions that are not transmitted to the supporting structure.

1,**2**,**3** Matti Orpana, Tensotech: 14.300 m^2 inflatable football field in only one panel.

It was moved with a special transport and it took only 2 hours to be inflated.

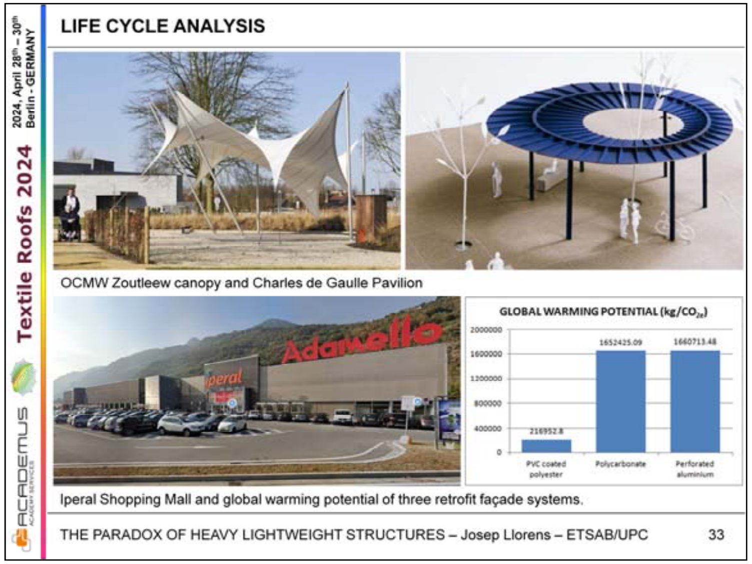
4,**5** The membrane of the 700 m^2 Almuñécar Aquarium textile roof was subdivided into 60 pieces but manufactured in only one panel to avoid on-site joints and balance stresses between panels.



In order to highlight the advantages of membranes from an environmental point of view, several comparisons have been made.

Pneumatic ETFE cushions with steel and glass of the 430 m^2 oval-shaped roof for the atrium of the Peace and Security Building of the African Union in Addis Ababa have been compared. The initial solution envisaged a steel and glass roof but an alternative proposal consisted of 2 layer pneumatically pre-stressed ETFE cushions. At the material level, the same area can be covered with ETFE cushions with approx. 60% less CO_2 emission than with glass (without the frame). At the system level, the glass option weighs around 15 times more. At the building level, ETFE foil cushions can also offer the possibility to include photovoltaic modules and control the solar transmission and energy transfer into the building to reduce mechanical air conditioning but still allowing enough light to pass through and thus saving energy.

The textile roof of the Chrifia Golf Club House in Morocco has been compared with a conventional metallic roof. The membrane performs much better because it weighs 4,5 kg/m^2 and has an embodied carbon value of 21 kg CO_{2e}/m^2 against the 45,2 kg/m^2 and 75 kg CO_{2e}/m^2 of the metal option.



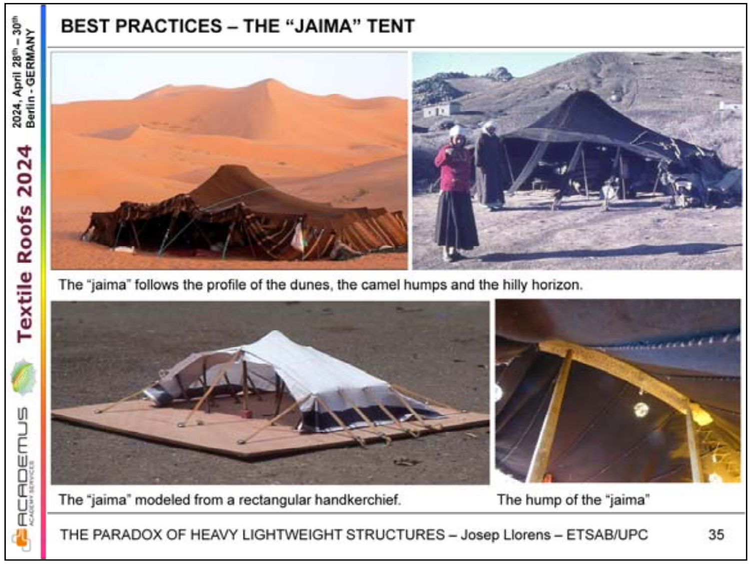
The global warming potential (GWP) of the membrane OCMW Zoutleeuw canopy has been compared with the steel/aluminium Place de Gaulle Pavilion, Eure. They have been analysed by means of the tool OneClickLCA. As a result, the membrane solution is better positioned in terms of environmental performance except for the end-of-life scenario, (because the fabric will be incinerated). Note however that, although the projects are quite different, it is advisable to design the shape and to choice the materials considering the criteria of environmental performance. (Eryuruk, A., Mollaert, M., Van Hemelrijk, D. & de Laet, L., 2023).

Three different façade retrofit designs based on similar approaches but achieved with different materials have been compared. The three solutions chosen are the adopted one with PVC coated polyester and two other alternatives with polycarbonate and aluminium perforated panels so that all three cases are translucent and require a similar substructure for the fixing of the elements. The three options exhibit a considerable difference between the Global Warming Potential. As a result, the PVC coated polyester deploys 216.952.8 kg/CO_{2e}, polycarbonate 1.652.425,09 kg/CO_{2e} and perforated aluminium 1.660 713,48 respectively. (Procaccini, G. & Monticelli, C., 2023)

A selection of historical and contemporary examples are presented to illustrate what is considered proper designs, either in whole or in part.

