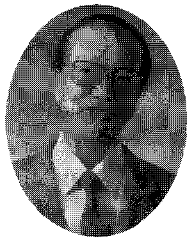
Membrane Structures
- Their Characteristics and Various Applications -



Mamoru Kawaguchi*

SUMMARY

A few characteristics of membrane structures which the author thinks important for design are described on the basis of his experience in research and design of this kind of structures.

Different in behaviors of air-supported and air-inflated structures are first explained for a better understanding of these structures. Attention is drawn to unfavorable behaviors of an air-beam when it is reinforced by diagonal members. The shallowest membrane structure which can be made as an airdome is pursued, and its application to a metal membrane dome is shown. Attempts which have been made by the author seeking for the possibility of membrane structures made of metal sheet, plastic film with and without reinforcement are described with realized examples. A 100m long jumbo carp is explained as an example of a flying membrane.

INTRODUCTION

Modern development in spatial structures can be characterized by remarkable trend for lighter envelopes. Membrane materials contributed very much for the advent of the lightest roofing components ever used in the record. Thus membrane structures have increasingly been used in spatial structures.

To the author, however, there seem to be some important problems to which one has to pay due considerations before he begins design or calculation of his membrane structures.

In the present paper the author would like to present his thought on some fundamental characteristics of membrane structures on the basis of his experience in this field, and to describe a few attempts which he has made with membrane structures.

1. MEMBRANE STRUCTURES

To understand the features of membrane structures it may be convenient to characterize them in contrast to shell structures which preceded them by some decades in the history and, consequently, with which we are more familiar than membrane structures.

The special features of membrane structures that

* IASS, President

distinguish them from general shell structures are threefold:

1) The shape of their surfaces in strongly connected with statical conditions of the surfaces.
2) Their shape as a whole is determined in a manner that is reverse to that for shell structures.
3) Interaction between the surfaces and the boundary membranes are different from that in shell structures.

These characteristics make the shape and structural behaviors of a membrane very much different from those of shell structures.

A sheet of membrane and be a structural component only when it is stressed in tension at least in one direction. As well known, the tensile stress is introduced into membrane in two different ways: by simply pulling the membrane at its ends, or by pressurizing an envelop made up with the membrane by means of fluid (air in most cases).

The membrane stressed in tension by the former method is referred to here as "pulled membran e" , and the latter as "pneumatic membrane".

The equilibrium of pulled and pneumatic membranes that governs their geometry under no external load is given by the equations

$$\alpha_1 N_1 + \alpha_2 N_2 = 0 \quad (1)$$

$$\alpha_1 N_1 + \alpha_2 N_2 + Pa = 0 \quad (2)$$

respectively, where α_1 and α_2 denote the principal curvatures of the membrane surface, N_1 and N_2 the normal stress resultants in the directions of the principal curvatures and Pa the differential air pressure.

These equations imply many things. It is easily understood that in general a saddle shape or a surface of negative Gaussian curvature is suitably made by pulled membrane, while a domical shape or a surface of positive gaussian curvature which cannot be made with pulled membrane can be conveniently made by pneumatic membrane. A plane is possible by pulled membrane, but not by pneumatic membrane. It can also be said that any smooth surface can be stabilized by air pressure, if wrinkles are allowed to take place in some part of the surface, while only a limited kind of surfaces can be stabilized by pulling at their ends.

2. AIR-SUPPORTED AND AIR-INFLATED STRUCTURES

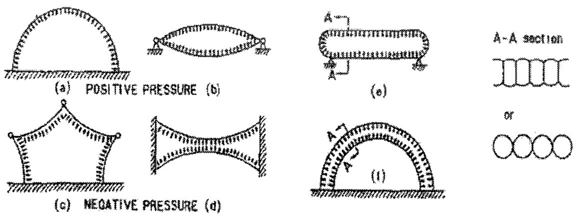
2.1 Air-Supported vs. Air-Inflated Structures

In the past three decades pneumatic structures have spread in the world on a large scale. They have been used as temporary or semipermanent coverings for a variety of buildings such as sports centers, exhibition halls and warehouses. A number of papers have also been reported on analysis, calculation method, fabrication techniques, properties of skin materials and many other subjects.

Fundamental grasp of the nature of pneumatic structures, however, seems to be lacking not only among architects who are interested in this field of design but even among structural engineers working in the same field. This brings confusion very often into mutual understanding of architects and engineers and more often into discussions among people of either side. The most elementary confusion may be seen in definition and classification of various pneumatic structures. Some call a pneumatic structure by the number of skin layers being used (e.g. single or double layer pneumatic structure), while some thers call it by the role of air in it (e.g. air-supported or air-inflated structure)/ People began to think this latter classification is more conveniently applied to the existing structures than the former.

