Tensile Membrane Structures

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Summary **The first part of this paper provides some basic information on current textile material used in the manufacture of membranes, together with some detailing, in special the different systems of joining. The second part describes some of the most recent membranes designed by the author, giving special attention to the most innovatory aspects.**

1. INTRODUCTION

According to their definition, membrane structures carry loads by membrane forces only, with no or only insignificant bending. If tensile *and* compressive membrane forces are permitted, we speak of shells. If the compressive forces are eliminated, we speak of tensile membrane structures. Their aim is to actually realize the surface itself with a material which is able to carry tensile forces only, in order to achieve extreme lightness or even translucence.

In order to eliminate the compressive forces in the membrane structure, they are to be pretensioned or prestressed which means that tensile stresses are to be built up in the surface to the extent, that even after superimposing the outer loads (dead load, wind, snow, etc.) the structure remains stable. Fig. 1. If we exclude a preloading of the structure with mass or weight as done in case of hanging roofs, there remain two basic methods to apply the necessary prestress: mechanical prestress of the surface applied from its periphery and pneumatic pressure, the first leading to surfaces with negative Gaussian curvature or saddle shapes the second to positive Gaussian curvature or dome shapes. Of course tensile forces can only be reached in the surface or membrane itself, the supporting structures for equilibrium necessarily contain compressed membranes as well, masts, compression rings, etc.

From that it follows that the art of designing such tensile membrane structures consists in finding for each case the reasonable compromise between the temptation of making free use of the shapes tensile membranes permit and the fact that these free shapes have to be paid for with costly supports. Optimal is the self-balanced structure, e.g. a pneumatic cushion surrounded by a ring acting in pure compression. Another principle problem of these structures is that their curved surfaces usually do not comply with the functional space requirements thus leaving a volume which is of no use but costs heating/cooling and maintenance. This again ask for self-control when conceiving the overall shape.

With respect to the structural design itself one cannot but emphasize the interrelation between the type of a membrane structure, its manufacture and its geometry, the latter being responsible for its load bearing behaviour. Fig. 2. From that it follows that the designer of tensile membrane structures has the choice between.

- cable nets with quadrangular («square») meshes
- cable nets with triangular meshes
- textile (foldable) membranes
- metal (non-foldable) membranes.

Whereas cable nets usually require a cladding, the textile and metal membranes can be considered to be the cladding itself which is able to carry the loads as well. /1/

In his invited lecture at the 30th anniversary of IASS, Madrid 1989, the first author, following Fig. 2, tried to cover this whole range of tensile membrane structures including cable nets.

This paper, however, restricts itself to some recent textile membrane structures which the authors designed in recent years. Before starting with these examples, some basic information on current textile membrane material and detailing is given.

2. TEXTILE MEMBRANE MATERIALS

Textile membranes usually consist of prooved or coated fabrics. Some types of non-wovens are in use for special applications.

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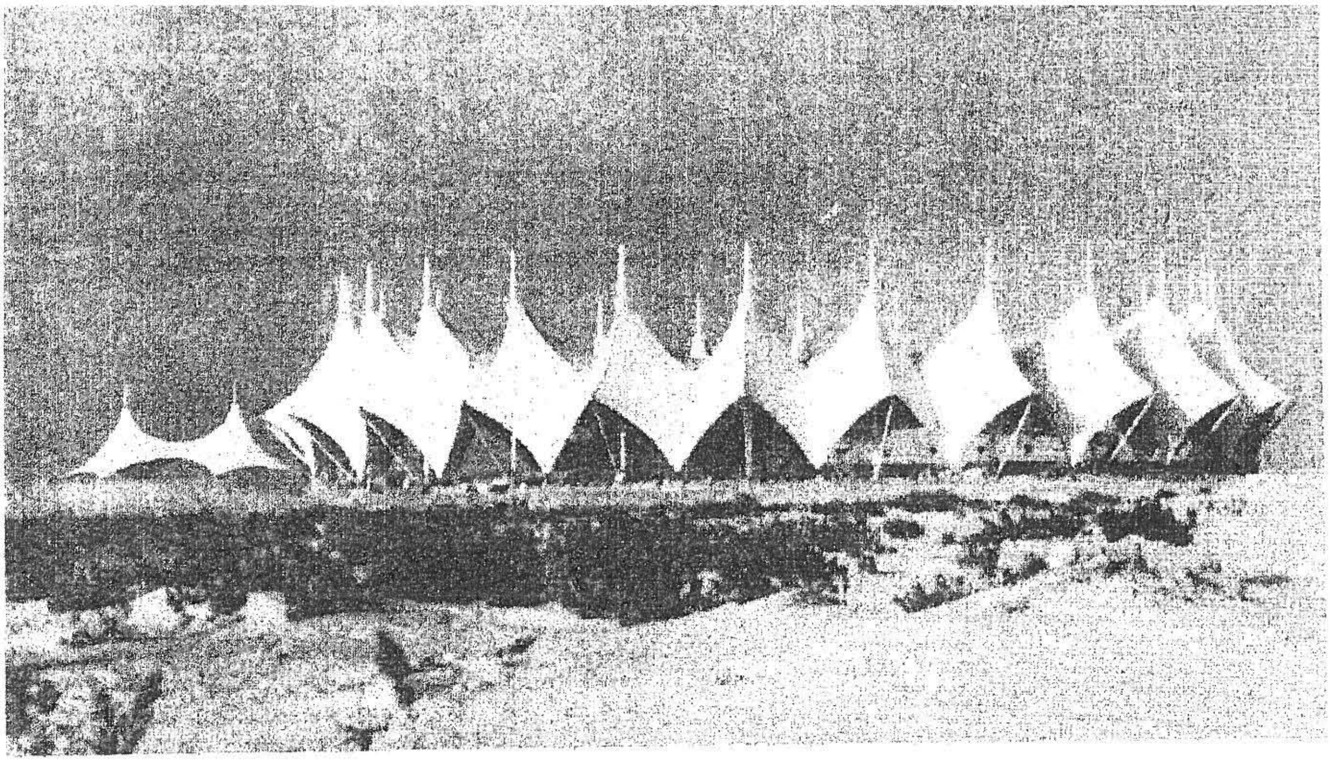

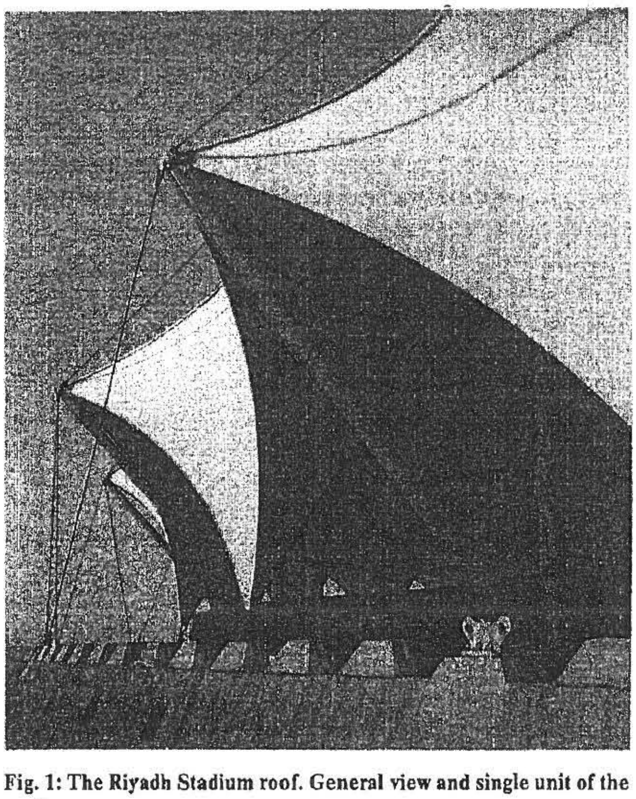

Fig. 1: The Riyadh Stadium roof. General view and single unit of the roof.

