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Transformations of tensioned membrane elements

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Abstract

The paper shows some existing retractable membrane structures. In most cases the opening of the roof means that the membrane hangs freely and that all pre-tension is released. It is the aim to analyse the possibility to open a roof by a combination of motion and transformation: membrane units are tensioned into (slightly) different forms.

First a structure, composed of identical wave formed membrane units, identical bar elements and cables, is proposed. The membrane elements are placed in a rectangular pattern like roofing tiles. With a *sliding* motion units can move one under the other. The form of the units remains almost the same.

Next a scissors system with wave formed membrane units is considered. The scissors are *folded* to open the roof. The membrane units have to change their form to fit in the folded state. Within certain geometrical limits the membrane units remain tensioned in the folded state.

All equilibrium calculations are performed with the EASY-software [1, 2].

1 Introduction

Convertible structures can open or close for different weather conditions. Since fabrics are flexible and lightweight they can easily be used for adaptable sunshades or roofs.

In the examples shown below the membrane hangs loose when the canopies close.

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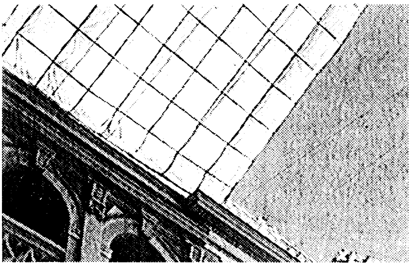

Fig. 1. Parallel sliding sunshade.

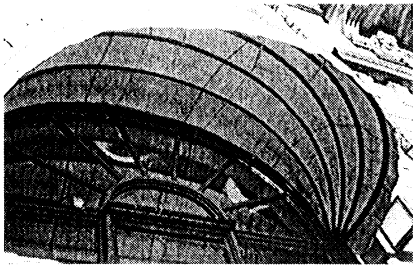

Fig. 2. Revolving sunshade.

2 Models of adaptable membrane structures

Within the following configuration it could be possible to rotate the units one under the other [3, 4].

Fig. 3. Units do not overlap.

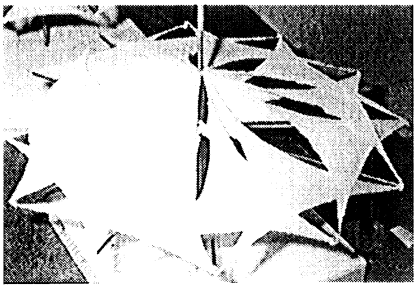

Fig. 4. Units do already overlap.

The membrane shown in Fig. 5 is tensioned to form several waves between the masts placed radial at both sides of the shelter: it is connected to two times five 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. The model is made of a stretchable material, which remains tensioned in the different configurations [5].

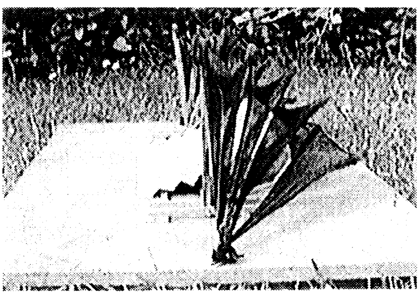

Fig. 5. Unfolded retractable roof.

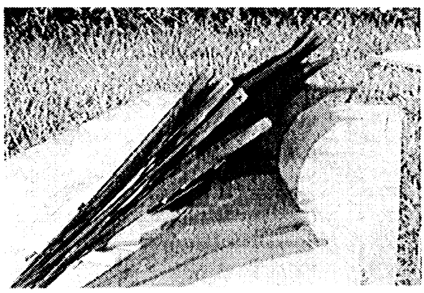

Fig. 6. Retracted position.

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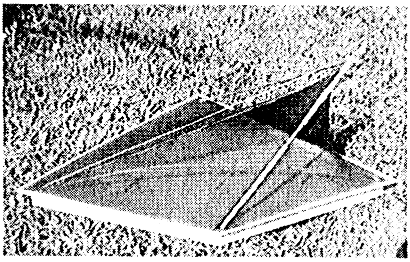
Also the next model can have different shapes. The "A-frame" can rotate about its two base points. Altering the slope of the "A-frame" and hence the connection point with the roof changes the position of the high point. Tension is introduced by the springs in the "A-frame" members. A material to build such an adaptable roof does not exist at this moment [6].