They relate to the primary structure especially in cases where bending is avoided or reduced.

Some innovations and improvements that favour efficiency and, therefore, sustainability are also shown.



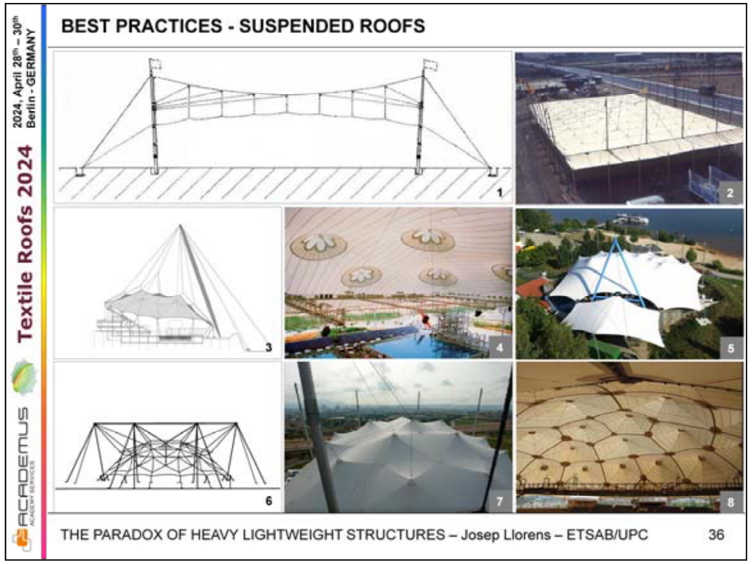
Since ancient times, the nomadic people of North Africa have used the "jaima" tent, an outstanding example of a properly designed sustainable structural membrane.

It is based on natural materials such as goat and camel hair and wood. It measures around 6 by 12 m and weighs 160 kg since it has to be light and limited in size to be carried by a camel (Kahn, 1973).

Starting from a rectangle, the fabric is stretched and tied to the ground with removable stakes. It is propped up by central poles higher than the perimeter ones, so that the final result has a double curvature, is pre-stressed, subjected only to tension and funicular. The aforementioned basic principles are fulfilled. The roof is not only an envelope, it is the structure.

In addition, from a climatic point of view, when there is dryness and hot the fibers contract and allow ventilation but if there is humidity, the fibers swell and close the pores .

In terms of integration into the environment, the "jaima" does not oppose arbitrary forms because it follows the profile of the dunes, the camel humps and the hilly horizon.



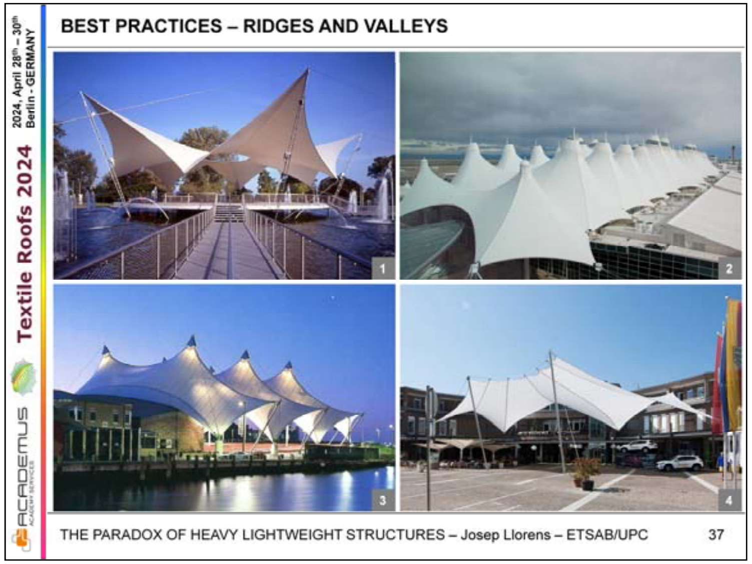
An effective way of optimizing the primary structure is hanging it, just like suspension bridges do. This idea has been explicitly formulated by Frei Otto in 1954 and consolidated in recent developments.

1,2 The "envelat" was a traditional tent-like construction, 24 x 36 m in plan. It succeeded in eliminating interior supports and creating a diaphanous large hall hanging from ropes submitted to tension, that is avoiding bending. It beats the circus tent, enlarged by increasing the number of interior masts, impeding the interior space.

3,4 The single membrane of the National Swimming Stadium in Kuala Lumpur is suspended from 13 individual points and a guyed mast. In addition to the layout of the patterns discussed above, it stands out for the absence of interior masts (Schlaich and Bergermann, 2005).

5 IF Group, 2011: Amphitheatre of the New Senftenberg Stage

6,7,8 The Abuja Velodrome has been covered with a polygonal cable-net of pentagons and hexagons filled with PTFE/glass membrane and supported by 8 main masts and 16 perimeter columns. In this way, the 10,649 m^2 of the velodrome were covered without beams, arches, trusses or interior masts (Stimpfle, 2008).