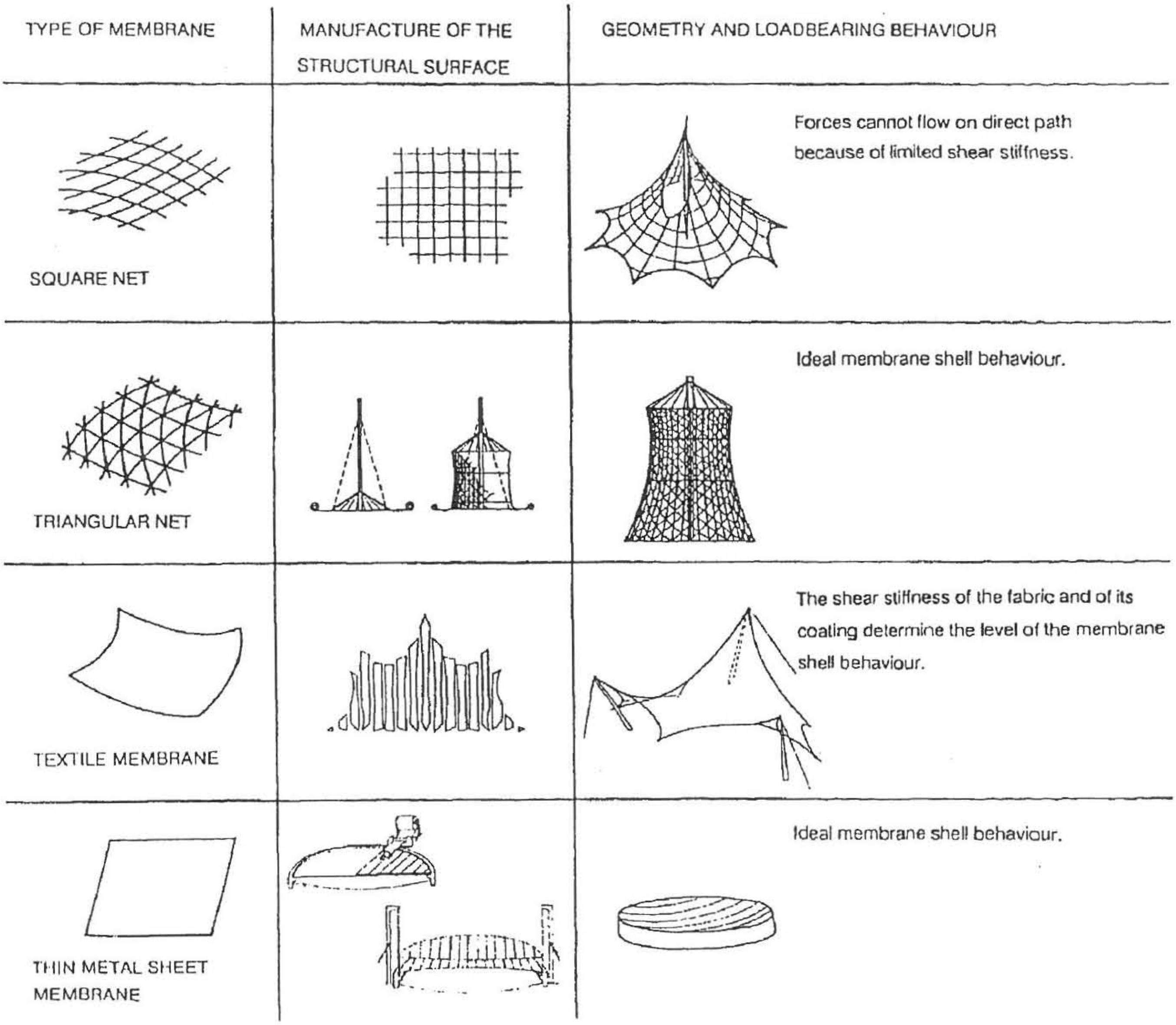

Fig. 2: Interdependence between type of membrane, the manufacturing, the geometry and the loadbearing behaviour.

Today, there is a wide range of natural and synthetic fibres which could be used for the production of the membranes. However, the typical demands on structural textile membranes and the necessity of series of detailed tests with the material itself as well as with its joints have, for common use, led to a small selection of fibres. Fig. 3, 4, 5.

The fabrics themselves are not waterproof. In addition, most of the fibres will be attacked by environmental effects, as e.g. sunlight radiation. Inter alia, this usually results in a reduction of strength and flexibility. The fabrics therefore must be prooved or coated.

Prooving is the preferential treatment for cotton and cotton/synthetic fabrics. Coating with PVC is the most common solution for Polyester —and Aramid-

Standard Fibre Materials

- Cotton / Synthetics
- Polyester
- Polyamid
- Glass
- Aramid
- P T F E

Fig. 3: Standard fibre materials.

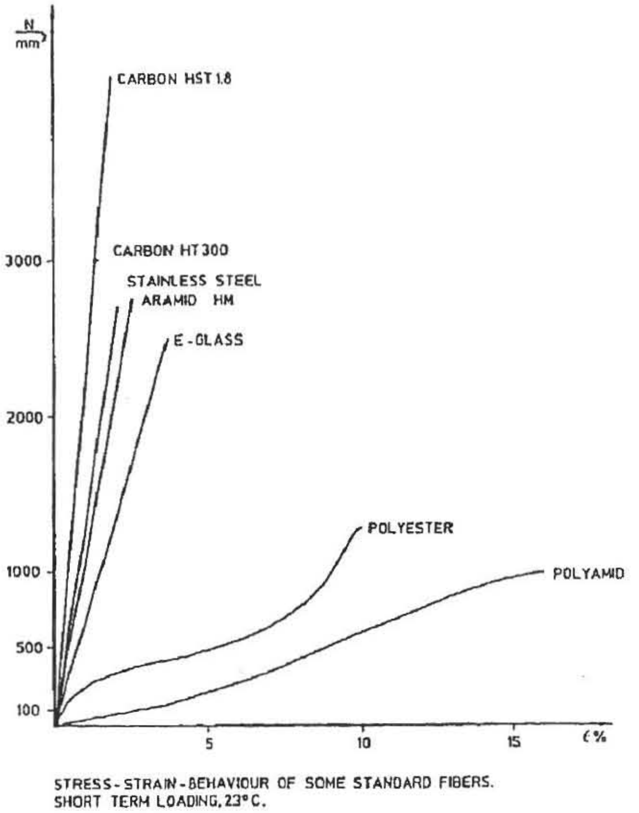

Fig. 4: Stress strain behaviour of standard fibres. Short term loading.

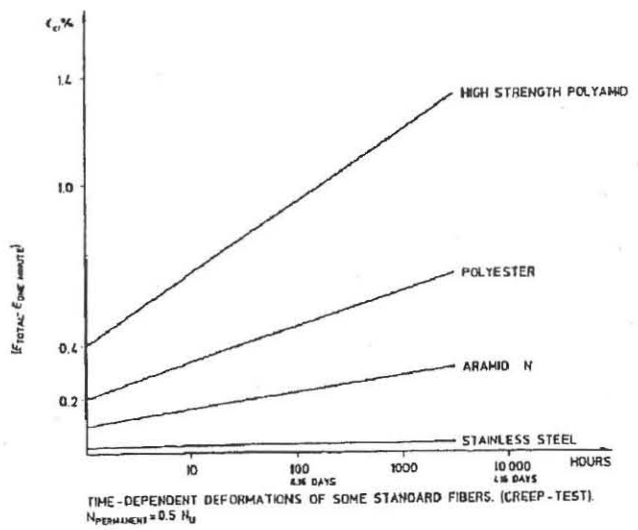

Fig. 5: Time-dependent deformations of some standard fibres (creep test).

fabrics, coating with PTFE is typical for glassfibre-fabrics. Fig. 6.

The coating system must be well suited to the fibres used for the fabric itself: on the one hand, the coatings are applied onto the fabrics at high temperatures which the fibres must be able to withstand, on the other hand, the chemical and mechanical adhesion to the fabric is of importance for the shear stiffness and with that also for the load bearing capacity of many of the structural details.

<u>Base Fabric and Typical Coatings / Finishings</u>

Cotton / Synthetics	- Prooving
Polyester	- Plasticized PVC/Painted/Films
	- PVDF
	- Synthetic rubber
Polyamid	- Plasticized PVC/Painted/Films
	- PVDF
	- Synthetic rubber
Glass	- PTFE
	- Silicone
Aramid	- Plasticized PVC/Painted/Films
	- PTFE
PTFE	- No coating required

Fig. 6: Base fabric and typical coatings/finishings.

The strength of a membrane depends on the type of yarn, the type of weave and the count used for the fabric. The PVC/Polyester and the PTFE/Glass materials which can be bought from stock show a strength up to 200 kN/m (short term tensile test, 23° C). On inquiry, qualities up to more than 300 kN/m can be produced. The strong qualities of PVC/Aramides can reach the order of 600 kN/m. However, because of their high price and missing translucency, the latter are chosen for special cases only. They have to be produced on inquiry therefore.

