AN AIR INFLATED STRUCTURE

by

RICHARD BAKER MORRILL

and

KAY MILTON LOCKHART

Submitted in partial fulfillment of the requirements for the degree of Master of Architecture in the Department of Architecture at the Massachusetts Institute of Technology.

August 22, 1960

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Signature of Head of Department

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ABSTRACT

The Masters Thesis in Architecture is normally a test of the students acquired knowledge, where he is required to submit a design solution for some pragmatic problem. The thesis project is, in this respect, work essentially beneficial to the student as a completion to his formal education. The possibility exists in the Masters Thesis, however, for research and investigation into fields that indicate some potential architectural use, but which have not been developed. This research could give a direction for further development in the future.

> The course of architectural development in the second half of the Twentieth Century is vague and uncertain. A refinement of now-existing forms and ideas is valuable to a point, but there is a general consensus that the work of the first half of this century left many problems unsolved and many others unrecognized.
>
> There are perhaps three major avenues of further development which have been proposed: A more intensive investigation and explanation of the structural potentialities of modern materials and the formal potentialities of these structures; a shift of emphasis away from the problems of individual buildings to those of the total environment, particularly to those of the urban complex; and finally a reintegration of contemporary architecture with our cultural tradition, and a wider acceptance of human as well as formal needs.[1]

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[1] Student Publications of the School of Design, Editorial, North Carolina State College, Raleigh, North Carolina, Vol. 6, No. 3, May, 1957.

Research into a facet of architecture that employs new materials and possibly new structural concepts might not necessarily be an end in itself, but a phase of a subject that would provide some base for a continuing study in the general problems of the system. Others with a common interest could use this material and continue to broaden its scope so that a fund of knowledge becomes a useful tool for future pragmatic solutions.

Brief investigation into the air structure concept has been motivated by an interest in the potential of new flexible materials to create long spans when the material is made rigid through air pressure. This economy of material for certain span conditions seems appealing, and with the proper technology perhaps could result in low cost structures for various uses.

Relatively little investigation of air systems has been done outside of research for specialized functions for the Army and Air Force. This implies a fresh area for research into the structural and architectural implications of air structures.

This report contains a description of various experiments of air structural systems and the observations made from these studies. A proposal is made for a system based upon the background of experiments completed. The proposal is made only as a graphic presentation of a possible development and not as a conclusion to the investigation. The conclusion reached in this project is better expressed in the summary, which attempts to catalog the special data developed from this research.

The Authors have initiated a collaboration on this project, in the belief that common interests and pooled effort can work to mutual advantage. This belief extends to the exploitation of an exchange of ideas that can further enrich and elaborate an elemental concept.

August 22, 1960

Pietro Belluschi, Dean
School of Architecture and Planning
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Dean Belluschi:

In partial fulfillment of the requirements for the degree of Master of Architecture, we hereby submit this thesis entitled, "An Air Inflated Structure".

Respectfully,

Richard Baker Morrill

Kay Milton Lockhart

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LIST OF FIGURES AND ILLUSTRATIONS

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INTRODUCTION

Objectives:

The development of an air inflated system or systems that utilizes the concept of double wall construction with air under pressure providing the rigidity for the structure.

Exposition:

Air structures have had a relatively recent development stimulated by the interest given to them for military application and their subsequent use for industry. The initial projects involving air structures sought to solve the need of a space enclosure for operating radar equipment that would provide good radio frequency transmissability. Development and research on air systems for radar installation enclosures proved their feasability and they are now widely used for this purpose. Recent developments in rockets and ballistic missiles have used air structures as housings that could be dismantled readily if launching were imminent. This research under Governmental auspices has been responsible for the acceptance of air structures for industrial use as storage shelters and recently for the enclosure of many varied activities.

All of the projects mentioned above are air structures of one membrane. The space enclosure is created by increasing the pressure within the total space and the membrane takes its patterned form due to internal air pressure which stiffens and stabilizes the membrane. The stresses to the system must be entirely resolved in the membranes, and the desire to maintain a relatively constant stress pattern over the surface has led to development of doubly curved surfaces of revolution. When inflated, this geometry not only establishes a relatively constant stress pattern in the membrane, but provides a shape that will best resolve aerodynamic loading.

