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Retractable membrane roofs

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Abstract

Since membrane structures are lightweight and flexible, they are well suited to being used for convertable roof systems. This paper gives a summary of the existing techniques. They are illustrated with projects from the seventies and recent designs.
In these designs the retracted membrane hangs freely when it is pushed aside. There could be another approach: some computer simulations show the possibility of restressing the membrane roof into a more compact folded position.

1. Introduction

Membrane roofs need a double curvature and a pre-tension in both principal directions to ensure a stable behaviour. Due to this double curvature, folding and sliding patterns cannot be chosen arbitrarily.
Convertible membrane structures can be classified as follows [1]:
If the supporting structure remains stationary and only the membrane moves, the movement can be

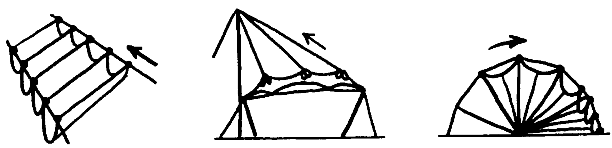

Figure 1. Parallel sliding Central sliding Circular sliding

If parts of the supporting structure move, these can be

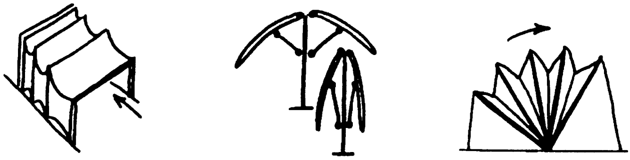

Figure 2. Sliding Central folding Rotating

It should be clear that unfolding always requires that the appropriate pre-tension is installed both in the sliding and in the transverse direction of the roof.
A third approach which stresses the membrane into a new shape will be illustrated.

2. Membrane movement

2.1 Parallel sliding:

2.1.1 The inner court of the Hohenems Castle:

For the annual "Schubertiade", which takes place in the inner court of the Hohenems Castle, the organisers installed a retractable roof in 1977.
The roof consists of a white translucent inner membrane, plus a loosely tensioned outer membrane to reduce the sound of the falling rain. The membrane is curved in the two main directions (a slightly convex arc moves along a concave arc).

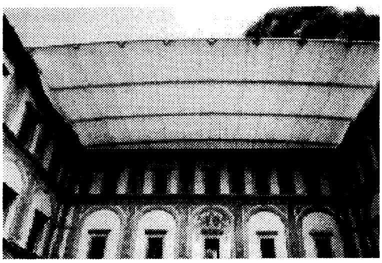

Figure 3. Hohenems Castle (Hoechst).

2.1.2 Open-air theatre in Tecklenburg:

The sliding roof of the open-air theatre in Tecklenburg is a much more recent structure. It was built in 1993 by IPL and Radolfzell.
The horizontally sliding roof is supported by a construction of six columns on each side. Five special rails are hung on these columns by means of a cable net

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construction. Along the rails six movable beams and six membrane cushions (each with a surface area of 200m^2) are fixed. When the roof is closed, the cushions are automatically filled with air: in this way the covering is stabilised against the wind. If the roof is not needed, the textile covering disappears invisibly in a "parking garage".

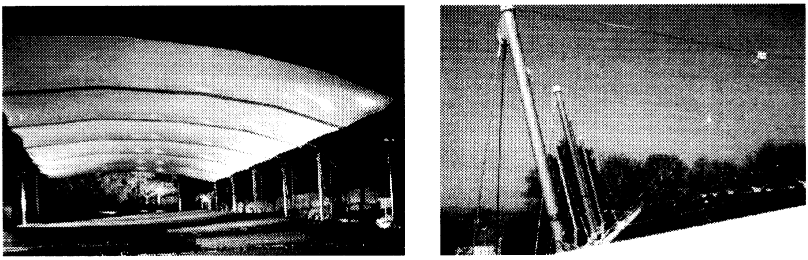

Figure 4. Open-air theatre in Tecklenburg (Carl Nolte).

2.1.3 Project by J. Collins and A.P. Goodfellow [2]:

At first, the membrane is attached by a number of wheels to the linear guiding tracks. Next, vertical struts are fixed to the membrane at their tops, while their lower points are supported by a diagonal cable net.
When the roof opens, these cables are straightened, the struts are pushed up and the membrane is tensioned in its doubly curved final position.