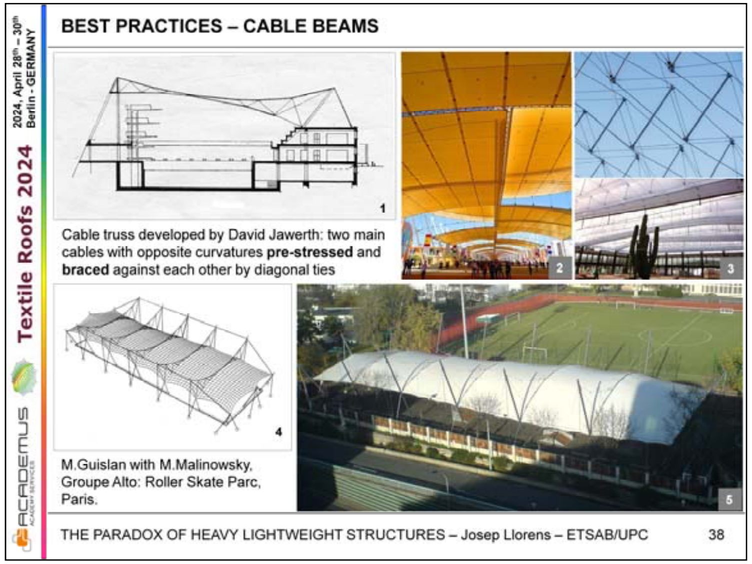
Ridges and valleys belong to the type of lighter primary structures without bending. They have been made with multiple variations, both in radial and parallel positions, starting from the Dance Pavilion in Cologne and followed by the great hall of the Denver International Airport, the Pier 6 Pavilion in Baltimore and many others.

1 The dance pavilion (1957) has the geometry of a concentric, so called star wave, with six peripheral high points and regularly distributed between them, six peripheral low points. The masts are optimized: trussed and tapered. In addition, there are no gussets on the upper part, which means that they are not big-headed.

2 Denver International Airport (1994).

3 The Pier 6 Concert Pavilion in Baltimore (1991) is a bending free ridges and valleys membrane roof that covers 3.500 seats. The masts are subdivided into different sections with the upper and lower ends tapered.

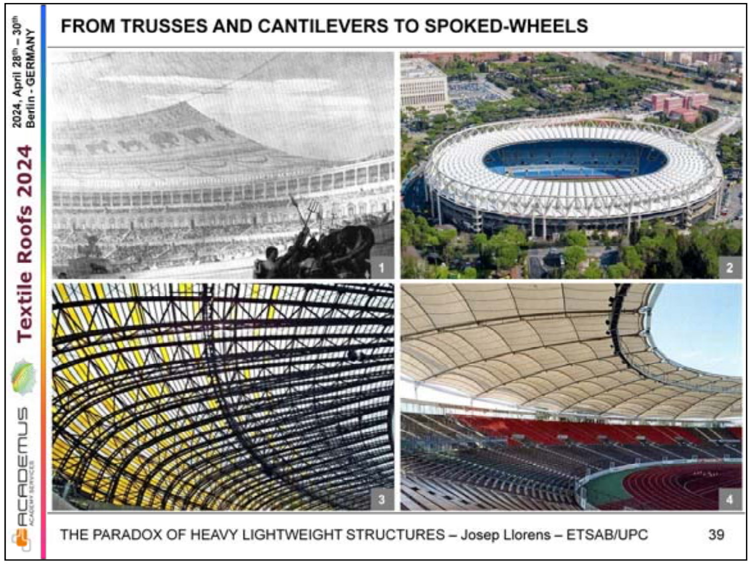
4 The Velden Gemonaplatz roof (2015) is a ridge and valley design invokes the lightness of an elegant silken hand fan. https://www.world-architects.com/en/str-ucture-stuttgart/project/temporary-membrane-roof



1 Cable-beams, introduced by David Jawerth, consist of two main cables with opposite curvatures **pre-stressed** and **braced** against each other by diagonal ties. The level of pretension ensures that both cables remain in tension under any combination of applied loading.

Two outstanding variations of the cable-beam concept are **2** the Decumano and Cardo at Expo Milano and **3** the Desert City Greenhouse in San Sebastián de los Reyes.

4,5 The Roller Skating Ring of Paris was covered with a textile roof for its low budget and light intervention. Five cable-stayed frames with masts at both ends tension the PVC-coated polyester fabric over the playing area (30x70 m). They follow the scheme developed by David Jawerth and made up of ten painted galvanized steel CHS masts (Ø273.6 mm weighing 300 kp per piece), stainless steel funicular cables (Ø 24 mm), diagonals (Ø 12 mm) and ties (Ø 24 and 42 mm), all in stainless steel. All fittings are also made of stainless steel. The fabric is attached to the lower funicular cable. Its panels are laced under a continuous flashing. Under extreme loads it works to a quarter of its ultimate strength. Total weight: 15 tons for 2.100 m², that is 7,14 kp/ m². It cost 600.000 € (286 €/m² in 2006, the foundations and VAT are not included).



If the cable beams are placed radially instead of parallel, the spoked-wheel is obtained.

1 It started in 80 AD in Rome and resumed in 1990 also in Rome.

2 Studio Tecnico Majowiecki re-introduced it in 1990 for the Rome Olympic Stadium.

Since then, large-scale sport stadium roofs have expanded all over the world imposing the tensile bicycle wheel where a series of pre-tensioned spokes join the central tension ring to the perimeter compression ring

It is a much more efficient structure than bending solutions based on trusses and cantilevers.