This type of air structure is simple in concept but is subject to wind and snow loads, and to all kinds of weather conditions the same as any other type of structure and they must be properly engineered to support such loads. The design of these air structures however, is far different from that of a conventional building. They may be considered thin shells, stiffened and stabilized by maintaining a sufficient air pressure differential within the structure to pre-tension the "shell" so that it can resist compression loads. As the flexible shell has no bending stiffness, it must resist non-uniform loading by distortion and redistribution of load.

The advantages in using the single membrane type of air structure are:

lightweight and small package size
economy of material
simplified joinery
ease of erection
structural efficiency

The disadvantages are:

total space is secured for inflation
ground anchorage is critical
form is limited
(articulation and a sense of scale are not present)
failure in the wall could propagate
(could cause panic in a public space)

For these reasons and for a desire to broaden the scope of air structures, the authors have decided to work with "cellular" systems only. This type of system would utilize a double wall unit that would gain its rigidity by inflation of each unit; these units would then be connected together to form a system. Inflation pressure would be constant throughout by proper valving between units. This cellular system lends itself to a greater variety of forms and now offers the possibility of opening up the space by merely providing a roof enclosure. Any failure in one unit would not propagate throughout the system and a damaged unit could be sealed off by special valving, and easily be replaced.

The disadvantages to this structural system would be its greater complexity in number of units, joinery conditions, and perhaps a system that is less efficient structurally than a single wall system.

Approach

1. Investigation of existing developments in air structures in relation to recent developments in membrane and thin shell structures to create an understanding of the static forces that

operate in an air supported system.

2. Determination of the structure in form and surface that satisfied structural requirements within the program requirements of the general span and use activity to be considered.

3. Type of building material feasibly satisfying structural requirements. (Inquiry into current trends in industry to produce materials adequate for air inflated systems.)

4. Within the structural system, determine a geometric breakdown that satisfies; structural requirements, esthetic considerations, acoustic control, and erection requirements.

5. General structural analysis including static solutions and details of size and support.

6. Construction and erection procedures in relation to program considerations.

7. Record data during design phase.

Note: The approach that has been cataloged above will give a general format to follow in arriving at a design solution. To implement this format the authors will construct models of elements of air systems in the belief that this will give a graphic understanding of the action of compressed air and membranes in tension under various conditions of material and geometry. The general impressions to these experiments will be noted.

DESIGN CRITERIA

General Building Type

The choice of a particular structural system was motivated, as noted, by other than program requirements. Structure does not exist apart from some functional need and though the authors' interest has been primarily in relation to the structure, we do not view this apart from activities to be served, space requirements of use, and considerations for the character of the structure in relation to its use. The logical design sequence emanates from an architectural problem to be solved. This sets limits on the design and also serves as a point of departure for design. In general this will set span and space requirements and create the special design criteria apart from structural considerations that relate to a specific usage.

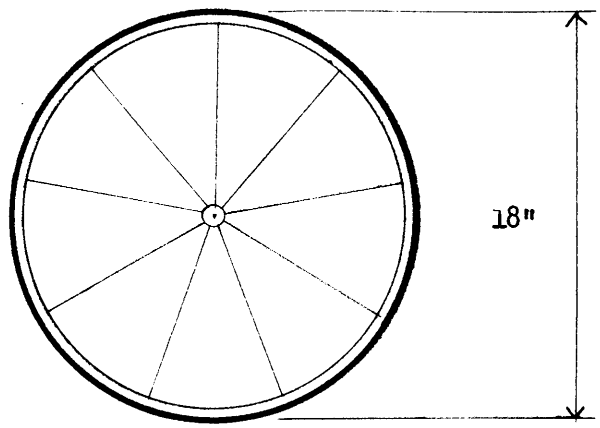
The advantages of an air system appear more numerous in a long span system mainly because of the economy of weight and material. The economy in terms of financial expense and construction seems a possibility with further development. One restriction in terms of life of existing fabrics leads to the development of temporary and portable systems. These limitations have suggested uses that could be well satisfied with an air system.

Certain spectator activities, such as hockey, tennis, swimming, skating, etc., require special span and space requirements and are affected by seasonal environmental changes. These would benefit from a space enclosure that was economical and could be changed or removed depending upon seasonal conditions.

The program requirements for these activities are well defined and concentration can be given to space enclosure, problems of lighting, mechanical requirements, acoustics, and services that relate directly to the general structural parti.