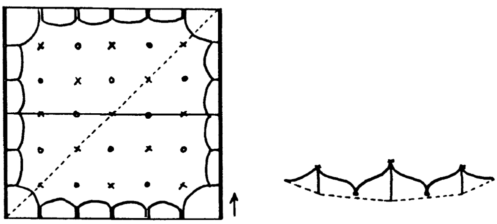

Figure 5. Tensegrity roof.

2.2 Central sliding:

Central sliding is a frequently used technique to retract undevelopable membrane roofs.

2.2.1 The skating-rink in Conflans, Paris [3]:

Frei Otto and J. Blasco designed a permanent steel frame structure, which consists of tubular lattice arches placed in the form of a scallop-shell. The structure spans an area of 85m x 46m, with a free height in the middle of 13m. The height of the lattice girders is 1m, and they are pin supported at their endpoints.

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The lower chords of the lattice arches are shaped as tracks for the self-propelled tractors of the membrane: it can be furled together in the central point of the radially placed arches.

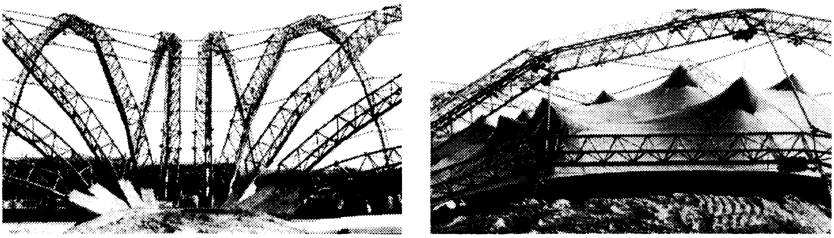

Figure 6. The skating-rink in Conflans, Paris.

2.2.2 The open-air theatre in Wiltz [4]:

This roof, designed by B. Rasch and J. Bradatsch, consists of a membrane covering fixed to a fan of cables. Opposite the stage the cables converge to a row of tubular steel posts to where, in fine weather, the membrane can be retracted to a closed position. Fully extended the roof covers an area of 1200m^2.

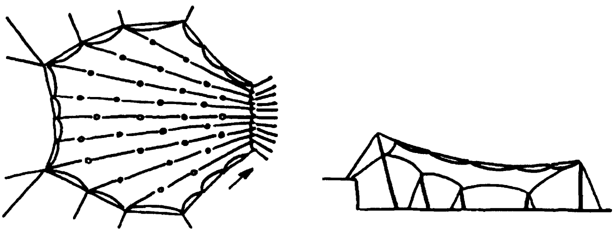

Figure 7. The open-air theatre in Wiltz.

2.2.3 The open-air theatre at Bad Hersfeld [5]:

One of the best known examples of retractable textile roofs is the open-air theatre at the ruined collegiate church of Bad Hersfeld, designed in 1968 by Frei Otto.

When the summer weather is fine, the membrane furls round an external mast, and when it rains, it can be unfurled in a few minutes. The membrane hangs on a single 32m high steel mast. Two cables guy the mast from behind, and in front fourteen trolley cables fan out over the nave of the church.

Each season the roof skin and tractors are erected, dismantled and serviced with the assistance of a crane jib permanently installed on the main mast head. The load-bearing support structure of masts, guy and tractor cables stands throughout the year.

The membrane has been renovated by Stromeyer Ingenieurbau in 1993.

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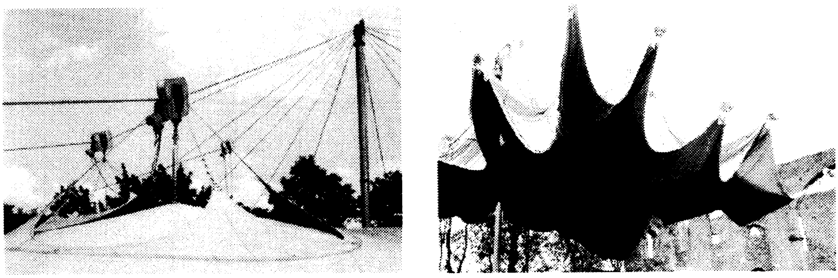

Figure 8. Open-air theatre at Bad Hersfeld (Stromeyer).