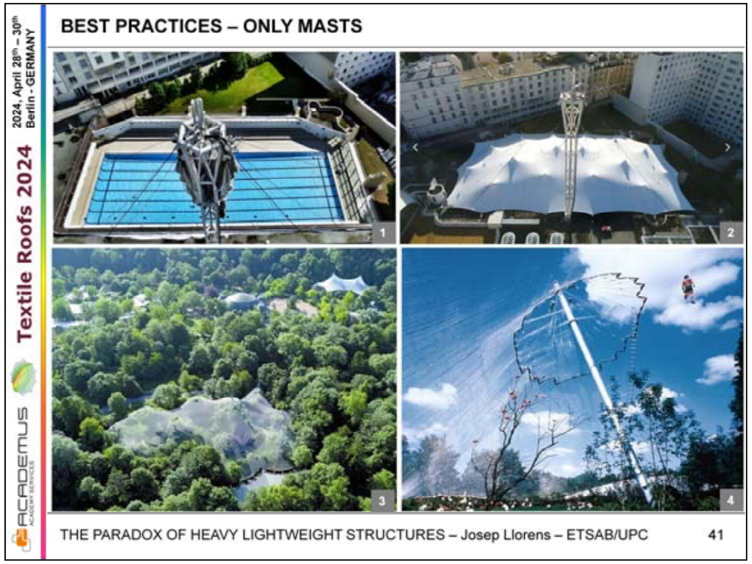
3 Rhode-Kellermann-Wawrowsky with Bollinger & Grohmann, 2011: Municipal Stadium, Gdansk.

4 Arat Siegel und Partner Architekten with Eiffel Deutschland and sbp, 2011: Mercedes Benz Arena, Stuttgart.

Current stadiums under construction:

1,2 Real Madrid Stadium: a closed box with trusses and cantilevers.

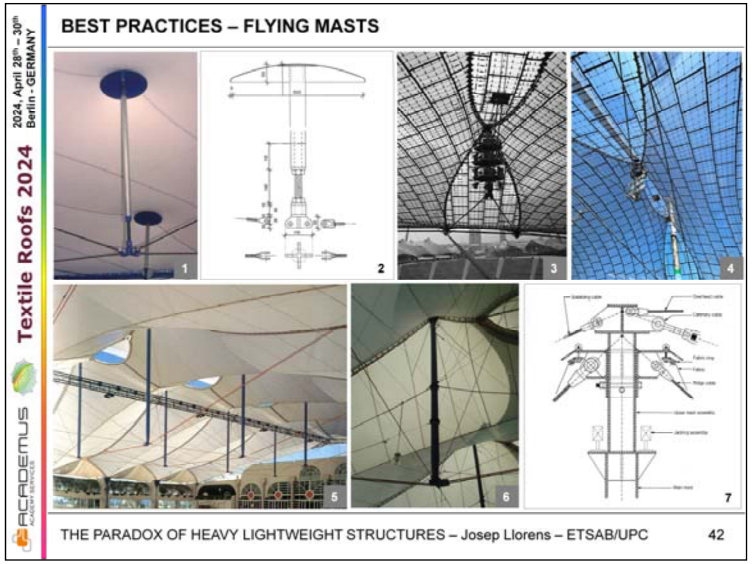
3,4 Barcelona Stadium: open to the surroundings covered by a spoked wheel, originally designed by sbp. Substitution and enlargement in red colour.



The masts may be the only supporting elements of the membrane. Their optimization has been presented in a previous section. If they do not interfere with the interior space, they are placed on the perimeter for which they need other structural elements such as cables to reduce the spans. Beams, arches or trusses can also be used but they detrimentally affect the efficiency, as it has been mentioned above.

1,2 Only one mast and cables were used for the Georges Hermant swimming pool in Paris for a convertible roof. Trolley cables radiate over the swimming pool from the top of a lattice 16 m high mast standing outside the roof. It is guyed by trolley cables and additional cables. The membrane is suspended and when retracted, hangs at the top of the mast (R.Taillibert 1969 & Groupe Alto 2019, 50 year later)

3,4 The net of the aviary in the zoo at Munich-Hellabrunn has a very fine mesh width of 60 x 60 mm and spans a large, high interior of 4.600 m^2. It is supported by 10 masts, suspended on clamping plates and made of stainless steel wire 3,5 mm thick, calculated to withstand a maximum snow load of 35 kg/m^2. The breaking load of the net is 22 t/m and it was welded together from strips on the ground, raised on the masts and then arranged in its ultimate shape (Otto and Rasch, 2001).



Flying masts supported on a cable net push up the membrane.

They keep the covered space free of structural supports.