In Fig.1 are sketched several possible varieties of pneumatic principles which may be used for covering purposes. Type(a) of Fig.1 is a typical air-supported structure of single layer membrane and is generally called an airdome. One may find examples of this type everywhere. Type(b) is a structure of double layer membranes inflated in a fixed or closed periphery. An early example of this type is the roof of the Boston Arts Center Theater where the periphery is cables stretched in a compression ring of 44m in diameter. Another example with a square periphery is a number of pneumatic roof panels for the space frame of the Symbol Zone for Expo '70 . In Types (c) and (d) air pressure inside the skins is kept lower than the atmospheric pressure. The Floating Theater in the same Expo is an example of Type (c) (Fig.8). The author does not know any example of Type(d) as yet. Type (e) is used as a beam-like structure, and an example of Type (f) is Fuji Group Pavilion in the Expo.

One may easily see that the example (a) to (d) are classified into Air-Supported Structures, While (e) and (f) are into Air-Inflated Structures, although "supporting" with negative pressure ((c) and (d)) may not directly appeal to intuitive understanding. It is important to note that the fundamental structural characteristics are very much different between the Air-Supported and Air-Inflated Structure. The necessary air pressure difference between air pressures inside and outside the skins) is usually low for Air-Supported Structures and it is high for Air-Inflated Structures, and the former is more economical than the latter as far as skin materials and air supply concern.



〈Fig. 1〉 Typical pneumatic structures

However, a lack of consistent understanding of Air-Supported and Air-Inflated Structures is seen among engineers. For instance, not a few engineers are liable to think that the increase in air pressure of either type of pneumatic structure always bring about increase in stiffness of the structure against all kinds of deformations. Some engineers thus expect to obtain a higher flexural rigidity of a pneumatic beam by increasing the air pressure in it. Incidentally, experiments on pneumatic beams of woven skins have given results which seemingly support this expectation [1]. But it is logically incorrect.

Behavior of a stressed membrane is characterized by the resistance of tensile forces in it against deformation. Most engineers know that this is expressed by an equilibrium equation in such a form that the forces multiplied by the second derivatives of deflection with respect to the lengths in two directions parallel to the membrane are equal to the load intensity. But not all of them see from the equation that the prestresses in the membrane resist only shearing-type deformations. In calculation of air-supported structures, no confusions are likely to occur, since they have only to "solve" the above fundamental equations for each particular problem. Deeper understanding is required when they deal with more elementary beam-like air-inflated structures.

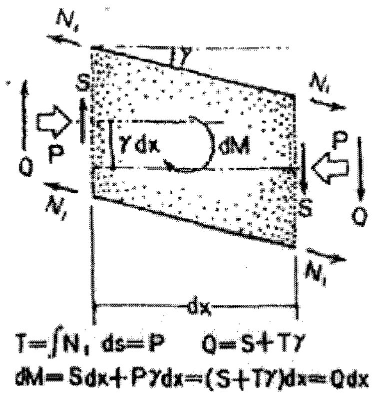
An example is shown in Fig. 2, where a shearing force Q is taken partly by the shearing stresses in the skin (S) and partly by the axial prestresses (T) in the skin material. It is easily seen in the figure that the axial prestresses resist shearing deformations only, and that a bending moment increment is associated with the shearing force just in the same way as in an ordinary beam. (This does not apply to the case of a prestressed skin "without" associated internal air pressure.) It is shown more visually in Fig.3 that air pressure completely cancels the resistance of axial prestresses in the skin in bending-type deformation, while the latter is valid in shearing-type deformation.

An apparent increase of flexural rigidity of the beam due to increase in the internal oar pressure in experiments as stated in the above is not a substantial character of pneumatic structures, but it should be attributed to secondary effects such as : (1) expansion of the cross section due to inflation; (2) material nonlinearity of yarns; (3) by-axial character of woven skin.

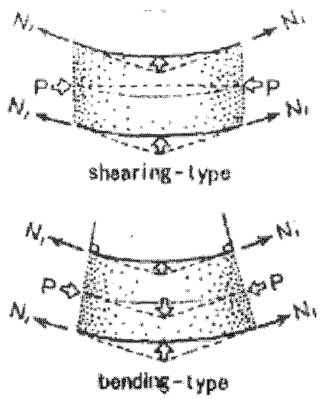
Another mistake which is rather often made by engineers may be a careless expectation of a favorable effect by introducing "lattice" elements in an air-inflated beam.

This effect was once examined by the author in a series of studies on air-inflated structures[6]. The result was as follows: Since lattic members are a web system, some increase in shearing stiffness is obtained by introducing those members. However, it should be noted that the lattice gives an unfavorable effect on the bending capacity of air-inflated beams (Nobody has pointed out this important drawback!).