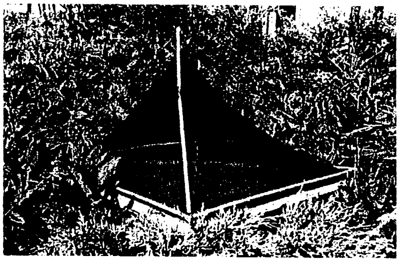
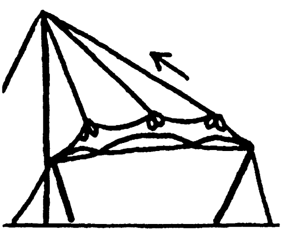


Fig. 7. Side position of the high point. Fig. 8. Central high point.

3 Retractable roofs

The swimming pool George Hermant in Paris, designed by Taillibert and Du Chateau, was built in 1967. The membrane covers an area of 1800 m^2, 30 internal and boundary points are attached to a system of cables and by means of these cables the membrane can be retracted up to the mast. This happens during summer. When the membrane roof is retracted the coated fabric hangs with folds and wrinkles [7].



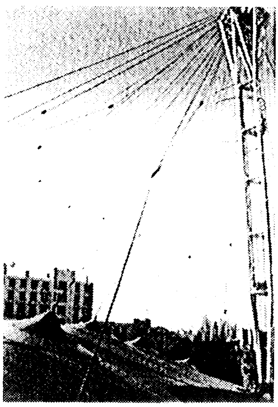


Fig. 9. Sliding scheme. Fig. 10, Fig. 11. George Hermant swimming pool.

The roof over the open-air theatre in Wiltz designed by B. Rasch and J. Bradatsch and built in 1991 also consists of a membrane covering fixed to a fan of cables. The membrane can be retracted where the cables converge. When the roof is open, the coated fabric hangs loosely under a second roof [8].

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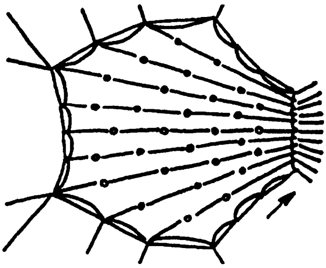

Fig. 12. Scheme of central sliding.

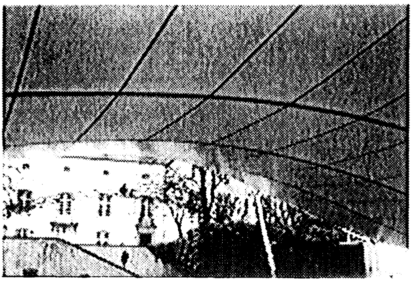

Fig. 13. The open-air theatre in Wiltz

The main objective of this study is to design an adaptable roof, where the membrane units remain tensioned in different configurations [9, 10, 11].

4 Sliding units

The system consists of membrane elements, identical bar elements and cables. One membrane unit covers an area of 1.8mx4.8m. The compression bars within the system have a length of 1.9m.

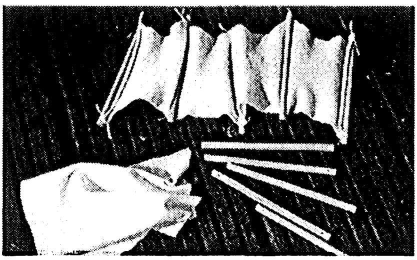

Fig. 14. Membrane and bar elements.

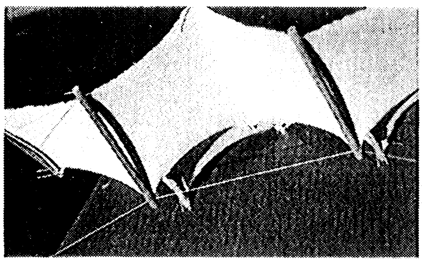

Fig. 15. Tensioning cables.