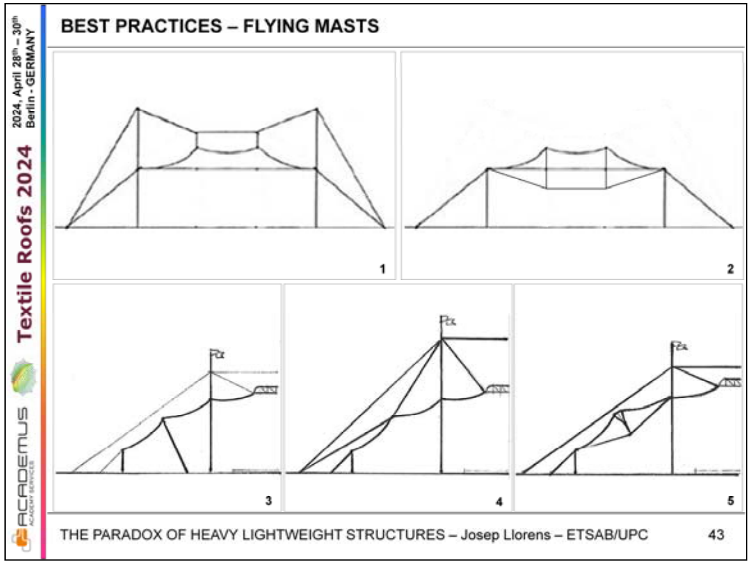
A softening plate or equivalent device on top of the flying mast enlarges the area of load distribution to prevent punching.

The bottom uses to be hinged with adjustability of the length of the mast.

1,2 Venezuela Pavilion Cafeteria flying mast.

3,4 The precursors of contemporary flying mats were Frei Otto and his team for the Munich Olympic Stadium, 1972. Flying masts appeared where the seats of the stands prevented the positioning of a mast directly on the ground and forced the high points to be suspended from cables.

5,6,7 A remarkable application of flying masts was the San Diego Convention Centre, 1989. Its 91,5 m span was solved with 5 bays of fabric panels stretched between ridge and valley cables and edge catenaries with two tent peaks each. The ridges consist of double cables spaced apart sufficiently to allow the suspension cables to penetrate through the roof (K.Ishii, 1999).



1,2 Flying masts reduce spans keeping the covered space free of structural supports.

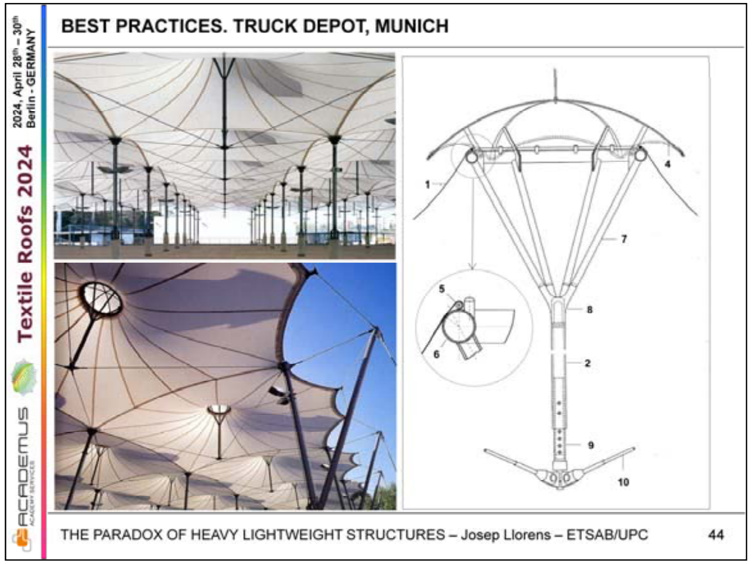
They also reduce considerably the height of the masts.

3 The traditional circus tent resorts to quarter poles

4 The "Cirque du Soleil" dispenses the quarter poles hanging the intermediate points.

This requires a significant increase in the height of the central masts.

5 Flying masts also eliminate the need for quarter poles without having to increase the height of the central masts.



Ackermann und Partner with sbp, 1999: "Truck depot. Office for Waste Management", Munich (replaced).

It is an outstanding example of proper design avoiding bending. It looked and was light. In addition to benefiting from the translucency of its membrane, it was also improved by the economy of its structural components and fittings. The design exploited the capabilities of the membrane. There was a balance between the size of the modules and the resistance of the fabric. The spans were chosen wide enough to let lorries pass through but without being too wide, in order to avoid or reduce the presence of secondary elements, such as cable nets or beams. Detailing was simple, coherent and homogeneous. There were few different types of fittings and sharpness was avoided by the utilization of rounded or tapered cast cable ends and plates.

They did not value it and replaced it after it collapsed.

Detail: **1** 1 mm PTFE-coated glass-fibre fabric membrane; tearing strength 130 kN/m. **2** CHS Ø 127x7,1 mm suspended column. **4** 40/90 mm steel flat. **5** Ø 21 mm stainless-steel cable. **6** CHS Ø 101,6x5 mm. **7** CHS Ø 60,3x7,1 mm. **8** Cast steel node. **9** Tensioning element: CHS Ø 108x7,1 mm. **10** Ø 22 mm steel tensioning cable with galfan coating (DETAIL 6/2000).

The cable dome developed by David Geiger consists of six main components:

1) The outer compression ring resists the pulling force of the radial ridge cables and first row of diagonal cables.
2) The central tension ring acts in tension resisting the pulling force of the radial ridge cables and the last row of diagonal cables.
3) Top-chord radial ridge cables pushed up by the posts.
4) Compression posts between hoops and radial ridge cables, pushed up by the diagonal cables.
5) Circular (in plan) tension hoops joining the bases of the struts.
6) Diagonal cables pushing up the posts and the central tension ring.

In addition, valley cables tension the membrane and provide doubled curvature.