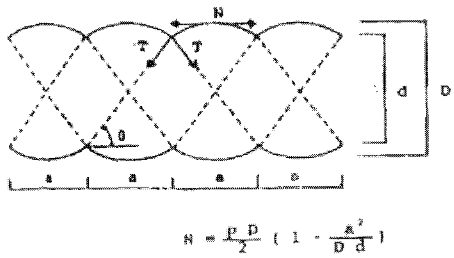
Referring to Figs. 4 & 5, it may be clearly seen that the prestress in the skin material decreases considerably due to the existence of lattic members unless the lattic members are close to vertical. When the slope of the lattic is 60 degrees the skin stress due to the internal air pressure is decreased to 2/3, and it becomes null when the slope is 45 degrees. Thus the bending capacity of an air-inflated beam decreases considerably by introducing lattic members.



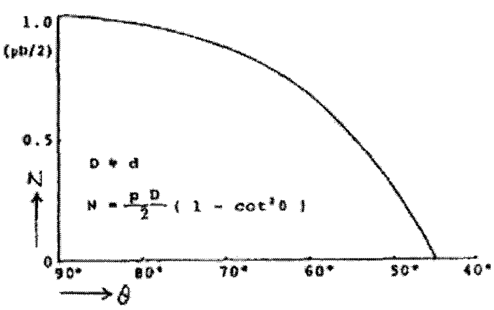
〈Fig. 2〉 Equilibrium in air beam



〈Fig. 3〉 Shearing



〈Fig. 4〉 Lattics



〈Fig. 5〉 Skin

2.2 Examples of Air-Supported Structures

One of the most prominent developments in the field of Air-Supported Structures may be a series of "low-profile" airdomes proposed by the late David Geiger.

For Expo'70 in Osaka Geiger designed the US Pavilion having an oval plan of 142m× 83.5m, covered by a cable-reinforced airdome. The skin material was PVC coated fiberglass fabric. The airdome was bounded by an elevated compression ring of reinforced concrete supported on top of the peripheral bank. The roof was very shallow, having a rise of only 6.1m. Fabrication and construction of the airdome went very well, and performance of the dome during the exposition was also successful, and thus the airdome for the US Pavilion in Expo'70 established the first example of the promising Geiger-Type Airdomes.

On the basis of the experience of US Pavilion, Geiger developed a permanent, low-profile airdome with an improved skin material.

The special features of the low profile Geiger-Type Airdomes are three-fold: The shapes of the domes are very shallow; the boundaries of the domes are elevated; and the skin material is fiberglass fabric coated with teflon resin. The first two features which brought out the low profile airdome with an elevated boundary assured a favorable uniform uplift of wind pressure over the roof area, and sufficient headroom for emergency evacuation below the roof when it is "deflated" by some accidental reasons. The third feature of the skin material made the structure "permanent" noncombustible building.

Stating from the University of Santa Clara Student Activities Center, he built seven domes of this kind in the U.S. and Canada by 1984. In 1988 a dome on the same principle was built in Tokyo. After realization of these airdomes, his interest shifted to Cable-Domes which are essentially tensegrity domes originally proposed by Buckminster Fuller. Geiger built two cable domes in Seoul, Korea, and two others for Illinois States University Arena and St. Petersburg Stadium before he died.

2.3 Examples of Air-Inflated Structures

A) Fuji Group Pavilion for Expo'70

Fuji Group Pavilion architecturally designed by the late architect Yutaka Murata and structurally designed by the author is the largest example of air-inflated structure ever built. The dome consisted of 16 arched air-tubes with a diameter of 4m and a length of 78m, which defined a circular plan of 50m in diameter at their bottoms. This arrangement of tubular arches produced a peculiar shape of the dome which projected forward by some 7m at the both ends. The tubes were held together at 4m intervals by an encircling horizontal band of 500mm in width. The central arch was semicircular, while the others arched higher and higher as their bases came closer to each other. The openings of 10m width at both ends of the dome served as the entrances. The tubes consisted of PVA fabric with a tensile strength of 2.0 kN/cm and a weight of 3.5kg/m^2 . The exterior surface of the fabric was coated with Hypalon and the interior with PVC. The lower ends of each air-tube were anchored to cylindrical steel shoes.

The internal air pressure of the tubes was kept at 800mm Aq. in normal conditions, and it was to be raised up to 2500mm Aq. in storm conditions.

B) Floating Theater for Expo'70

The floating theater of the Electric Power Pavilion for Expo'70 which designed by the late Yutaka Murata and the author was an example of a really unique pneumatic Structure.