EXPERIMENTS OF AIR INFLATED SYSTEMS

TEST 1 - FIGURE I



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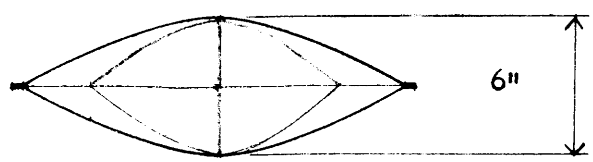


SECTION

DESCRIPTION

9 equal divisions patterned to form
a pyramid of 9 sides

MATERIALS

Rubberized fabric with taped and
glued joints

Illustration board compression ring

TEST 1

1. Intention of test - To observe the reaction of compressed air on a membrane surface and to discover forces at work within the structural unit.

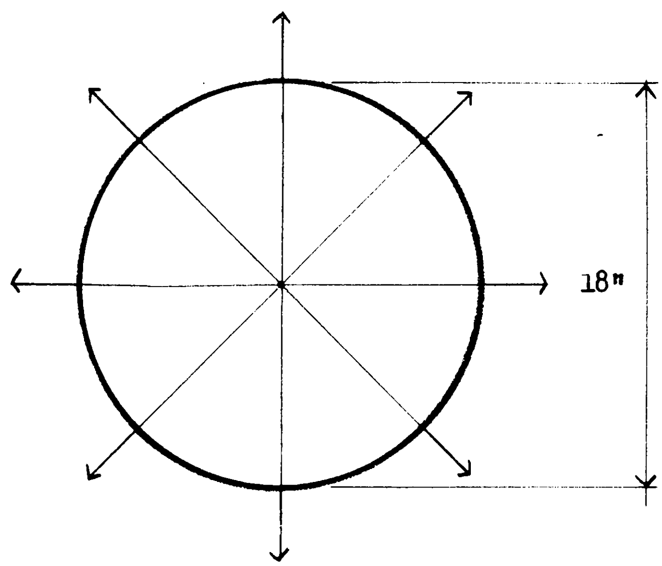
2. Observations - The first observation was that the continuous edge member tended to warp decidedly upon introducing air within the membranes. This was caused by the force of air on the membranes tending to pull inward on the edge member, thus resulting in a pull that was exerted equally in all directions due to its circular shape.

It was also learned that the expected and desired arching of the membranes never appeared due to lack of rigidity of the edge member and due to the improper patterning of the material. As the somewhat conical shape was maintained under high and low degrees of tensile stress in the membranes, it was decided that the material should be patterned to the desired form before air is introduced into the structure. Not only does it take considerable air pressure to change the shape of an inflated unit, if the fabric is relatively non-elastic, but it introduces unequal tensile stresses over the surface of the membrane.

3. Conclusions - It was decided that a model should be constructed employing both a more rigid frame, and a pattern for

the membrane panels that would allow for a more constant curvature over the structure's surface. This would tend to distribute the tensile stress more equally across their surfaces.

TEST 2 - FIGURE II



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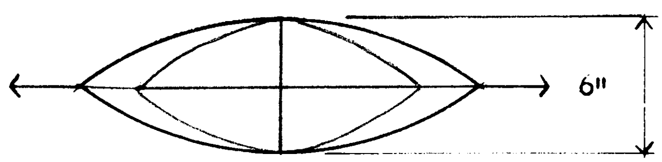


SECTION

DESCRIPTION

8 equal divisions of the surface patterned to form a circle in plan and curved surface in section once inflated

MATERIALS

Rubberized fabric, stitched seams
"Celotex" compression frame
cotton cord tension lines