1,**2** Geiger Engineers, 1990: Tropicana Field (former Suncoast Dome), St.Petersburg.

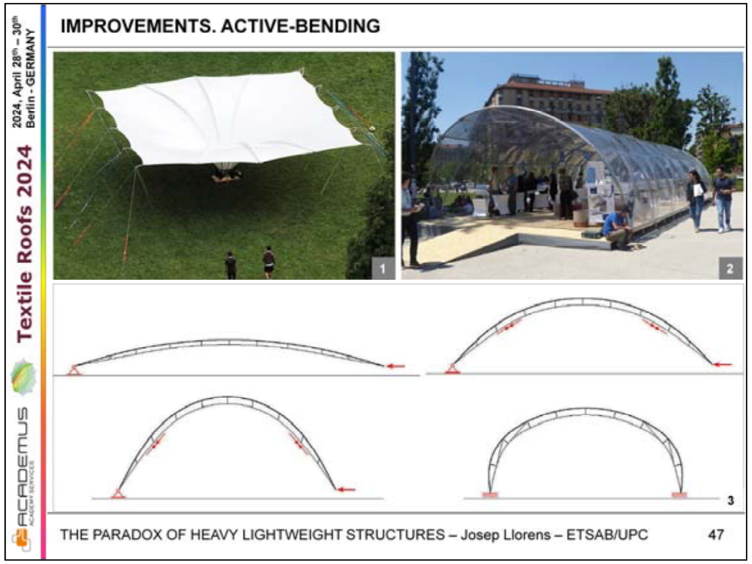
3,**4** Guri & Casajuana Architects with Arqinetgral (J.Llorens, Ch.García-diego & H.Pöppinghaus), 2004: Bifid Tension Dome, Forum of Cultures, Barcelona.

Tensairity combines the lightness and simplicity of an airbeam with the load bearing capacity of a truss structure. The first developed Tensairity structure has the shape of a cylindrical beam, where the inflated hull is reinforced with a strut and two cables. The cables are spiralled around the hull and connected at both ends with the strut. The air-pressure in the hull pretensions the cables and stabilizes the strut against buckling enabling an optimal use of the materials in the beam. Tensairity structures combine minimal weight with a very high load bearing capacity. They do have a compact transport volume and can be fast and easy deployed (*https://www.tensairitysolutions.com*/)

1, **2** G.Stowell, Architect with form TL and Canobbio, 2010: The sports canopy for the National Tennis Centre, London is a wide-span membrane which consists of five Tensairity beams with membrane panels in between.

3 Maco Technology, 2014: The Ducati hospitality tent is also based on Tensairity beams which span 12 m.

4 S. Dubuisson, Architect with Tentech, 2014: Inno-wave-tion exhibition pavilion, a combination of a tensile compression ring with Tensairity.

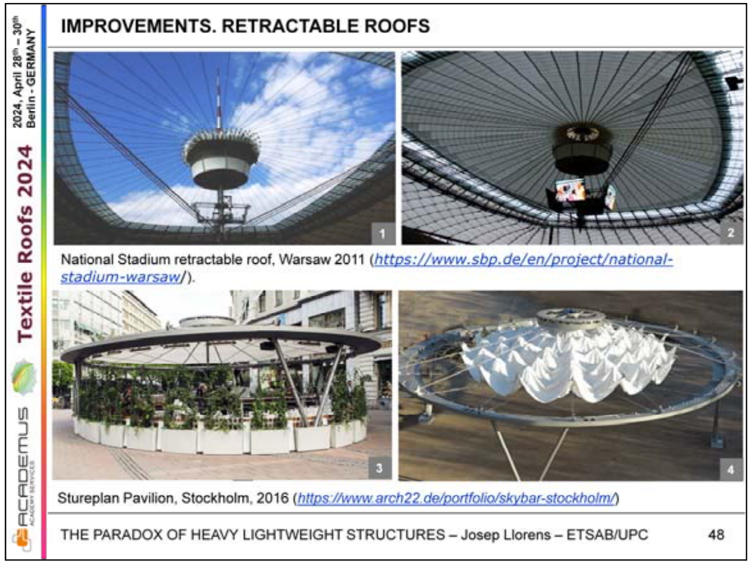


Active bending can be defined as a form-finding process that derives from the elastic deformation of a rod or plate structure.

It is a process that creates curved geometry out of planar, straight members or surfaces

1 Institute of Building Structures and Structural Design, 2011: an innovative membrane structure for a schoolyard roofing comprises 7.5 m long, elastically-bent fiberglass rods (in pockets) for the pre-stressing of the membrane.