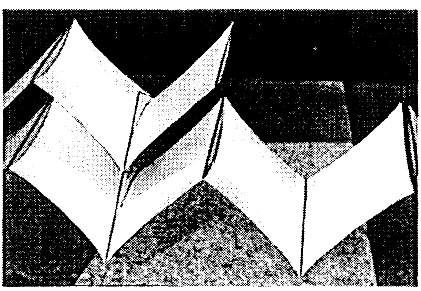

Fig. 16. Interconnecting V-shaped elements.

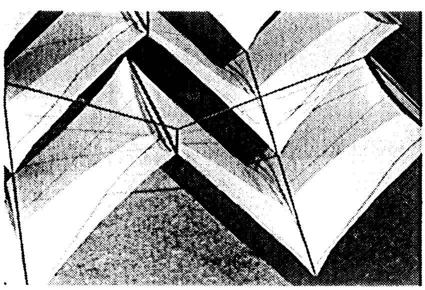

Fig. 17. Tensioning cables

The membrane unit has the form of a wave. It is reinforced with three internal cables, reducing the sag where the interconnecting cables are located. The opposite corners are connected by bar elements to take the pre-tension in the

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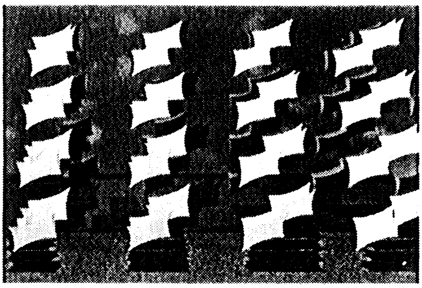
transverse direction. V-shaped cables connect the wave formed membranes together.

To enlarge the composition a new (in Fig. 16: higher) membrane unit is connected to the configuration by *interconnecting cables*. The lowest node of the new unit is connected to the two nodes along the valley cable of the lower unit with a reversed V shaped cable. The highest points in the existing configuration are connected to the new unit by means of V shaped cables (like in the middle of Fig. 16). *Tensioning cables* are added to hold the (free) boundary nodes of the membrane unit.

5 Possible relative positions

The following drawings illustrate that two membrane units can be connected in different ways. The displacements are based on the fact that the form of the units remains the same and that the total length of the interconnecting cable is considered to be constant. This means that one unit *slides* over the other.



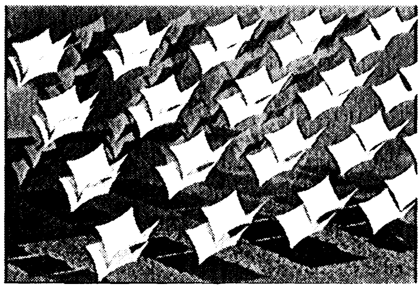


Fig. 18, Fig. 19. Movement of a first membrane unit relative to the second unit

6 Different configurations

In a first run all boundary nodes of the membrane units are fixed, in such a way that all units are identical. Secondly the connecting nodes become free, the lengths are fixed and the equilibrium form is calculated for different positions of the anchoring points.

First a compact lay out is implemented by specifying the appropriate position of the fixed boundary points (taken from Fig. 18).

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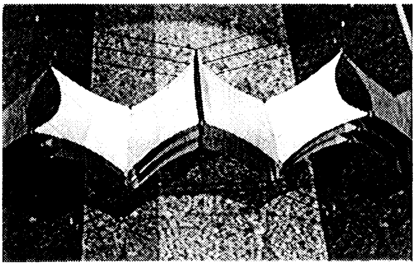
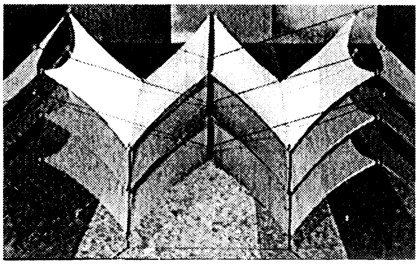

Fig. 20. Compact lay out, seen from above. Fig. 21. Front view

Next a deployed lay out is analysed by changing the position of the fixed boundary points.