2.3 Circular sliding:

2.3.1 Project by G. Fecknall [2]:

This next roof is supported by a system of cable longitudinal trusses distributed radially in the transverse direction, on top of the two main arches.
Although the overall shape is synclastic, the membrane can be tensioned in the two principal directions. To open the roof, the membrane slides in the transverse direction.

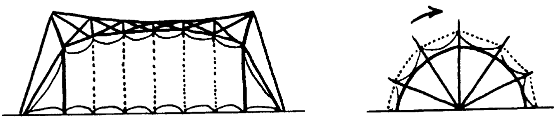

Figure 9. Project by G. Fecknall.

3. Movement of the supporting structure

3.1 Sliding:

Both circular and parallel sliding have been applied to lightweight membrane roofs as well as to rigid structures, even for very large spans.

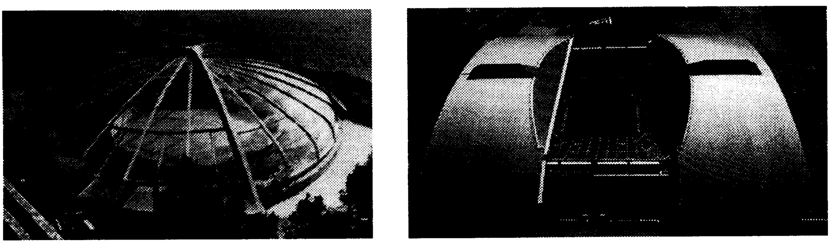

Figure 10. The Adriatic Hotel and the Ariake Coloseum.

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The dome of the swimming pool of the Adriatic Hotel in Primosten (Split) [6] has a diameter of 26.6m. Two of the 120° segments can rotate to a position which is under the fixed segment.
The Ariake Coloseum (Tokyo) has an area of 144m x 126m. The two halves of the roof can slide to an open position.

3.2 Central folding:

The best known example of this construction type is the umbrella.

3.2.1 The umbrellas at the Bundesgartenschau [7]:

For most of its long history the umbrella has been carried as a portable shelter from sun and rain. Frei Otto transformed it to an additive element of architectural enclosure.
As the central mast is elevated the tips of the cantilevered arms arc upwards, coming to rest in an upright position against the fully extended mast. The outer member of the cantilevered arm retreats along the inner member during folding, and so decreases the height needed for folding the membrane.

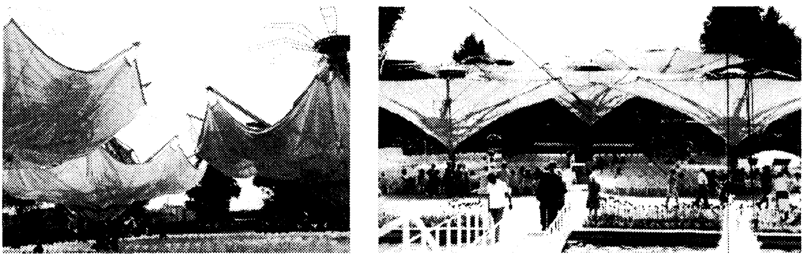

Figure 11. The umbrellas at the Bundesgartenschau.

3.2.2 The umbrellas for the Prophet's Holy Mosque in Madinah [8]:

B. Rasch created the amazing shading system for the Extension for the Prophet's Holy Mosque in Madinah.

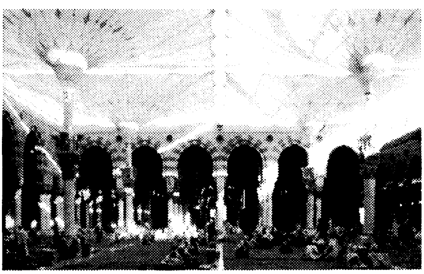

Figure 12. The umbrellas for the Prophet's Holy Mosque in Madinah.

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Within the two courtyards stand 12 minaret-shaped columns, which are computer controlled shade umbrella's. They have a size of 17m x 18m, and a height of 14m. The woven PTFE fabric Tenara, created specifically for this project, was designed to withstand continual folding and unfolding.