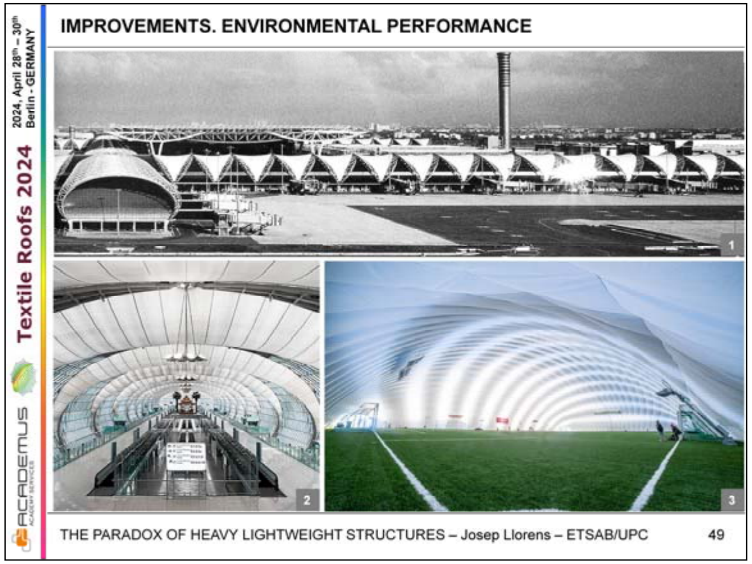
2, **3** C.Mazzola & A.Zanelli with Form TL and Canobbio, 2019: "TemporActive Pavilion", an ultra-lightweight temporary structure consisting of bending active GFRP arches, a restraining system made of stainless steel cables, and an ETFE translucent membrane envelope.



1, **2** gmp Architekten with sbp, 2011: The National Stadium of Warsaw features a complex and elegant cable roof structure that can withstand all weather conditions. The fixed part of the roof is supported by a ring cable which maintains its stability by means of supports, a single compression ring and the anchoring of the diagonal pillars in the foundations. The construction is complemented by a central needle, floating in the centre above the pitch, and 60 radial spoke cables, which act as load-bearing members for the operable inner roof that folds up towards the centre.

3, **4** A part from large sporting venues, retractable membrane roofs are an effective solution for urban spaces (Kugel, 2023), such as the Stureplan Pavilion in Stockholm. It is a convertible roof encircled by a compression ring supported on 4 V-shaped columns. A central flying mast is carried by 16 pre-stressed steel cables and the membrane is deployed and retracted sliding on them. Because the pavilion is only used during the summer, a simple mounting and dismounting process takes only one day. Fixed foundations are not needed because they are replaced by ballasted weights. This allows for setting up in different locations.

Nikolai Kugel claims the suitability of retractable roofs for the climate control of the urban space where they can be retracted at night to let the pavement irradiate. (*https://www.scipedia.com/public/Kugel_2023a*)



Remarkable progress is taking place introducing translucent insulating materials such as aerogels, printing capabilities which increase solar absorption and reduce solar transmission, low emissivity coatings, and multi-layer, sandwiched and composite membranes, including inflated cushions, analogous to double glazing, to improve thermal, acoustic and energy performances.

1,**2** The three-layered roof of the Suvarnabhumi Airport, Bangkok 2006, is an example: three layers maximize the comfort. From top (outside) to bottom: PTFE-coated fibre glass for weather protection, transparent polycarbonate sheet for noise protection attached to a steel cable mesh and inner low-e coated open wave acoustic membrane.

3 Canobbio Textile Engineering, 2016: Air hall for the Helsingin Jalgapalloklub football team field, Helsinki. It is double-layered with two membranes completely detached to avoid thermal bridges along the perimeter and condensation, achieving energy savings of 49% compared with single membrane solutions at the same climatic conditions. Another peculiarity of this project was the use of different fabric bands with different translucency percentages so as to allow the light to filter and going to save further on the lighting system.
https://www.canobbio.com/en/portfolio/energy-p-p7-helsingin-jalkapalloklubi-2/

In addition, new environmentally friendly applications such as environment protection and energy harvesting have emerged.

1,**2**,**3** Ackermann und Partner with Taiyo Europe GmbH, 2011: “Truck depot. Office for Waste Management”, Munich.

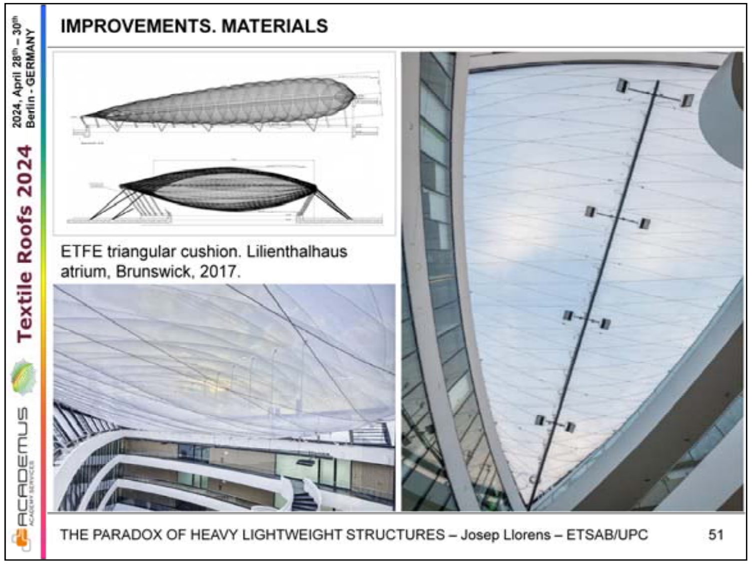
The canopy of the waste-management-vehicle maintenance facility was replaced by steel columns carrying three-chord trussed girders, transverse steel arches with tension rods, inverted flying pyramids and ETFE 11 x 3,3 m cushions with solar cells embedded in the middle layer.

Part of the energy is fed into the public grid, the rest operates three ventilation units that provide the air pressure required to keep the cushions inflated.