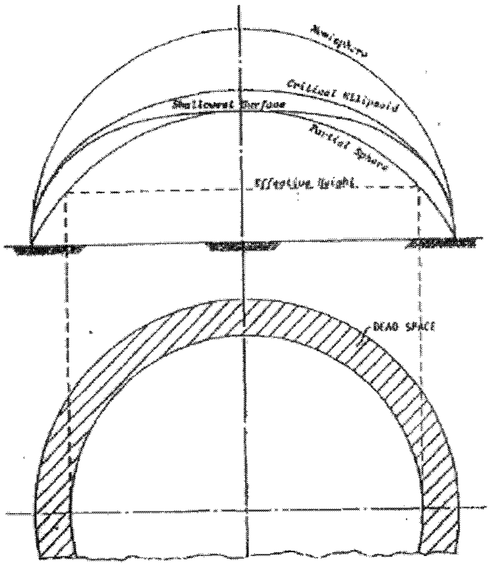
Beside the fact that the theater is a "boat" floating on a small artificial lake by means of pneumatic open cells controlled by air pressure, the theater was featured by a hybrid nature of air-inflated and air-supported structures. The theater which had a circular plan of 23m in diameter was covered by a membrane roof supported by three air-inflated circular arches having a diameter of 4m.

Beneath the roof membrane was extended a ceiling membrane. The space between the roof and the ceiling membranes was negatively pressurized, and by this negative pressure the roof membrane was tightened downward, while the ceiling membrane was raised upward. The tubular arches were pressurized to 1500mm Aq (which was to be raised up to 3000 mm Aq in storm), and the air pressure in the space between the roof and the ceiling was kept at -10mm Aq.

3. THE SHALLOWEST POSSIBLE PNEUMATIC FORMS

When one designs an airdome, a general requirement concerning the shape of the dome may be that the air volume inside the dome should net be too big. This condition can be fulfilled by adopting a shallow shape for the dome. This requirement is of general nature from the viewpoints of economy and efficiency of the architectural space. However, if the shallow shape is attempted by means of a sphere the height is decreased along the periphery, and a considerable amount of dead space is produced (Fig. 6).

To avoid this dead space the shape of the dome should be such that the surface is vertical along the periphery. One possibility for fulfilling this requirement is an ellipsoid of revolution produced by rotating an ellipse around its minor axis. It is well known, however, that an ellipsoid of revolution can not be shallower without wrinkles than the one whose major axis is 2 times the minor axis (critical ellipsoid), when it is intended on pneumatic principle. A shell of revolution generated by a special curve has been found shallower than the above critical ellipsoid to be the shallowest surface in the sense stated above, as it will be discussed in the following.



〈Fig. 6〉 Shallow envelops

The same problem was investigated by G.I.Taylar in 1919 concerning the shapes of parachute [11]. Since the work of Taylor had only a limited circulation, and it was not known in the field of structural engineering, it was independently studied by the author in quite a different manner.

3.1 The Shallowest Possible Form

The membrane stresses in a shell of revolution subject to uniform internal pressure p are given by the well-known expression,

$$N\varphi = pr_2/2$$

$$N\theta = pr_2(1-r_2/2r_1) \quad (3)$$

where N_φ and N_θ are the meridional and circumferential stress resultants, respectively, and r_1 and r_2 are the radii of the first and second curvatures of the surface. The condition that no wrinkles occur in the membrane is $N_\varphi > 0$ and $N_\theta > 0$ which with Eq.(3) gives

$$r_2 \geq 0$$

$$r_1 \geq r_2/2 \qquad (4)$$

After some considerations it may be found that the condition of the shallowest possible pneumatic form is

$$r_1 \geq r_2/2 \qquad (5)$$

or in an analytical expression

$dz/dr = r^2/\sqrt{r_0^4 - r^4}$

where z is the coordinate along the axis of the dome, positive downward, and r is the horizontal distance from the axis, r_0 being the radius of the peripheral circle.

The shallowness ratio of this surface is

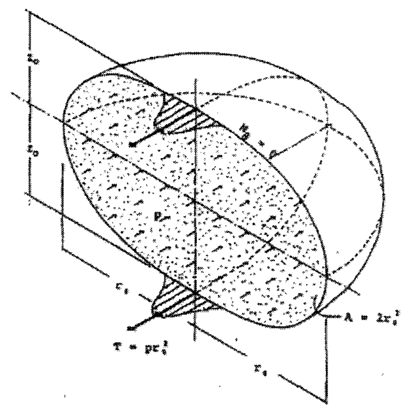
$\lambda =$

where Γ denotes a Gamma function.

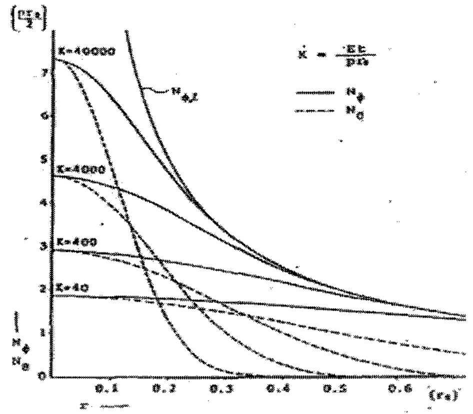
For the critical ellipsoid that is the shallowest of those which are possible by pressurization without wrinkles, $\lambda = 1/\sqrt{2} = 0.7071$. So the surface obtained above is 1.5% shallower than the critical ellipsoid.