3. TYPICAL JOINTS AND EDGE DETAILS

3.1. Joints

Within a textile membrane, the high-strength fibres are the loadbearing elements. Joining two strips therefore means to create a connection which is able to transfer the forces from fibre to fibre.

Three groups of joints may be distinguished:

Welding, especially high-frequency (HF) welding, is the type of joint mostly used. Within welded joints, the forces are transferred from one fabric via the fused coatings to the other one. The strength of the detail therefore is determined by the strength of the coating itself and by the adhesion of the coating to the fibres of the fabric. Fig. 7

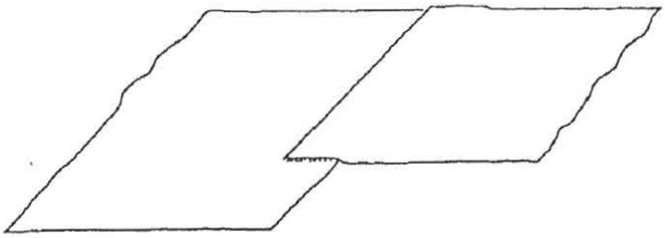

Fig. 7: Welded joint detail.

Today, high quality HF-welds of PVC/Polyester membranes show a strength up to 95 % at 23° C (70 % at 70° C) of the strength of the fabric itself. The light qualities of PVC-coated Aramidfibre-fabrics can reach the same range. For heavy qualities of this material, the combination of welding and sewing is inevitable.

Welding of PTFE/Glassfibre membranes is done in a high-temperature contact-welding process. The strength of these joints is about 80-90 % (23° C and 70° C) of the strength of the fabric.

The second group of joints are the sewed connections. Sewing, the oldest technique in joining fabrics, is of reduced importance today. There are several reasons to that:

Today's welded joints usually are of such good quality that they produce a strength which is even higher than that possible with sewed seams. In addition, sewed seams are not completely waterproof and the sewing threads may be attacked by environmental effects. Additional measures therefore must be taken in order to protect the joint, Fig. 8. Sewing therefore may become non-economic if applied to the very long (standard) joints of single strips. However, for a lot of details, especially if forces have to be introduced into the membrane locally, sewing, also in combination with welding, yields optimal results.

The strength of the sewed seams of the PVC/Polyester membranes is about 70 % at 23° C (50 % at 70° C) of the strength of the membrane itself. For the PVC-coated Aramidfibre qualities, sewing is used in combination with HF-welding. An ultimate strength of about 80 % at 23° C of the strength of the membrane itself can be reached. For the PTFE-coated Glassfibre materials, sewing is not possible.

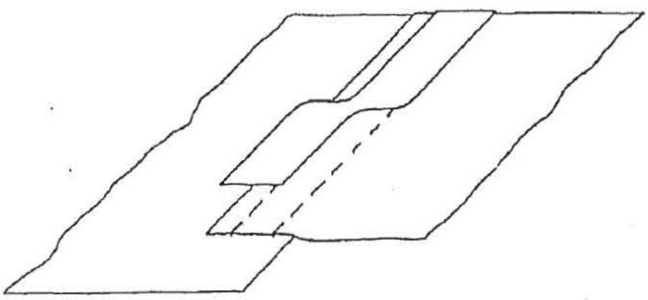

Fig. 8: Sewed joint with protecting film.

The third group of joints may be named as «Mechanical Joints». It is typical for this group that the forces are transferred via clamping, bolting or ropes passing through eyes in the membrane. Figs. 9, 10, 11. The joints belonging to this group are used for the assembly of large membrane elements on site usually, with those according to Figs. 10, 11 for low strength or temporary connections only.

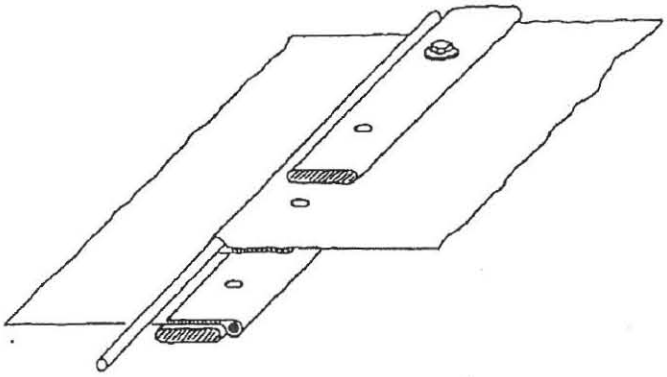

Fig. 9: Clamped connection of two membranes.

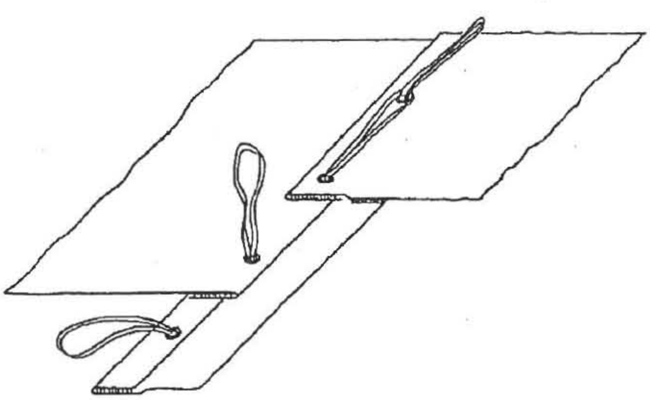

Fig. 10: Typical lopp-fastener detail.

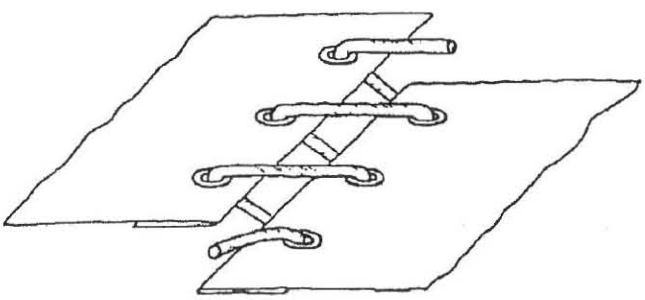

Fig. 11: Membranes with plastic or metallic eyes, connected by a zig-zag curved plastic rope.

The strength of the joints according to Fig. 10 depends on their detailing. Usually, 80-90% (23° C) of the strength of the membrane itself can be reached.

3.2. Edge Details

Along their edges, the membranes meet a structural element which collects the membrane-forces and carries them to the foundations.

These edge elements implicit some general structural and detailing problems:

– The highly loaded edge elements are normally of steel and therefore much more stiff and rigid than the membrane itself. This strongly influences the elastic deformations and therefore the membrane stresses within the edge area.

– In order to avoid local overstressing of the membrane, the edge elements have to take up all components of the membrane stresses acting along the edge. The transfer of forces perpendicular to the edge causes less problems than the transfer of tangential forces.

To guarantee the flow of forces from the flexible, only tensioned and very thin membrane into the edge elements, their connection needs very careful detailing.

There are different types of edge details. In general, one may distinguish the

– only-tensioned (comparatively flexible) edge elements

– rigid and stiff edges (beams under compression and/or bending)

The only-tensioned edge elements usually consist of steel cables. The connection between the membrane and the cable is done either with an edge pocket, Fig. 12, or with clamping details analogeous to Figs. 14, 15. In the case of small membrane forces, details analogeous to Fig. 11 can be used.

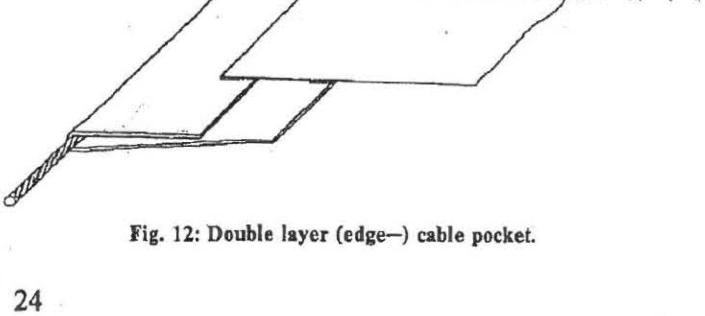

Fig. 12: Double layer (edge–) cable pocket.