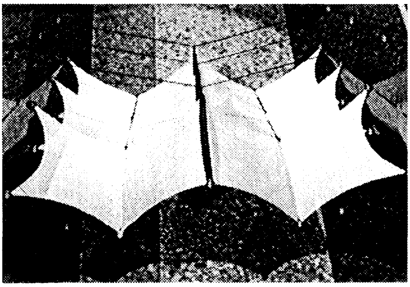
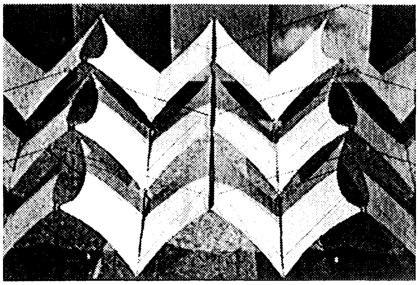

Fig. 22. Deployed lay out, seen from above. Fig. 23. Front view

The stresses obtained in both cases (without external load) are of the same order of magnitude.

7 The sliding path

If the upper unit remains in position, the second one can move according to a curved path drawn in the middle of Fig. 26, the lowest unit follows the second one according to the curved path drawn at the bottom of Fig. 26.

It is feasible to slide the membrane units into a different pre-tensioned state. To allow for the movement the pretension is temporarily released.

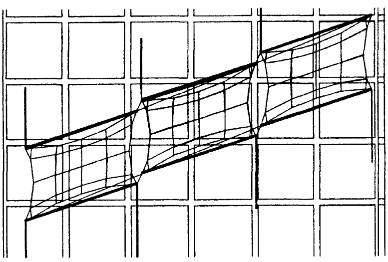
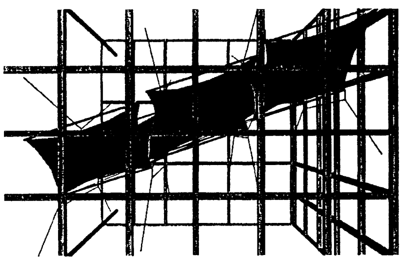

Fig. 24, Fig. 25. The deployed lay out.

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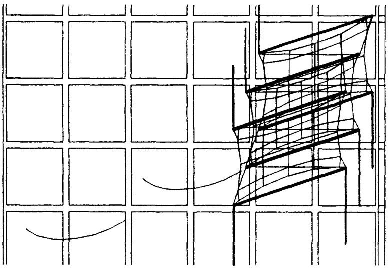
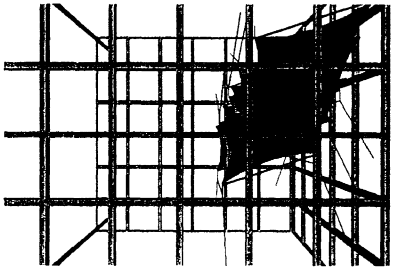

Fig. 26, Fig. 27. The sliding movement and the compact lay out.

8 Folding units

A different supporting structure of scissors is considered to analyse a retractable roof with a foldable membrane [12]. It is checked that in the different configurations an acceptable level of pre-tension can be maintained.

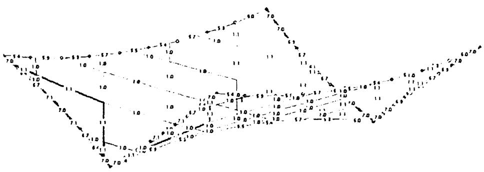

Fig. 28. Unfolded state.

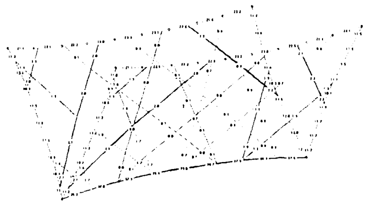

Fig. 29. Folded state of the membrane unit.