It is known that in this surface $N_\theta = 0$ and $rr_1 = r0^2/2 =$ const. From the above relations one may see that the curvatures r1 and r2 are infinity at the apex, and it causes the stresses and displacement to become infinity at this point. Singularity of the surface as characterized by the above should be given due consideration.

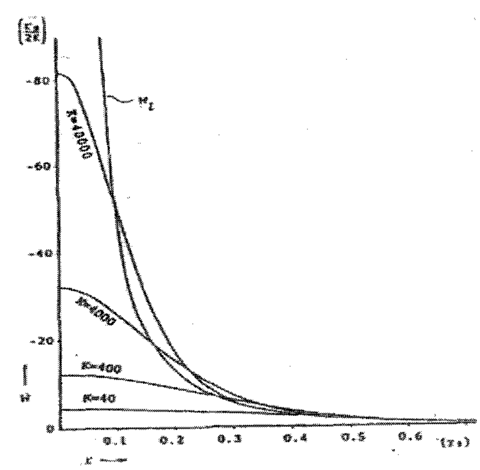
Nonlinear analysis of the surface in the vicinity of the apex reveals that the singularity does not occur in the actual dome where the stresses distribute as shown in Figs.7 & 8, and the deforemation as in Fig.9.(detailed discussion in Ref.[16]).



〈Fig. 7〉 Stress in shallowest dome



〈Fig. 8〉 Stresses near the apex



〈Fig. 9〉 Deformation near the apex

3.2 Shape Test of the Shallowest Surface

To see the possibility of the shallowest surface to be pressurized without wrinkles, a model test was carried out with plastic film. The model is a complete surface or a balloon having the shape of the shallowest membrane surface. The specified dimension of the model is such that the diameter of the equatorial circle is 100 ㎝ and the total height of the balloon is 59.9㎝.

Polyester film of 0.075㎜ in thickness is used as the skin material. The balloon was inflated by air to the internal pressure of 0.01～0.03 N/$㎠^2$. No wrinkles were observed on the surface of the balloon. For comparison a balloon in the shape of an ellipsoid of revolution which has an equal flatness ratio to the above was also tested. It can be clearly seen in the figure that distinct wrinkles are formed along the equator of the ellipsoid, as is readily expected from the fact that the balloon is far flatter than the critical ellipsoid.

4. METAL－MEMBRANE STRUCTURES

4.1 Strip-Membrane Structures

Tension Structures such as tents and pneumatic structures have almost exclusively been adopting fabric or film of synthetic resins or fiberglass as their skin materials. On the other hand, membrane structures of metallic skin have also been attempted(Ref.[12～15]).

These attempts have been based on advantageous characters of metallic materials such as steel, stainless steel and aluminum alloy.

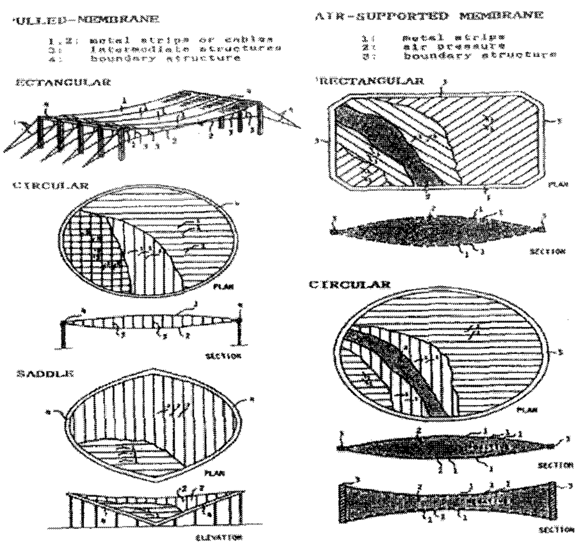
Most of them presuppose that metallic skins are homogeneous and isotropic. In some cases the skin materials are tailored to form desired three dimensional surfaces, while in some other cases flat skins are stressed up to their plastic regions by means of pre-loading or air- inflation to assume their final shapes, but what is common to them is that the thin metal elements are welded to each other to constitute a sheet of homogeneous and isotropic membrane.

However, it is neither easy nor economical to weld thin metal membranes all along their edges so as to develop the considerable part of their strength in all directions.

Another method of utilizing metal membranes for tension structures is to adopt them in the form of strips. This method which may be referred to as strip (or band or ribbon) system utilizes the strength of metal strips mainly in their longitudinal directions.

The strips are connected firmly at their ends to the boundaries so as to fully develop their strength in the longitudinal direction, but they are not connected or only subsidiarily connected to each other along their longitudinal edges.