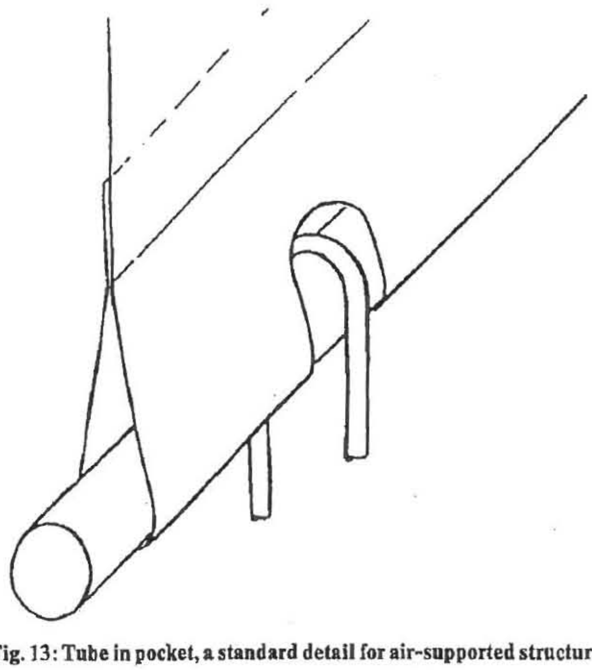

Fig. 13: Tube in pocket, a standard detail for air-supported structures.

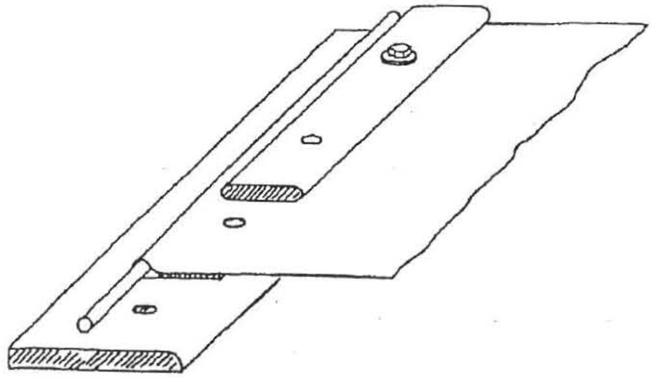

Fig. 14: Standard edge clamping detail.

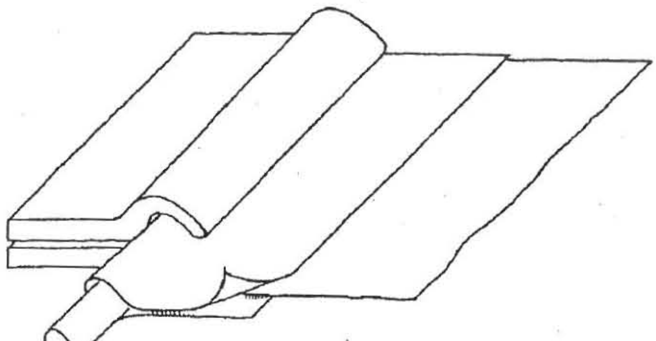

Fig. 15: Edge clamping detail for highly loaded membranes.

The strength of these edge details depends on their individual detailing. For the PVC-coated Polyester fabrics, the edge-cable pocket details show a strength of up to 95% of the strength of the fabric itself (short term test, 23° C).

The steel cables are in use because of their low price and because they can be anchored easily to the foundations. However, the solution is restricted to membranes with any size of radial but limited size of tangential forces in the membrane along the edge: only small tangential forces can be transferred via friction.

In the case of high tangential forces along an edge cable pocket, a fabric belt, which is running parallel to the edge cable, is sewn onto the membrane very often. The belts are designed to collect the tangential forces and to carry them to the foundations. Such fabric belts show another stress-strain behaviour than the edge cable. In addition, their loadbearing behaviour is time-dependent. Therefore, it is difficult to predict the level of forces each of the two edge elements will take (2, 3).

In the case of small membrane forces and small radii of the edge curves, a fabric belt as the only edge element can be sewn onto the membrane directly. These belts can carry the forces directly to the foundations or they can be anchored in short distances onto a steel cable running parallel to the edge curve. This type of edge is called a garland cable solution.

The optional solution is an only-tensioned edge element the stiffness of which corresponds to the stiffness of the membrane and which also is made out of fibres in order to allow easy connection onto the membrane (2, 5).

The design of rigid and stiff edges is more developed. The standard solution is the edge clamping detail where the membrane is connected directly onto the foundation, Fig. 14. Geometry of the detail, manufacturing and loadbearing capacity are similar to the clamped connections of two membranes, Fig. 9. For the PVC-coated Polyester fabrics, up to 90 % of the strength of the fabric itself can be reached (short term test, 23° C).

In case only small forces have to be anchored, the tube in pocket detail is a well proven solution. Fig. 13.

The standard membrane materials and their associated details offer a wide range of structural possibilities. Following, some structures recently designed by the authors will be presented in order to pint out some of the specific advantages as well as problems of the single materials and of membrane structures in general.

4. ROOF OF THE STADIUM IN RIYADH, SAUDI ARABIA

Following an architectural design of J. Fraser, J. Roberts and Partners, London, with Geiger and Berger, New York, the grandstands of the new stadium in Riyadh have been covered by a 50.000 m² membrane roof to protect visitors against sun and rain. Fig. 1.

The roof which has been opened in 1987 consists of 24 units, arranged in an annular shape of 134 m inner and 270 m outer diameter. Each of the units shows, see Fig. 16

- a vertical main mast
- a pair of suspension and stabilizing cables, which are put under prestress by a center ring cable
- the staying system, comprising an upper stay and two triangulated lower stay cables, deviated by a 45° inclined edge mast.

These three elements form a primary structural system which has been erected first. The membrane units, edged by ridge, valley and catenary cables, have been fixed into this primary system afterwards.

The membrane is a PTFE-coated glassfibre-fabric. Its ultimate strength is specified to be 150 kN/m in both directions. This assures a safety factor >10 for permanent loads like prestress and >5 for short term loads like wing. The PTFE/glassfibre material has been chosen for this structure because of its

- very low degradation under intensive UV-radiation impact
- high resistance against the abrasive action of sand
- the «self-cleaning», means antiadhesive behaviour of the PTFE-coating.

Each of the 24 membrane units consist of four individual membrane parts, resulting on a maximum size of 850 m² per piece. The single pieces have been manufactured in the shop and folded into a crate for transport to site. The membrane units finally have been assembled on the ground of the stadium, using a clamped connection. After teh installation of the entire membrane roof had been finished, the final prestress was introduced by jacking up the rings at the top of the main masts (4, 5).

5. A CONVERTIBLE ROOF FOR THE ARENA IN ZARAGOZA

The Arena of Zaragoza/Spain has been designed and erected in the last decade of the 18th century. The existing structure is circular in plan with a diameter of about 100 m. It shows a 3-story gallery onto the top of which the perimeter of the new roof has been placed,