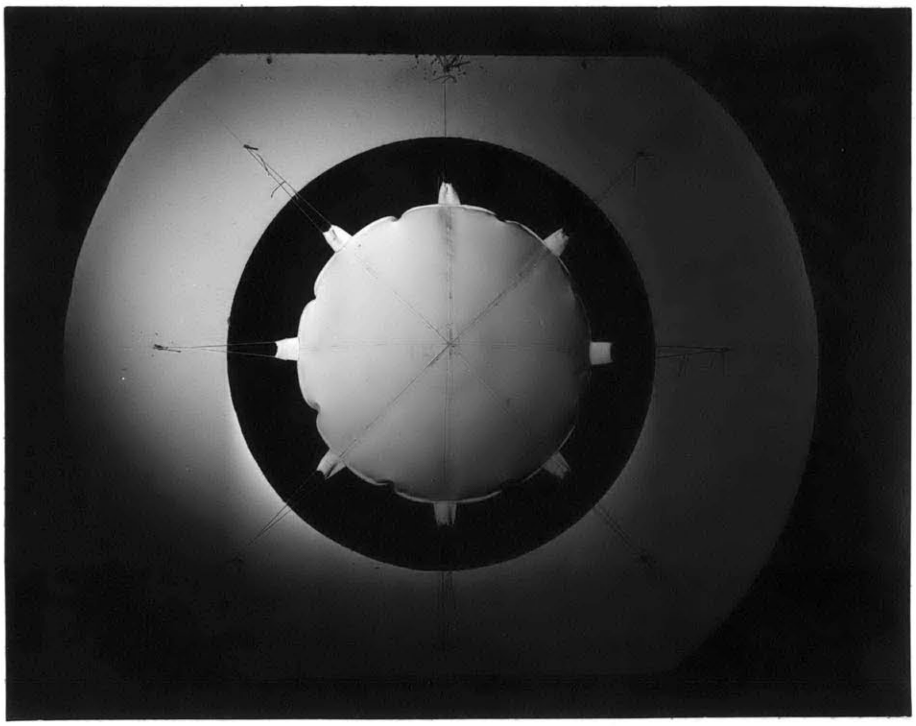


FIGURE III, PHOTOGRAPH OF MODEL, TEST 2

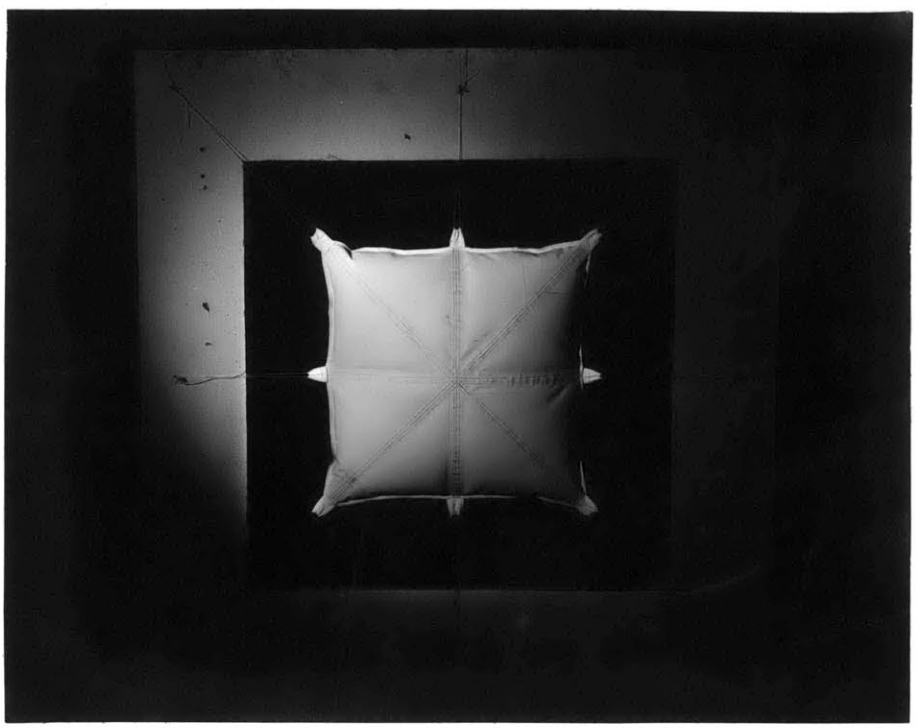


FIGURE IV, PHOTOGRAPH OF MODEL, TEST 3

TEST 2

1. Intent of Test - The construction of an air inflated unit with a greater curvature in section which will allow a more equal distribution of tensile stresses in the membranes than the previous conical shape. To observe forces at work within the structure and to observe the reactions of the tensile stresses developed in the membranes acting on the points of restraint.

2. Observations - Upon inflation of the structure, it was discovered what had initially forced the rather weak compression ring of the previous experiment to deform and warp. By supporting the structure at eight equally spaced points around the perimeter, buckling of the edge was observed between each support. The cause for this action of the edge was that as the structure tended to reach a sphere, there was a greater force being exerted on the top and bottom membrane than on the line of the edge. The edge was essentially being pulled towards the center of the structure, due to the air pressure working on the two membranes. As the circumference of the structure was being reduced by greater and greater air pressure, the edge was put into compression and once the compression forces overcame the tensile forces in the membrane, the edge buckled. This

observation resulted in the conclusion that a continuously supported edge member must be employed for proper stability and equilibrium of forces.