Though the strength of the strips in the transverse direction is not fully utilized in this method, the fact that thin metal plates or sheets are most easily available in the form of coils would make it far more practicable and economical than the isotropic membrane method



〈Fig. 10〉 Strip-type membranes

previously stated. Applications of the strip system to tension structures, both hanging and pneumatic, are illustrated in Fig.10.

An example of the strip system applied to a pneumatic structure is reported below.

4.2 Air-dome without Hoop Stresses

When we try to realize a single-skin air supported structure or an air-dome of metal membrane, the difficulty which we may first encounter is how to shape it. An air-dome is generally not shallow, and consequently we need a form on which we put the cut elements of metal sheets and connect them with each other to shape the dome before we pressurize it. The form in this case should be accurate and rigid enough for the above work.

Moreover, the skin of an air-dome is normally stressed in two directions. Suppose we are to construct a spherical dome and tailor the dome with meridional strips just like a globe, then the connection between the strips should be strong enough to transmit the hoop stresses which are as big as the meridional ones.

Thus an air-dome of metal membrane demands reliable connection of constituent strips which requires considerable works in-situ on the form. It seems hardly possible for us to realize a dome of that kind economically. It may be possible only in some special cases. One of them is the case where the surface is very shallow. Another is the case where no hoop stress occurs in the surface when it is pressurized by air.

In what follows an attempt in the direction of the latter case is presented.

The existence of a surface that develops no hoop stresses under internal air pressure has been proved in the previous chapter.

So, it was attempted to utilize the "shallowest possible pneumatic form" for the purpose of obtaining a metal membrane air-dome in which no hoop stress develops under internal air-pressure.

4.3 Design and Construction of A Test Dome

4.3.1 General Idea

The benefit of adopting the shallowest possible surface for the metal membrane air- dome is dual. With the surface we obtain an air-dome of the least air volume with the least skin meterials and the least possibility of producing dead space along the periphery of the plan. Moreover, it enables us to do without any accurate or rigid forms for construction because of the following advantages.

As stated in the previous section, no hoop stresses occur in the surface when it is inflated by air. It menas that no change occurs to the surface if it cut along the meridians (except at the crown), as long as airtightness is kept there.

It further suggests that if we cut the skin strips so as to constitute the meridional elements of the shallowest possible surface and assemble them without any connection between each other, then the surface is obtained by pressurization and the adjacent elements automatically locate themselves side by side, provided airtightness is assured during the inflating operation.

4.3.2 Design and Construction

A test dome was designed to have a circular plan of 20m in diameter which was covered by the shallowest possible surface, the equator being on the ground level. So the theoretical height of the dome was 5.991m.

The dome was provided with a central skylight of 3m in diameter made of 200 thick transparent polyester film. A revolving door was to consist of 72 meridional strips of 0.3mm thick stainless steel sheet. When the inside air pressure is brought to the design value of 30mm Aq. above the atmosphere, each strip produces a tensile force of 1.27kN, or the maximum stress of 32.3N/㎟ at the connection to the tension ring. The strips are connected to the tension ring at the upper ends and to the footing at their bottoms by means of highstrength friction bolts. For mutual connection the strips are bent up along their edges and fastened by means of ordinary bolts at an interval of 300mm. The connection is made waterproof in a way similar to a batten seem.

Fabrication of the stainless steel strips was very simple. The developed shape of an element strip was patterned on a sheet in full size, and all the strips were cut to the pattern. No effort for special accuracy was asked. Cutting was made with ordinary hand shears(metal scissors).

After holes for bolts and notches were punched and notching was made with hand shears, the strips were lined with foamed polyethylene mats and transported to the site in coils.

Several ropes radially arranged over the canvas sheet and controlled by hands proved effective to assure uniform inflation of the surface under somewhat strong wind. As the inflation proceeded, the rise of the dome was increased and the outer ends of the strips which were set more than 3m away from their final positions got closer to the footing. When they came sufficiently close to the footing, they were connected by means of highstrength bolts to angles which had been fixed to the footing by anchor bolts.

While the air-supply was continued, the dome stopped to change its form and the internal air pressure began to increase rapidly. And it was observed that the adjacent edges of the strips automatically aligned side by side for connection to each other. The dome thus took its final shape.

The erection took less than two hours. Bolting and the seam treatment of the mutual connection of the strips took the following few days. The entrance work was done in that period.

The airtight canvas sheet was then taken out, and the dome was completed.

The dome has experienced a few strong winds, including the one which blew at a speed of some 30m/sec, without any damage.