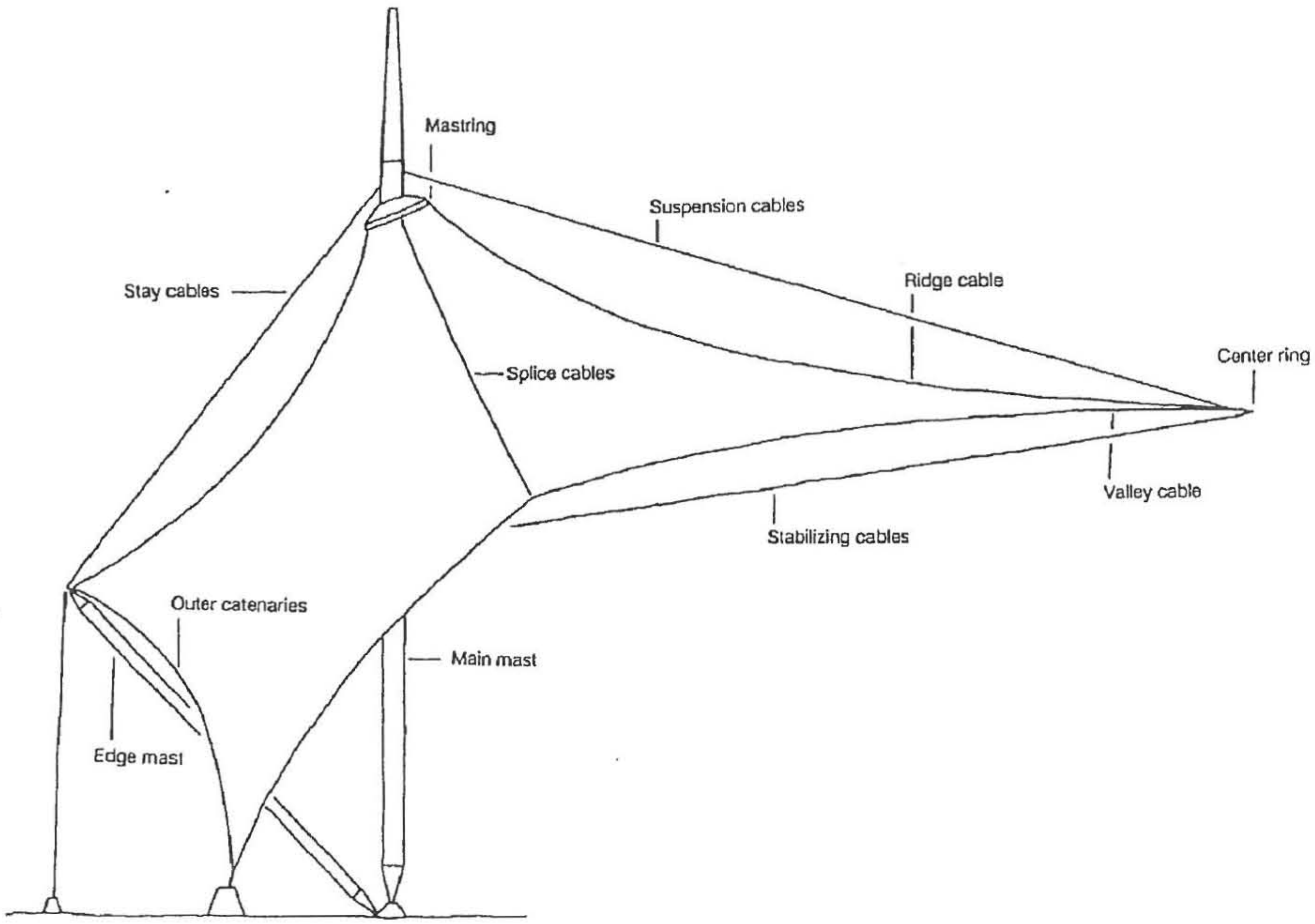

Fig. 16: A single unit of the Riyadh roof: Structural elements.

Fig. 17. This circular roof covers 15.000 seats. It consists of a permanent (ringshaped) outside and a convertible central part. The central part of the roof structure shall be installed in 1990.

The permanent part of the roof is a lightweight «Rim, spokes and hub» –type primary structure. The «rim» has been realized by a polygonal steel-ring, the «spokes» are formed by radial prestressed cables. The «hub» consists of an upper and a lower ring-cable, connected by 16 tubular posts. The permanent membrane finally has been arranged between the lower set of the spoke-cables.

The convertible part of the roof shall be installed within the central opening. Fig. 18. Along its perimeter, it will be attached onto the lower ends of the tubular posts. A central point shall be suspended from a spoke-type cable system. The prestressing of the convertible roof is planned to be done with a hydraulic jack which is part of the central point. Opening and closing of the roof will be done in the unstressed position (central jack released) by 16 electric engines.

Both, the central convertible membrane as well as the permanent membrane are the same type of PVC-coated Polyester fabric. This material has been chosen because of its flexibility which allows easy folding and which guarantees a small size of the folded roof-package. The strength of the membranes is 115 kN/m (warp direction, short term test, 23° C).

6. RETRACTABLE ROOF OLYMPIC STADIUM MONTREAL

Initially, the convertible roof of the Montreal Olympic Stadium should have been installed for the 1976 Olympic Games. Caused by several reasons, the final decision for the installation of the roof has been made in 1984. The initial concept of architect R. Taillibert was followed in general, but the original design was considerably reworked (5, 6).

The 20.000 m² fabric roof of the Montreal Olympic Stadium is the world's largest convertible membrane-roof. A onepiece membrane is suspended by cables at 26 intermediate points from a 168 m high inclined tower. Along it's perimeter, the membrane is edged by

Fig. 17: The Arena in Zaragoza with its membrane-roof.

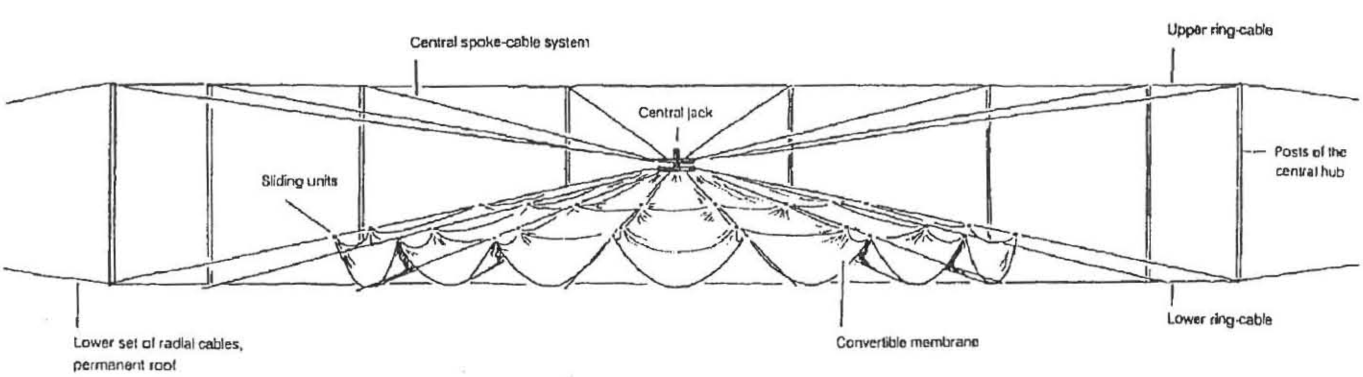

Fig. 18: The Zaragoza roof while the convertible membrane is in motion.

17 garland cables which transfer the forces to the existing concrete roof covering the grandstands. Fig. 19.

The roof may serve as an example to show that in certain cases the feasibility of a whole concept or structure depends on the solution of a single detail:

The retraction process as originally proposed and also later followed in principle –but not in detail– is sketched in Figs. 20, 21, 22. (It should be noted that for simplification in this and all following sketches, the actually 17 edge connections are represented by 4, the actually 26 suspension points by 2.). It proceeds stepwise as follows:

– release prestress by releasing the suspension cables and lowering the suspension points