We observed that the surface of the two membranes acted far more uniformly under air pressure than the previous experiment. Even here it was realized that there were tensile stress concentrations on the membranes and that by increasing the cross-section curvature of the surfaces we had only lessened these stress concentrations.

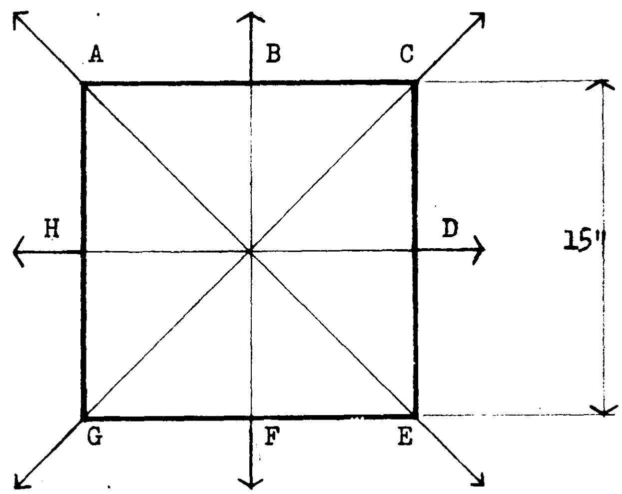
3. <u>Conclusions</u> - A gas such as air operates according to well known physical principles regarding volume and pressure. A sphere is the ideal shape for a container of gas under pressure for it provides a maximum volume in relation to surface area. If a container is rigid and gas in introduced under pressure, the container will maintain its shape until the tensile stresses created in the container by the pressure exceed the structural limits of the container. If the container is non-spherical, stresses upon the surface of the container will not be equal and deformation will likely occur at points where compressive stress takes place. If the container is spherical then deformation will only occur when the tensile limit of the containing material is reached.

This appears to be a governing factor in flexible air containing units when air under pressure is introduced. A flexible material cannot take compression unless the material has been pretensioned. A flexible unit then, under internal pressure, operates most efficiently if it is spherical, or if it is not spherical, then some external force must be introduced to equilibriate the unequal stress patterns that will occur on the surface of the unit.

It was at this time, after the construction of two air inflated models and observing their conditions and characteristics, that the use of this type of structural unit became an important consideration. Due to the comparative lightness in weight of an air inflated system, it was decided that one of the structure's attractive features is its possible portability. The development of the structure could then regard small cellular inflated units that could be handled easily, assembled easily, and put into operation with a minimum of specialized work done in the field.

The development of a unit that could be connected with other similar units would precede an experiment which concerned itself with the composition of adjacent connecting units. As joinery of component units of a structural system is of a prime consideration, and the shape of each component and the intersection of units is critical, the geometry of units and a geometric system for these units becomes a major element of the design. Since most previous connections have been done with a zipper method with a high degree of success, the employment of a similar technique seemed feasible. In consideration of the problems involved in connecting circular forms together, cellular units should be constructed of forms that are easier to connect together with a zipper technique. As a straight line, retangular edged unit is perhaps most convenient in connection, it was proposed that a square inflated unit be constructed.

TEST 3 - FIGURE V



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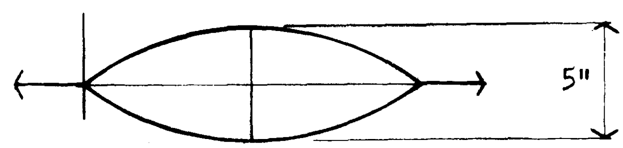


SECTION

DESCRIPTION

8 equal divisions patterned to
form a square in plan and a curved
surface in section once inflated

MATERIALS

Rubberized fabric
Stitched and glued seams
"Celotex" compression ring
Cotton cord tension lines

TEST 3

1. Intent of Test - The construction of an air inflated unit, rectangular in plan and curved in section, that would be most ideal regarding joinery. To study internal and external forces of such a unit once inflated, and to devote particular concern to the eventual structural form of which this unit would be a part.