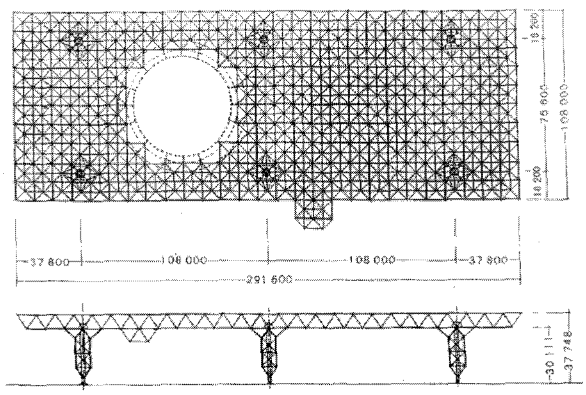
5. OTHER TYPES OF PNEUMATIC STRUCTURES

5.1 Polyester Film Air-Panels

Plastic films are one of the ideal membrane meterials when transparent roofs are desired. Double membrane air-supported panels which roofed the top of the grand roof of the Symbol Zone for EXPO'70(Fig. 11) are an example of such application.

The author in cooperation architecturally designed the grand roof of the Festival Plaza by Kenzo Tange, and structurally with Yoshikatsu Tsuboi.

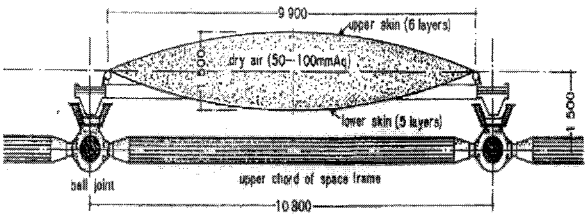
243 pieces of the transparent air-roof panels were used to fill the 10.8 m×10.8m grids of the upper chords of the space frame.



〈Fig. 11〉 Grand Roof of symbol zone, Expo'70

A typical section of the roof panel is shown in Fig.12. The skin material of the roof panel is biaxially extended transparent polyester film with a thickness of 250μ. The film has a good mechanical property. The film was produced in an endless strip of 1,100mm in width. Each of the upper and lower skins is composed of several layers of rows of the filmstrips.

The direction of rows of a film layer is perpendicular to those of the adjacent layers to form a kind of overlapped network of the filmstrips. To the outmost surfaces are added layers of specially processed film of 200μ in thickness for a better resistance against ultraviolet rays. The inside air pressure is usually kept 50mm Aq. above the atmospheric pressure, which is raised to 100mm Aq. in case of very strong winds.



〈Fig. 12〉 Polyester film air-panel

5.2 Mesh-Reinforced Airdomes

The skin of pneumatic structures usually plays a dual role of keeping the differential air pressure between exterior and interior spaces and resisting the tension induced in it by the external loads as well as the air pressure. For larger structures where the fabric skins are not strong enough to cover the whole roofing areas, cables are sometimes employed to reinforce the skins. In this case the skins tend to take more the part of airtightness than that of tension members which is mainly taken by the reinforcing cables at large. Generalization of this tendency suggests a rational pneumatic structure in which the above dual role is more separately taken by different systems.... skin materials for airtightness and mesh, networks and/or cables for tensile resistance.

5.2.1 Principle of Mesh-Reinforced Airdomes

Mesh-reinforced air domes jointly developed by the late architect Y. Murata and the author are examples of such pneumatic structures. The skin of the domes consists of a very thin plastic film being pressed by the differential pressure against a net of comparatively fine meshes which covers the space between boundaries and/or reinforcing cables.

The role of the plastic film is to keep each mesh of the net airtight, and as the size of the mesh is of the order of some centimeters, the tensile strength required for the film is very small. Other properties of the film such as ductility, transparency and durability are therefore more important.

No connection is needed between the net and the film, as the latter closely contacts the former by the differential pressure. For the area where a high external pressure is expected to occur under strong wind another layer of the net and film is overlaid to prevent the inner film from being pushed apart from the net.

One of the special features of the system is that it is not neccessary for us to worry about the cutting patterns of the net or the film, as domes of different boundary shapes can be produced by a flat net and a flat film.

5.2.2. Airdome for Portopia'81

A typical example of this system if Fuyo Group Pavilion for PORTOPIA'81 Exposition in Kobe held in March 1981. The pavilion is a mesh-reinforced airdome of 36m in diameter accommodating four inside domes of space frames covered with a mesh-reinforced PVC film. The inside domes are connected to each other by means of corridors and their interior spaces with a normal (atmospheric) air pressure are used for exhibition purposes.

Only the space between the outside and inside domes where plants are grown is pressurized to 30mm Aq. (to be raised up to 70mm Aq. in case of) above the atmospheric pressure. The skin is again reinforced by wire ropes arranged along 12 meridians and on the top. Each rope is bound with the mesh at several points along its length.

5.2.3 World Orchid Conference Pavilions

A more recent example of the same system may be the two Pavilions for the 12th World Orchid Conference held in March in Tokyo, designed by the author in cooperation with the late Architect Y. Murata.