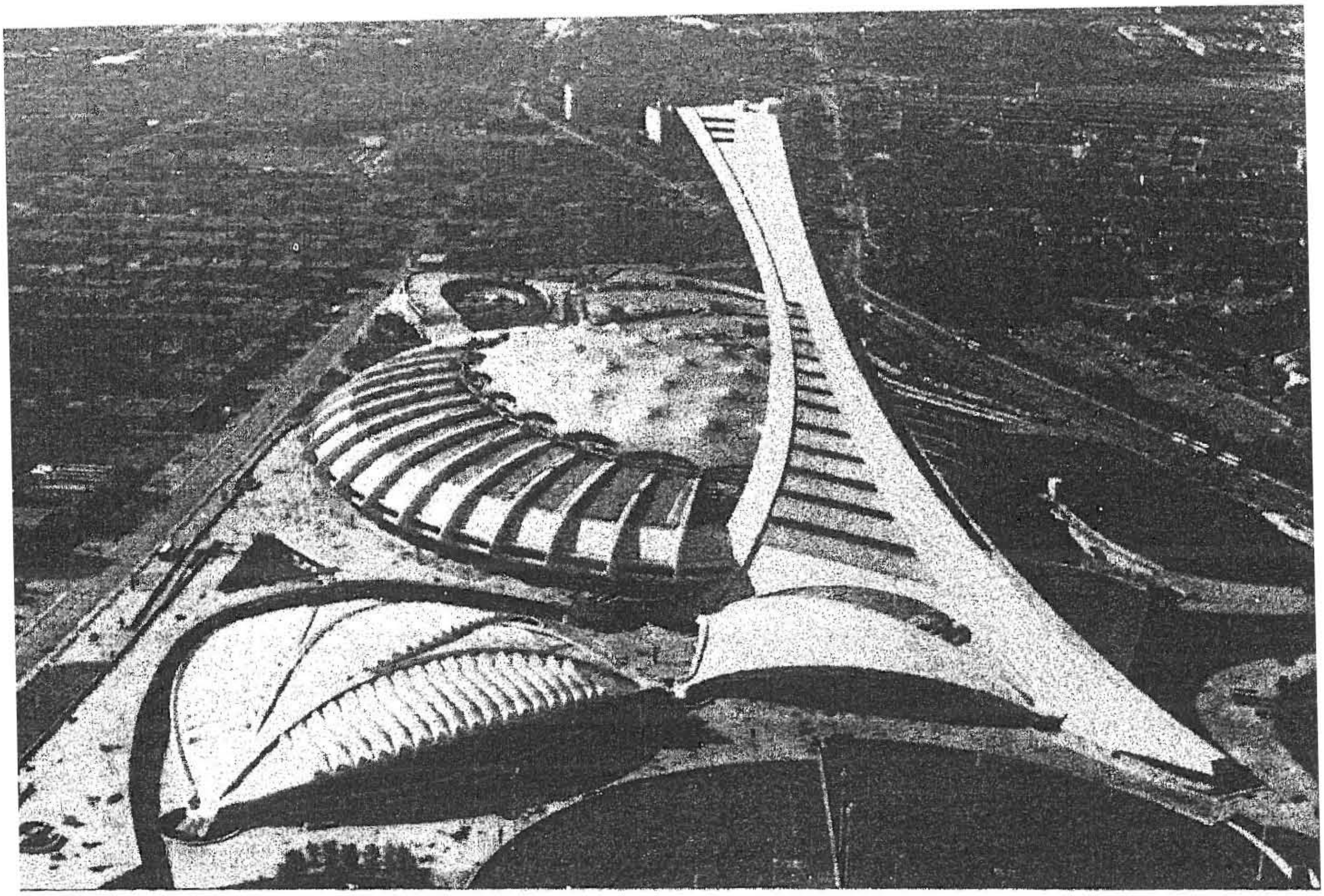

Fig. 19: Overall view of the Olympic Stadium Montreal.

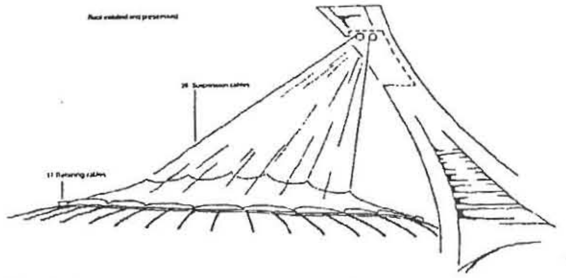

Fig. 20: The Montreal roof in the closed and prestressed position. Initial concept. Simplified representation.

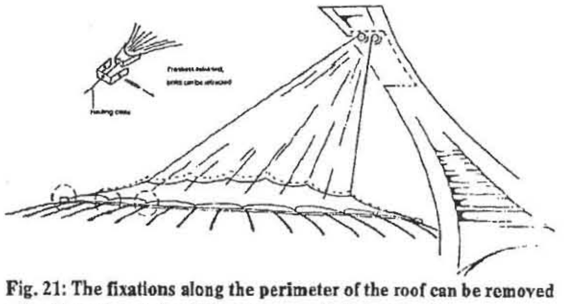

Fig. 21: The fixations along the perimeter of the roof can be removed after the prestress has been released. Initial concept.

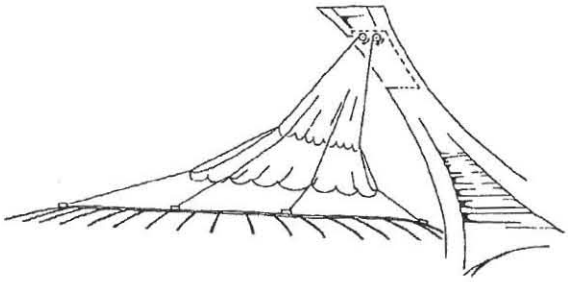

Fig. 22: Lifting of the roof. Initial concept.

— remove bolts from edge connections

— lift roof by winding the suspension cables and releasing the holding back cables.

The diameter of the suspension ropes was originally proposed to be about 40 mm. It was intended to install all 26 winches in the tower top and to wind and also prestress these ropes directly through these winches. The whole roof, including of course the suspension cables and the tower itself, were designed for 1/3 of the design snow load. A snow melting system was to be installed.

Having had already extreme difficulties to find a really acceptable seam for the PVC/Aramid fabric, imposed to us by the client since he had bought it already in the early 70's, in combining sewing and welding we by all means wanted to avoid high temperatures. This cannot be avoided if the melting system works under realistic conditions and will then reduce the strength of the seams dramatically. Further and mainly, isn't it rather likely that the power supply breaks down in a snow storm? A building is not a machine! However, including a snow load of 1.35 kN/m^2 the diameter of the suspension cables was to go up to about 130mm and with them the diameter and size of the winches. No chance anymore to accommodate them in the tower, beyond their high costs and inoperability.

In this context it must be mentioned that it is detrimental to a rope if it is coiled and stressed simultaneously. Especially where it leaves the winch it is subject to permanent bending under full stress and which means that its diameter has to be further increased to reduce the axial stresses, increasing again the bending stresses and the size of the winches. A vicious circle.

The solution came from the simple idea to uncouple lifting/coiling from prestressing/load bearing, i.e. to coil the ropes as long as they are unloaded and to stress them as long as they are straight. With this, the most loaded suspension cable needed a diameter of 95 mm «only». It is coupled at its tower support to hoisting cables of 30 mm diameter. The coupling socket rests on a hydraulic jack for prestress and release, Fig. 23. In fact, only 12 out of the total 26 suspension cables rest on jacks, because this is sufficient to prestress or release the whole roof. This reduces not only costs but simplifies the retraction operation. To further ease the congestion of the tower top, the cables are not coiled there but only deviated down to the tower base on rollers, Fig. 24. The winches which are now only to accomodate the small hoisting cables and to carry the dead load of the roof find sufficient place at the tower base. Fig. 24.

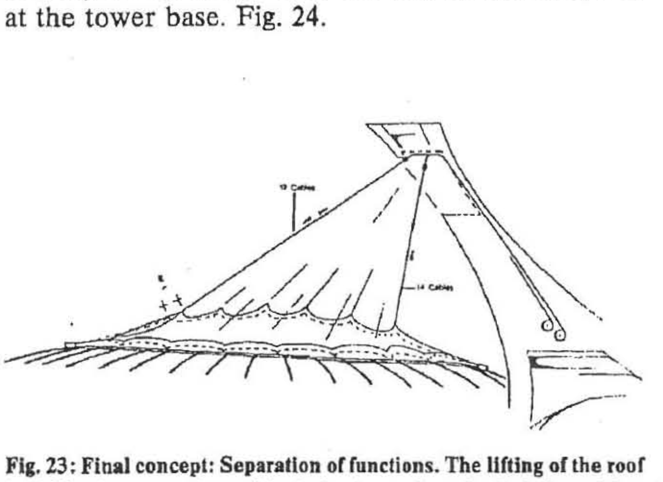

Fig. 23: Final concept: Separation of functions. The lifting of the roof including its suspension cables is donde now by using hoisting cables.

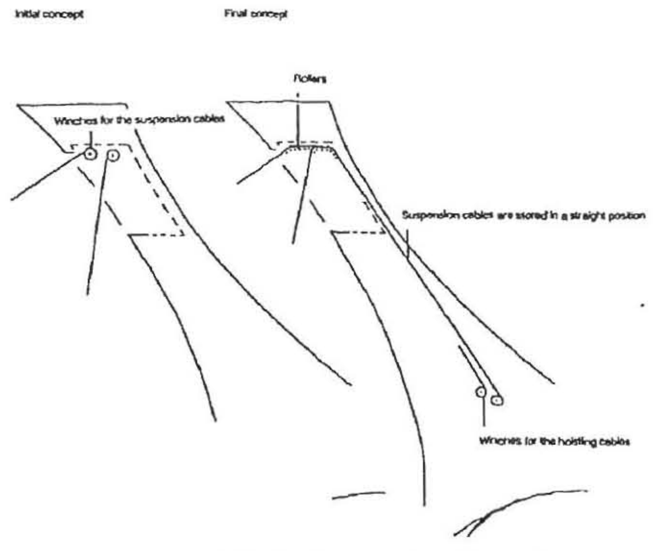

Fig. 24: Final concept: During the opened position of the roof, the suspension cables are stored within the tower in a straight position. Only the small hoisting cables have to be coiled.