2. Observations - The first observation upon inflation of the unit was the considerable amount of buckling along the edge, between AB, BC, CD, DE, EF, FG, and GH. Not only was there buckling on the edge, but there was a noticeable crease that developed in the material between BC, CF, FG, and HB. This latter buckling was thought to be caused by improper patterning in the cut of the material, plus the fact that there exists a lower membrane stress in the corners of the inflated unit. It was also noted that there was a tremendous concentration of tensile stresses in the membranes on both sides of lines BF and DH. These stresses were caused by air pressure forcing the upper and lower membrane apart, and since points B, D, F and H are the nearest to the center of the unit (Z axis), where the two membranes are the furthest apart, the tensile forces in the membrane are the greatest at this point. Essentially what is happening is that as the air pressure is forcing the top and

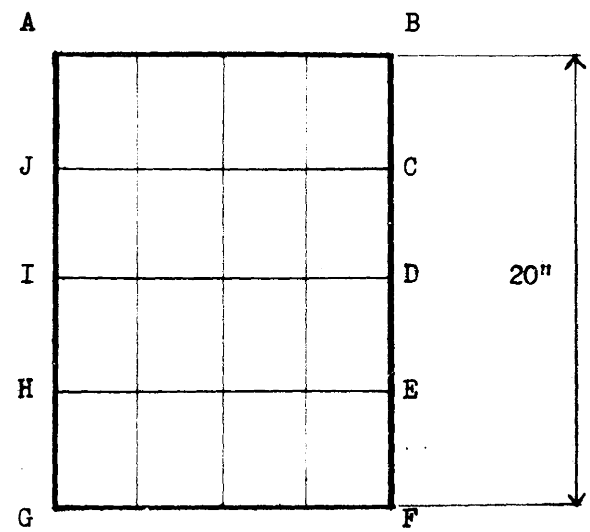
and bottom membranes apart, the edge of the unit is being pulled towards the center of the unit (Z axis), so that the air is forcing the material into a spherical shape. As long as there is continuous restraint around the edge the unit will keep its form, but without this support at the edge, and with sufficient air pressure, the square form will tend to approach a sphere.

3. Conclusions - Perhaps the most important conclusion was that the edge of each unit must have a sufficient depth to have any kind of efficiency in a structural system. It was reasoned that if the surface area of the edge walls were increased the tendency to buckle would be lessened because the area of the side walls would more closely approximate the area of the upper and lower membranes, and the air pressure would stress all membranes more equally throughout the unit. As the depth of the edge becomes greater, the unit more closely approaches a spherical shape, and as a sphere carries tensile stress in its membrane more equally than any other shape, the increase in depth of the side wall membranes creates a far greater structural efficiency.

In the consideration of a structural system the increase in depth of the side wall has some obvious advantages. The greater rigidity between units and a resultant greater stability to the entire structure would be the first advantage of this change in depth. Secondly, there would be less of a tendency for each unit to deform in buckling, and a far more constant shape would be maintained for the entire structure under lower and higher air pressure differentials. Thirdly, the increase in depth would aid in the transfer of shearing stresses throughout the structure due to the increase of material in the side walls or "webs" of the structure.

It was decided that a series of experiments and models should be initiated of structural systems incorporating the small air inflated units that have been studied to this time. It was proposed that a simple barrel vault be erected as a linear unit, to study the effects of air inflation in a vault form.

TEST 4 - FIGURE VI



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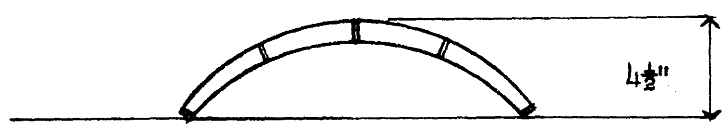