Three frames of three scissors are placed in parallel planes. In the numerical model they are represented by a system of pin connected bar elements with a common rotation axis. The size of the membrane unit is 5.5m x 5.5m.

9 Possible lay outs

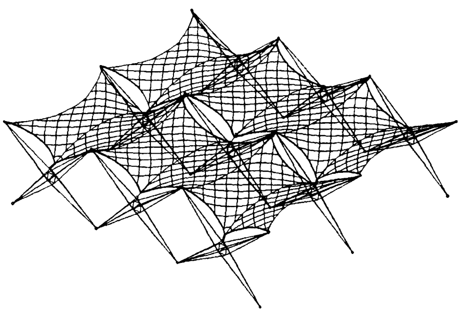

Fig. 30. Unfolded state.

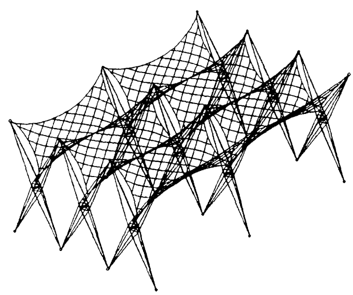

Fig. 31. Folded state with tensioned membranes.

The possible lay outs are controlled by the degree of freedom in the scissors system.

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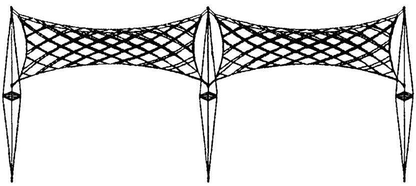
10 Different configurations

The form finding is performed when the scissors are in an (intermediate) open position (I). The internal net (representing the coated fabric) has been oriented at 45°. Next the scissors are placed in a more open position (II) and the previously defined membrane units are tensioned into a *new* equilibrium form by means of the cable elements connecting the corner points of the membrane to the end nodes of the scissors. Finally the scissors are placed in a more closed position (III, Fig. 34).



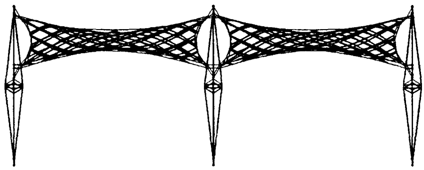


Fig. 32. Side view of the equilibrium form (I). Fig. 33. More open scissors (II).

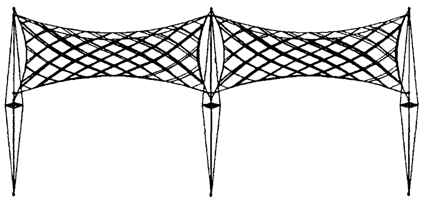
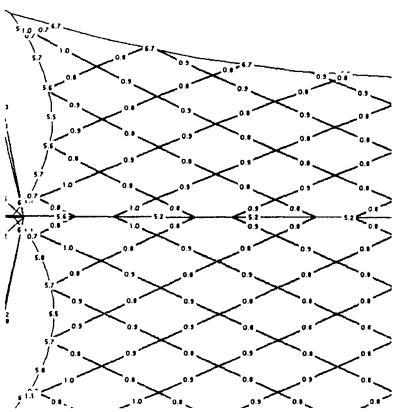


Fig. 34. Side view when the scissors are closed (III).



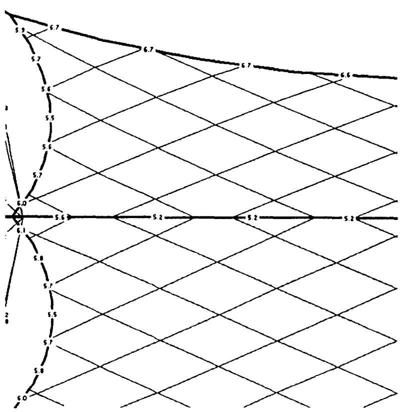


Fig. 35, Fig. 36. Axial forces [in kN] in the membrane and in the cables (I).