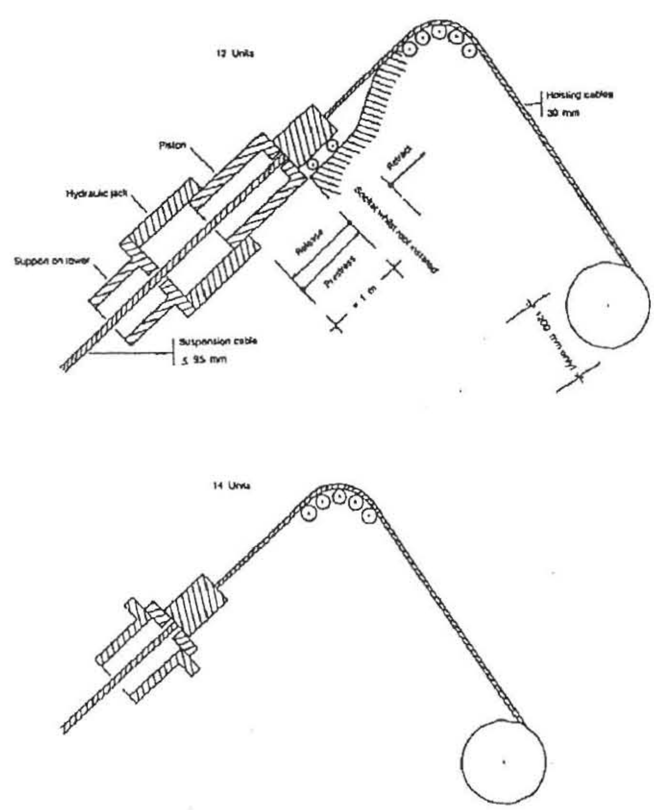

Fig. 25: Final concept: Prestressing and replacing is done by using hydraulic jacks which shift the sockets of the suspension cables.

To be complete a further asset to the original design should be mentioned: To control the roof's motions during lifting and to wrap it, a «lasso» cable was introduced, connecting similar to a curtain's lace the 17 edge connections. Fig. 26. Easy to say but difficult to accomplish. The cast steel joints needed to join the edge and lasso cables, which are to be lifted with the roof, have a total weight of more than 50 t themselves.

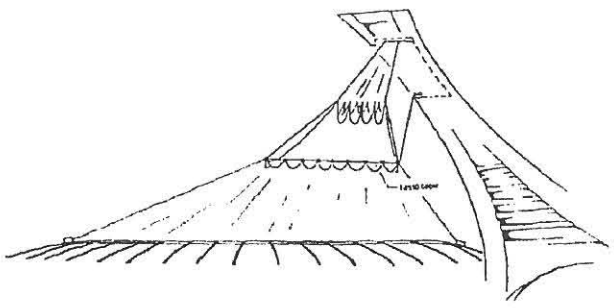

Fig. 26: Final concept: A circular lasso cable has been introduced in order to guarantee a controlled folding unfolding of the membrane.

7. THE «COUVERTURE DES ARENES DE NIMES»

The roof for the Roman arena in Nimes/France is an airinflated cushion-type structure. It is ellipctic in plan with main axes of 90 resp. 60 m. The building has been designed in order to cover the central part of the arena during wintertime, means the structure will be installed each year in October and it will be removed the following April. Fig. 27. The first assembly was in December 1988.

The upper and the lower membrane of the cushion are edged by 30 garland cables each. At the points where these cables join together, they are fixed onto a polygonal steel-ring. The tensioned membrane and this steel-ring in compression form a self-balanced structure. Fig. 28.

The steel-ring is supported by 30 columns with a height of 10 m each. Horizontal forces are taken by four x-shaped cable bracings which have been arranged between the columns. A transparent facade spans from the ring to the outside perimeter of the building.

Caused by the annual montage/demontage cycle, the structure has been designed under the imperative of a minimized deadweight and of «easy-to-connect/disconnect» details. All details therefore show pins or bolted connections. The ring may be dismantled into 30 elements, the columns can be taken away easily after some few bolts have been removed. The membrane cushion consists of an upper and a lower membrane which can be joined quickly by an airtight zip. The

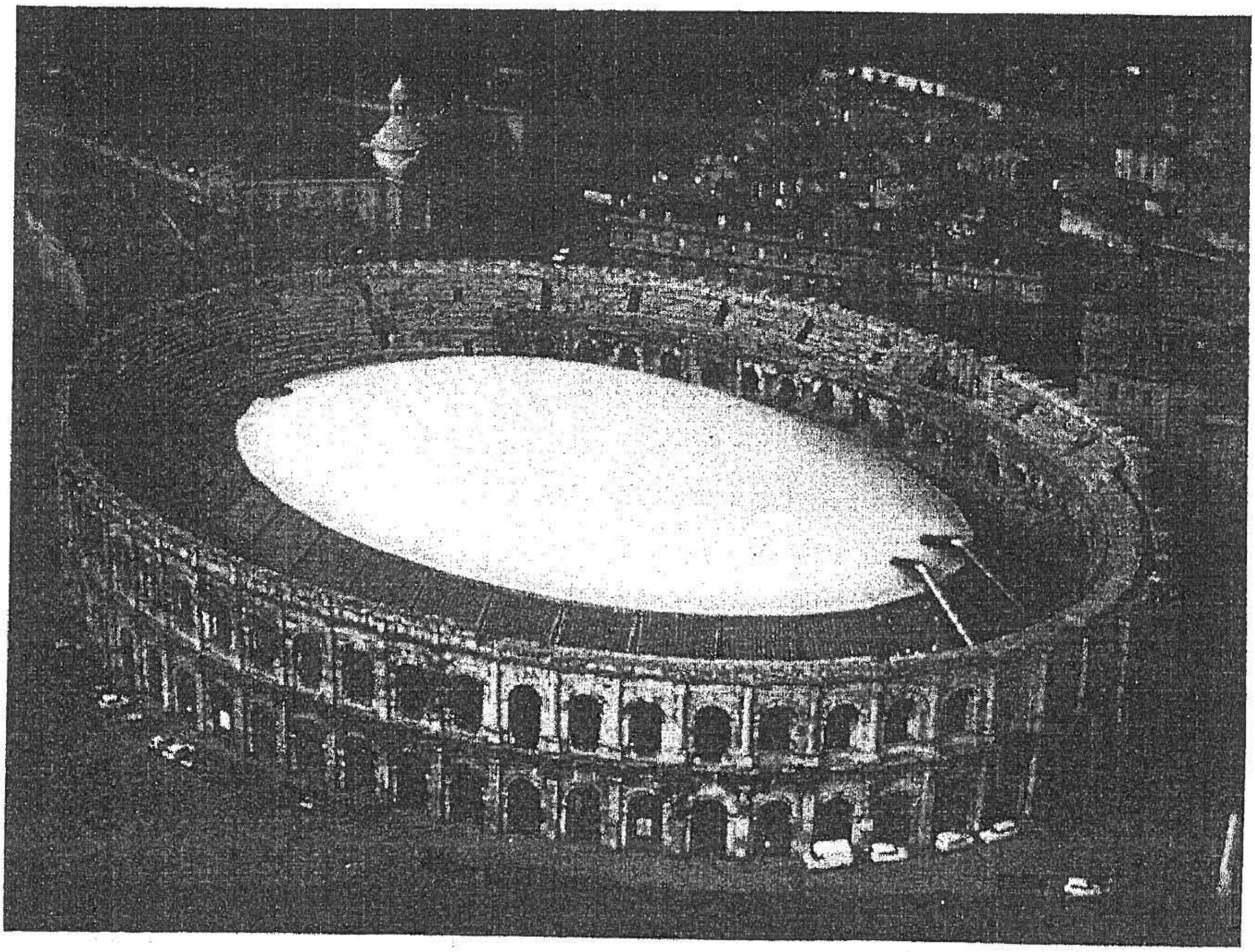

Fig. 27: The «Couverture des Arenes de Nimes»