The Dome I of the Pavilion covers a circular plan of 75m in diameter, having a height of 19.5m. The airdome is reinforced by two-way wire ropes spaced at some 5m. Each bay of the dome bounded by the wire ropes is structurally constituted by a fishing net of 10㎝ mesh with PVC film of 0.1mm thickness for air-tightness extended inside the net. The internal air pressure is kept 30mm Aq above the atmosphere for normal conditions which is raised up to 70mm Aq against strong winds and snow load.

5.3 Flying Membrane

There is a tradition in Japan for people to fly fabric carps on the 5th of May to celebrate the Children's Day. Traditional flying carps which are made of cotton fabric are almost exclusively fabricated in a small city named KAZO located in the suburbs of Tokyo. The normal size of flying carps is 3 to 5 meters in length.

A few years ago the author was consulted by the city about the possibility of flying a 100m long carp which people of the city had made for the purpose of advertising their city.

The questions were threefold:

1) Can the jumbo carp fly?
2) Can the cotton skin stand the flight?
3) Other technical problems.

The most interesting point of the problem was that people used the same fabric as for the carps of normal size. A dimensional analysis for flying conditions of the jumbo carp, calculation of membrane stresses and a series of wind tunnel tests revealed that:

1) The jumbo carp begins to fly at the same wind speed as for a carp of normal size.
2) In spite that the skin is subject to twenty to thirty times as high stresses as those of a normal size carp during the flight, the cotton fabric is strong enough to stand it.
3) But the seams of the membrane are too weak to stand the stressed during the flight.
4) Technical problems such as details of the mouthpiece and how to raise the carp up to a necessary height can be solved in an economical way.

On the basis of the above informations the jumbo carp was consolidated along the seams, provided with a specially designed mouthpiece, and it was raised by means of a truck crane on a fine day of April, 1988. The jumbo carp, a huge flying membrane, began to fly with the breeze, and swam elegantly in the sky.

Since that time the flight of the jumbo carp has been one of the most important annual events of the city.

REFERENCES

1. Bulson,P.S., "The Behavior of Some Experimental Inflated Structures", Proc. 1st. Col on Pneu. Str., 1967, Stuttgart
2. Kawaguchi,M., Chin,Y., "On Nonlinearity of Prestressed Suspension Roofs", Reprot of Tech.

Colled of Hosei Univ. No.17,1968 Tokyo
3. Siev,A., Eidelman,J., "Stress Analysis of Prestressed Suspended Roofs",J.Str.Div.,Proc. ASCE,Aug. 1964
4. Tsuboi,Y., Kawaguchi,M., "The Space Frame for the Symbol Zone of Expo '70",Proc. LASS Pacific Symposium PartII, Tokyo & Kyoto, 1971
5. Kawaguchi,M.,et al., "Engineering Problems of pneumatic Structures", Proc. LASS Pacific Symposium Part II, Tokyo & Kyoto, 1971
6. Kawaguchi,M., et al., "A Study on Beam-Type Pneumatic Structures", Proc. AIJ Annual Convention, Sapporo, 1978(in Japanese)
7. F.Otto et al., "Zugbeanspruchte Konstruktionen", Ullstein Verlag, 1962.
8. Bauer,L., et al. "On the Collapse of Shallow Elastic Membranes", Proc. Symp. on Nonlinear Elasticity, Univ. Wisconsin, USA, 1973
9. Bomberg,E. et al., "Nonlinear Theory of Curved Elastic Sheets", Q. App. Math., 1945
10. Marguerre,k., "Zur Theorie der Gekrummten Platte Grosser Formanderung", Proc. 5th Int. Cong. App. Mech., 1938
11. Taylor, G.I., "On the Shapes of Prarachutes", Paper written for the Advisory Committee for Aeronautics, 1919
12. Siev,A., Kuentz,C., "Air-Inflated, Stainless Steel Membrane Roof", LASS Pacific Symp. Part II, 1971
13. Ludkovski,I.G. et al., "Thin Sheet Membranes as Hanging Roofs", loc. cit.
14. Schlaich,J., Greiner,S., "Vorgespannte Flachentragwerke aus Metallmembranen", Bauingenieur 53, 1978
15. Greiner,S., "Membrantragwerke aus dunnen Blech", SFB 64, Univ. Stuttgart, 1983
16. Kawaguchi,M., "The Shallowest Possible Forms", LASS Bulletin No. 63, 1977
17. Kawaguchi,M., et al. "Engineering Problems of Pneumatic Structures", LASS Pacific Symp. Part II, 1971
18. Kawaguchi,M., Abe,M.,"Tests on Durability of a Plastic Film Employed in Pneumatic Roofs",A.I.J.Ann. Conv., 1978(in Japanese)
19. Kawaguchi,M.,"A Review on Innovative Spatial Structures in Japan", LASS Symposium, Bangalore, 1988
20. Kawaguchi,M., "Pneumatische Konstruktionen" Anniversary Publication for Frei Otto, "Der Umgekehrte Weg", Arcus, 1991