The ductwork and drainage pipes are concealed within the trussed girders.

https://www.ackermannarchitekten.com/entry/ueberdachung-des-carports-des-abfallwirtschaftsamts-muenchen/

4 Synthesis Design + Architecture with Buro Happold, 2013: Rapidly deployable portable charging station for a hybrid car.

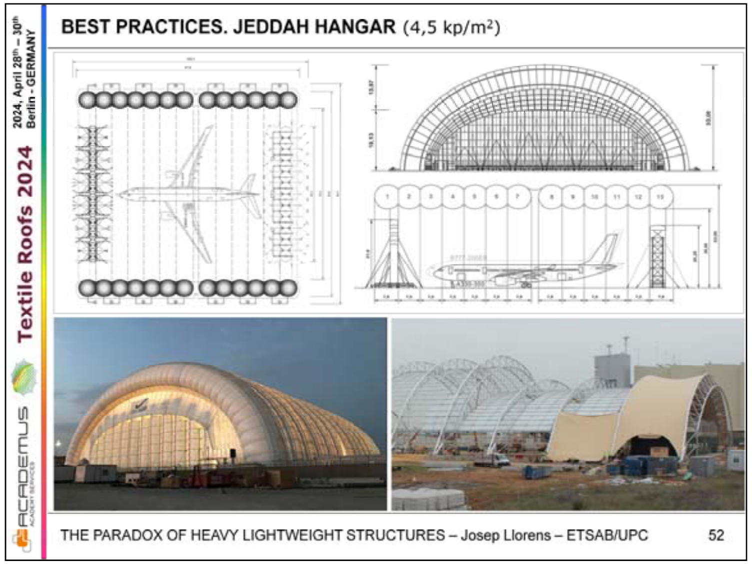


The materials improve constantly extending their longevity and incorporating new features including photovoltaic cells, sensors, LEDs, acoustic absorption capability, transparency or translucency.

The use of ETFE foil has been extended and consolidated because it compares favourably with glass and steel sheets, improving safety and attenuating environmental impact.

Its lightness reduces the structural load, and its flexibility increases the allowable deformability, so the supporting structure can be considerably reduced in size.

Architekten Rüdiger with form TL, 2017: a single ETFE triangular cushion for the atrium of the new Lilienthalhaus in Brunswick. In the initial design a glass roof was intended but its primary steel structure would have been very heavy and would have required a sprinkler system. That is why a lighter and cheaper alternative was chosen. The installation has been easier and faster in comparison to the initially planned glass roof.



BuildAir 2019: Hangar H75 – SAEI, Jeddah. It is the largest inflatable hangar of the world to shelter and maintain aircrafts. In addition to size (97,9 x 90 x 33 m), other outstanding values are:

- structural efficiency: 40.000 kp / 8.811 m^2 = 4,5 kp/m^2
- storage volume of parts (700 m^3) = 3 ‰ of the built volume (228.365 m^3)
- total time (including design, manufacture, transport and installation): 6 months.

These values are *much lower* than those of a conventional hangar (bottom right).

Description:

The main body is based in a succession of 13 Ø 7,5 m inflated tubes at a low pressure of 20 mbar that could be increased to 25 mbar in case of peak wind loads. They are reinforced by belts and anchored to the base slab. The hangar is complemented by two inflated vertical enclosures at both ends. All the set-up before inflation took a month and the inflation of the main body has been performed in one day (TensiNews 40, April 2021).

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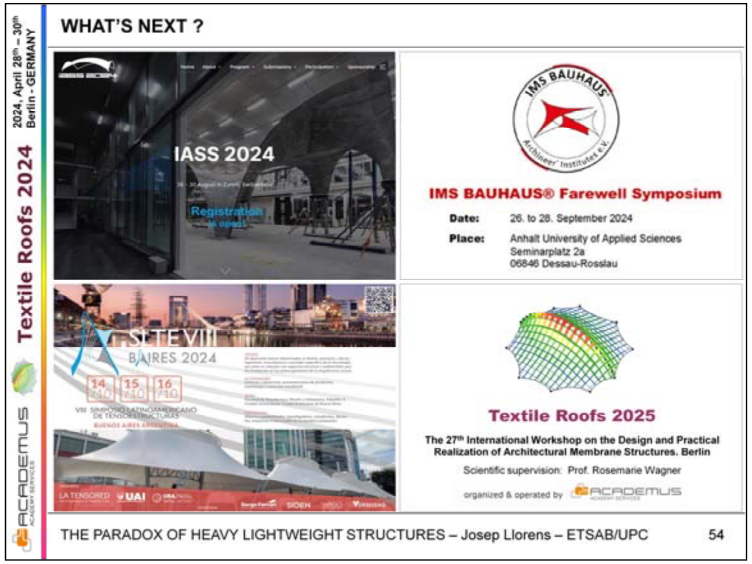
6 CONCLUSIONS

- Although design tools have progressed, some membrane structures are still designed without taking advantage of their structural characteristics.
- The result is usually a disproportionate steel structure that is cladded to generate the (arbitrary) projected shape.
- In order to achieve an appropriate result, it is (highly) recommended to respect the principles of only tension, funicularity, curvature and pre-stressing, as well as to take advantage of the available design methods to properly determine the form (in equilibrium), the loads and the hybrid behaviour of the structure.
- Bending avoided and compression optimized.
- Several improvements have been introduced that can be investigated further.
- Best practices are a good source.



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