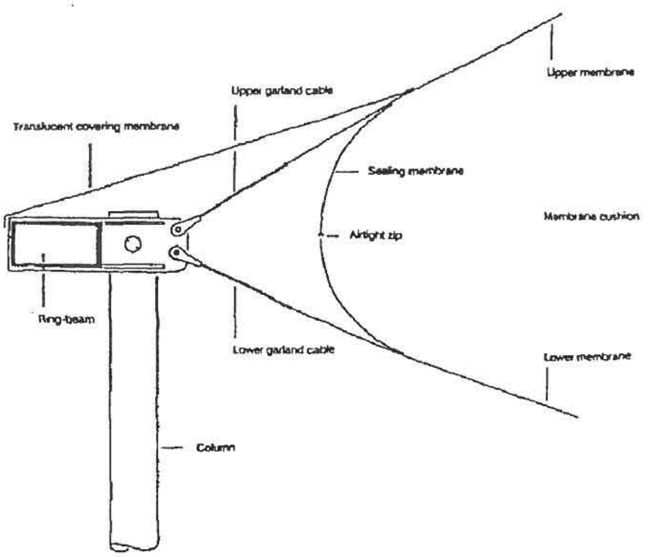

Fig. 28: Arenes de Nimes: Fixation of the cushion onto the compression ring, principle.

facade finally consists of 480 identical hollow box-type polycarbonate beams with a deadweight of about 30 kg each only.

Strands and hydraulic jacks are used for the lifting and lowering of the membrane/cable structure and for the ring. The entire erection as well as the jacking system have been developed for this building especially.

PCV-coated Polyester membranes have been chosen for the membrane cushion because of their suitability for multiple folding, storage and installation cycles. The upper membrane shows a strength of 150 kN/m (warp direction, short term tensile test, 23° C), the lower membrane, which is reinforced by a cable net, shows a strength of 88 kN/m.

The structure has been designed to resist extreme load conditions. The maximum windload corresponds to 200km/h. The maximum design snowload is 90 kg/m^2, means the total weight of snow is about twice the deadweight of the entire building (7).

8. PNEUMATIC FORMWORK SYSTEMS

The pneumatic structures show an almost unlimited variety of shapes. They are characterized by short erection and dismantling times, low weight, re-usability and the easy realisation of curved surfaces. They therefore may be seen as an appropriate tool to bring up shell construction again: by using them as a (pneumatically stabilized) formwork.

In general, pneumatic formwork may be used for the erection of

— masonry

— clay

— plastic foam

— ...

shells. However, the method becomes most interesting if it is used for the erection of large span concrete shells (8).

The first time pneumatic formwork has been used was in 1936. Since that time, a number of different systems and procedures has been developed. The most important ones are (9, 10, 11, 12).

— high internal pressure formwork.

— concreting in single layers, which is appropriate when using shotcreting

— concreting in sections with hardening intervals

— stabilizing the formwork with additional cables, also in combination with the reinforcement

— stabilizing the formwork with plastic foams

— finish concreting before the material starts hardening (e.g. Bini-method).

The individual measures also can be combined.

All of the methods mentioned above are characterized by the intention to reduce the deformations of the formwork. This limitation and the control of formwork deformations is of importance because the formwork can remarkably change its shape under the load of the concrete. In addition, the concrete usually starts hardening while the concreting is still in progress. While it is hardening, the initially large deformability of concrete decreases appreciably. When it reaches minimal ultimate strain, the concrete is still very weak. In this phase, formwork deformations can yield to a permanent damage.

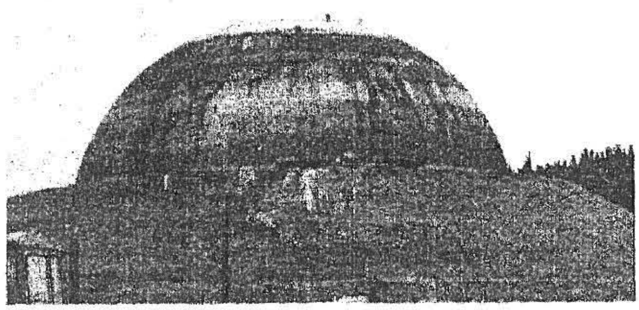

Fig. 29: A large concrete shell under construction. Air supported formwork realized with Vinyl-coated Polyester-fabric. The span of the formwork is 58 m. Photo: H. Harrington.

Several hundreds of concrete shells have been erected up to now with pneumatic formworks. Their spans go up to about 70 m with an associated thickness between 10 to 15 cm. Fig. 29. It is remarkable that nearly all of them are dome-type shells. On the one hand, it is evident that domes are efficient structural systems. On the other hand, shapes which keep the concrete always under compression are much more efficient and they also may be much more interesting from the architectural viewpoint. Textile membranes allow the realisation of such optimum shell shapes without remarkable additional costs caused by the geometric complexity of the formwork. The use of pneumatic formwork therefore is a great chance to revive concrete shells with their pleasing architecture. Fig. 30.

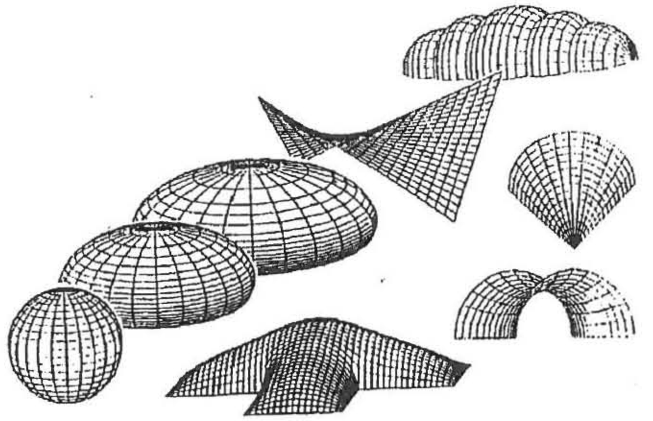

Fig. 30: Concrete shells: Some of the shapes which could be realized by using pneumatic formwork.

REFERENCES

1. Schlaich, J.: Les Structures Legeres. Annales de l'Institut Technique du Batiment et des Travaux Publics». Serie: Technique Generale de la Construction. N.° 479, Dec. 1989.
2. Gropper, H., and Sobek, W.: Zur konstruktiven Durchbildung ausschließlich zugbeanspruchter Membranränder. Proceedings 3. International Symposium «Weitgespannte Flächentragwerke». SFB 64, University of Stuttgart. Stuttgart, 1985.
3. Schlaich, J.; Kleinhanss, K., and Gabriel, K.: Membrandach aus der Sicht des planenden Bauingenieurs. Proceedings of the Symposium «Beschichtete Chemiefasergewebe» at the University of Aachen. Aachen, 1979.
4. Bergermann, R.: The Membrane Roof for the Riyadh Stadium (Saudi-Arabia), IABSE Structures C-41/87. IABSE Periodica 2/1987.
5. Schlaich, J.; Bergermann, R.; Seidel, J., and Sobek, W.: Some Recent Membrane Structures. Proceedings of the lst International Symposium on Non-Conventional Structures. London, 1988.
6. Lainey, L.; Morin, N.; Schlaich, J.; Bergermann, R.: Retractable Roof Olympic Stadium Montreal. Proceedings of the IVBH-Symposium. Helsinki, 1988.
7. Bergermann, R., and Sobek, W.: Covering «Les Arenes de Nimes» with an air-inflated Fabric Structure. Proceedings of the lst International Techtextil-Symposium in Frankfurt. Frankfurt, 1989.
8. Schlaich, J.: Haben Betonschalen eine Zukunft? Beton 9 (1982).
9. Sobek, W.: Auf pneumatisch gestützten Schalungen hergestellte Betonschalen. Doctoral dissertation, University of Stuttgart. Stuttgart, 1987.
10. Schlaich, J., and Sobek, W.: Suitable Shell Shapes. Concrete International, January 1986.
11. Sobek, W.: Concrete Shells Constructed on Pneumatic Formwork. Proceedings of the IASS-Symposium on Membrane Structures and Space Frames in Osaka, Japan. Elsevier, Amsterdam, 1986.
12. Sobek, W.: Schalungen aus pneumatisch vorgespannten Membranen zur Herstellung von Überdachungen, Speicherbehältern und Leistungssystemen. Proceedings of the 2nd International Techtextil-Symposium in Frankfurt. Frankfurt, 1990.