3.3 Rotating:

3.3.1 The swimming pool at Unterlüss [9]:

Three steel arches span the swimming pool at Unterlüss. The central arch has a span of 26.35m and a rise at the centre of 13.6m.
Six pulleys run along each arch, between which supporting wires span longitudinally. At the back of the structure the membrane is firmly anchored to a sloping ramp; on the movable side it is bound to a tube which is curved to follow the shape of the structure.
The envelope consists of two layers of fabric, with an intermediate air space of 3cm. When the envelope is closed it is stabilised with a positive inner pressure.
To open the roof envelope the movable tube is moved up-and-over towards the the back to lie on the sloping ramp.
The roof was built by L. Stromeyer & Co, in 1972.

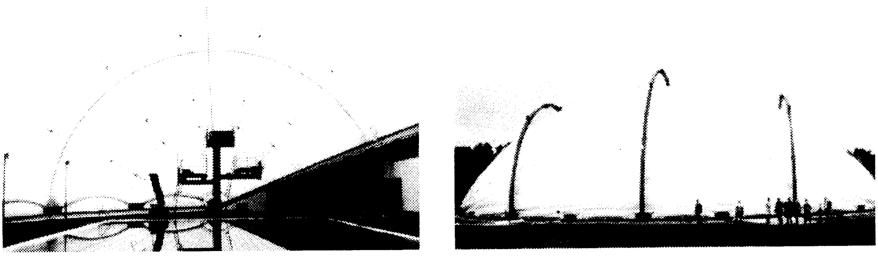

Figure 13. Swimmimg pool at Unterlüss.

3.3.2 Project by A. Ash, R.J. Frazer, A.G. Joyce [2]:

The membrane roof is tensioned to form several waves between the masts placed radially at both sides of the shelter: each element is connected to four mast tops and anchored outside at the extremities of the structure.
The whole envelope can be folded towards the back, by rotating the masts around their base point.

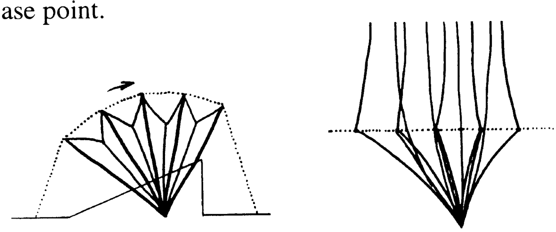

Figure 14. Project by A. Ash, R.J. Frazer, A.G. Joyce.

4. Stressing the membrane into a folded shape.

In the previous examples the retraction of the membrane envelope implies a complete release of the pre-tension.
Two simulations illustrate the possibility of restressing the membrane into a new compact shape.
All the calculations have been performed with the EASY software from Technet, based on the Force Density Method [10]. The membrane roof is modelled by a bi-directional net of pin-connected straight elements. No account is taken of any shear resistance of the coated fabric.

4.1 Circular folding:

Circular folding can easily be applied to circular wave forms.
The equilibrium shape of the following octagonal membrane roof (the radius of the circumscribed circle is 10m) has been calculated with a uniform pre-stress of about 1kN.

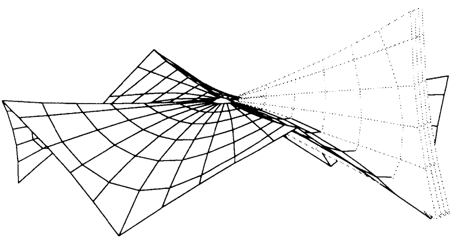

Figure 15. Folded and unfolded shape.

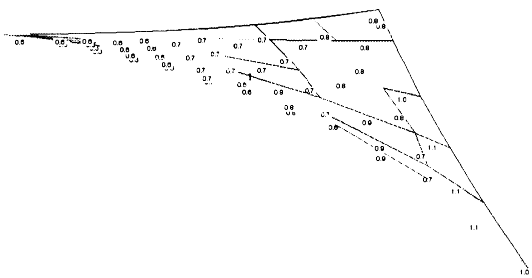

Figure 16. Front view of the unfolded shape. Axial forces [kN].

In a second step, one quarter of this octagonal surface has been fixed at 2 points (the central point and one low point of the octagon, moved outside to stretch the radial line), while the 2 other corner points have been stretched upward.

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The result is a flat almost triangular shape. The tension in the radial direction is about 4kN, while the forces in the initial hoop direction are almost zero.