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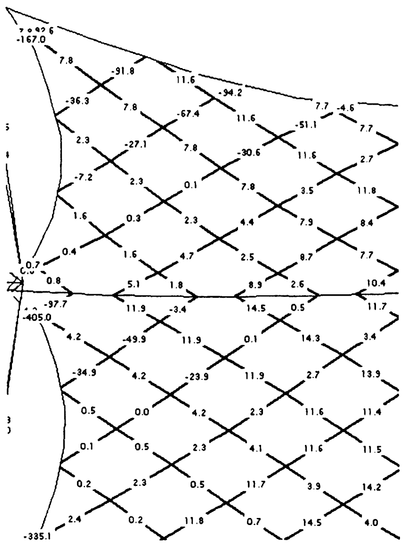


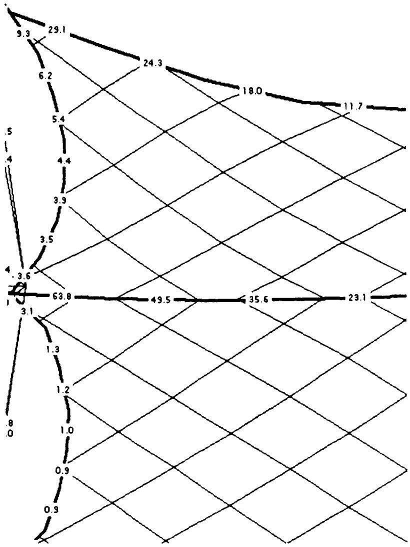
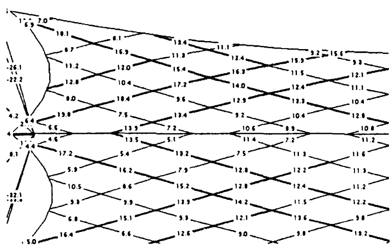


Fig. 37, Fig. 38. Axial forces [in kN] in the membrane and in the cables (II).



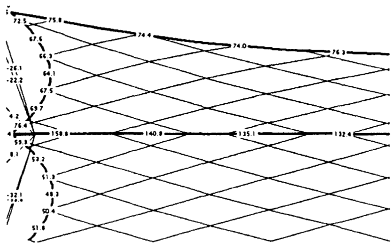


Fig. 39, Fig. 40. Axial forces [in kN] in the membrane and in the cables (III).

The axial forces in the folded state are much higher. It can be observed from the front view (Fig. 41) that the shape of the membrane changes and the distances between the corner points of the membrane and the end points of the scissors vary. Different lay outs require different lengths for the connection elements. The obtained levels of tension strongly depend upon the changes in length.

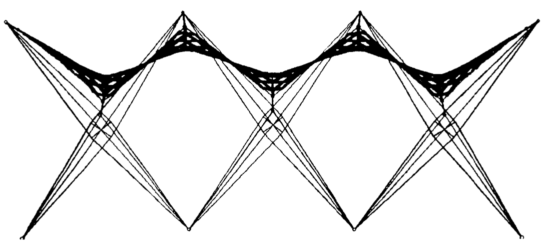


Fig. 41. Unfolded state: front view.

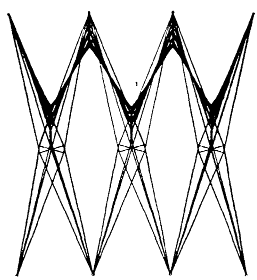


Fig. 42. Folded state

11 Conclusion

The study considers retractable membrane roofs made from identical units. The objective was to verify the possibility to tension the same membrane units into different lay outs in such a way that they almost never wrinkle or carelessly fold when the roof is retracted.

Two cases were considered: the *sliding* of units in a cable system and the *folding* of units in a scissors system. When the geometric restrictions are taken into account, namely if the curvature only changes slightly from one configuration to another, the numerical results do indicate that transformations from a pre-tensioned state into a different pre-tensioned state are possible.

The influence of the varying boundary conditions for a unit in a large sliding system and of the variations in the connection elements in a folding system will be the subject for further analysis.

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