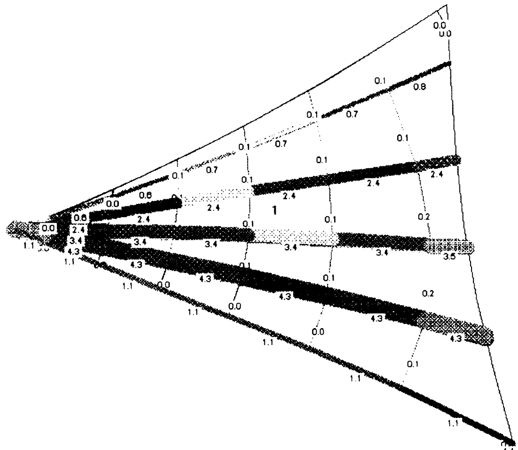

Figure 17. Front view of the folded shape. Axial forces [kN].

4.2 Rotation.

If there is a straight line in the surface, rotation about this as an axis can take place without any change in the membrane stresses. If there is an approximately straight line, this could also be used as a rotation axis, but with consequences for the stresses.

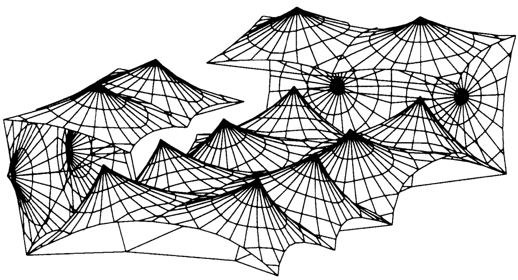

Figure 18. Initial and intermediate state.

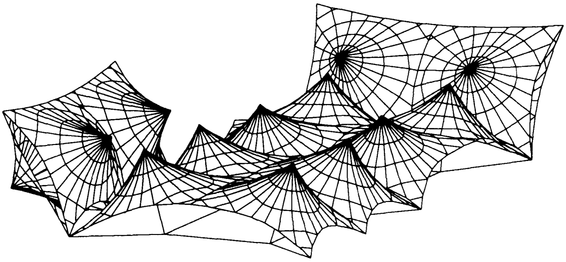

Figure 19. Initial and folded state.

The basic module (one top) of the membrane roof spans an area of 6m x 6m. Four modules form a structural entity.
In this simulation one half of the roof rotates about one of the axes of symmetry. The axis chosen the one along which the surface has a low curvature. The two nodes on the rotation axis have been moved outward to stretch the fabric in this direction.
A uniform force density of 1kN/m was set for the formfinding. In the folded shape the stresses have been distributed in a different pattern:

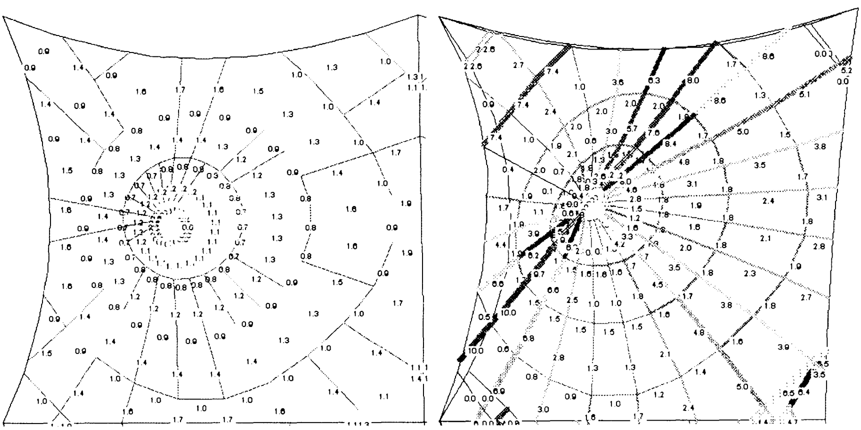

Figure 20. Forces in the initial and folded shape [kN].

5. Final remarks.

The simulations show how a membrane roof can be calculated for different boundary conditions, taking different tensioned forms.
It is clear that any arbitrary form is not automatically transformable into any other arbitrary form, that the allowed deformations vary with the used coated fabric, and that the resulting stress patterns need to be verified for the appropriate load cases.

The advantage of the pre-tensioned folded state is that the membrane can remain stable during the movement from its open to its closed position, and that in this way damage due to improper furling could be prevented.

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