SECTION

DESCRIPTION

4 equal divisions of vault with illustration board arches, edges, and purlins

MATERIALS

Rubber sheeting
Glued joints
Illustration board framework

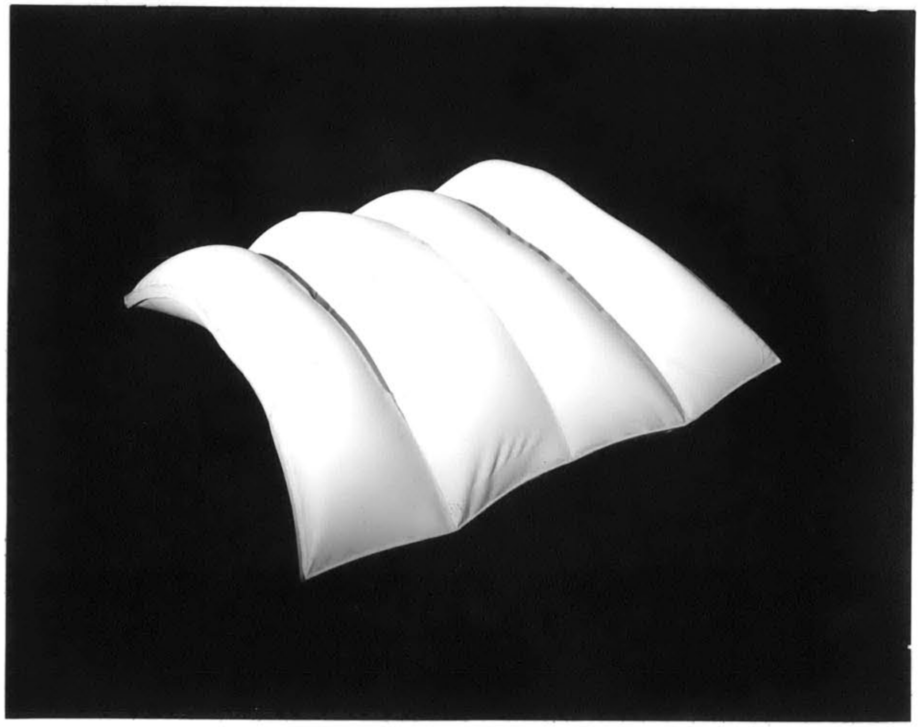


FIGURE VII, PHOTOGRAPH OF MODEL, TEST 4

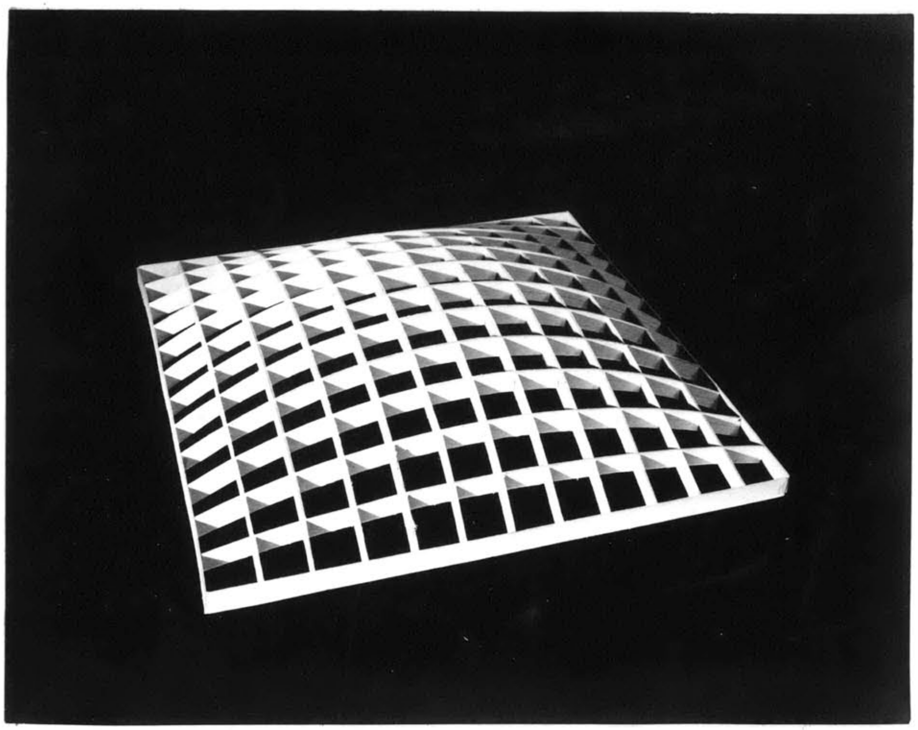


FIGURE VIII, PHOTOGRAPH OF MODEL OF "PUCHA" SURFACE

TEST 4

1. Intent of Test - The construction of a simple barrel vault using curved inflated arches, to study internal and external forces at work within such a system.

2. Observations - As air was introduced into the model it was observed immediately that the rigid edge members at the spring line of the vault were deformed inwards by air pressure at work on the upper and lower membranes. The rigid arch members AB and GF were also pulled inwards due to the same action of the two membranes. The under surface or lower membrane of the vault showed considerable buckling along its surface, except for the lines where the rigid arch members restrained the material. The resultant action of the air inflation was one of which the entire vault tended to flatten out; plus, tending to pull in or foreshorten the length of the structure.

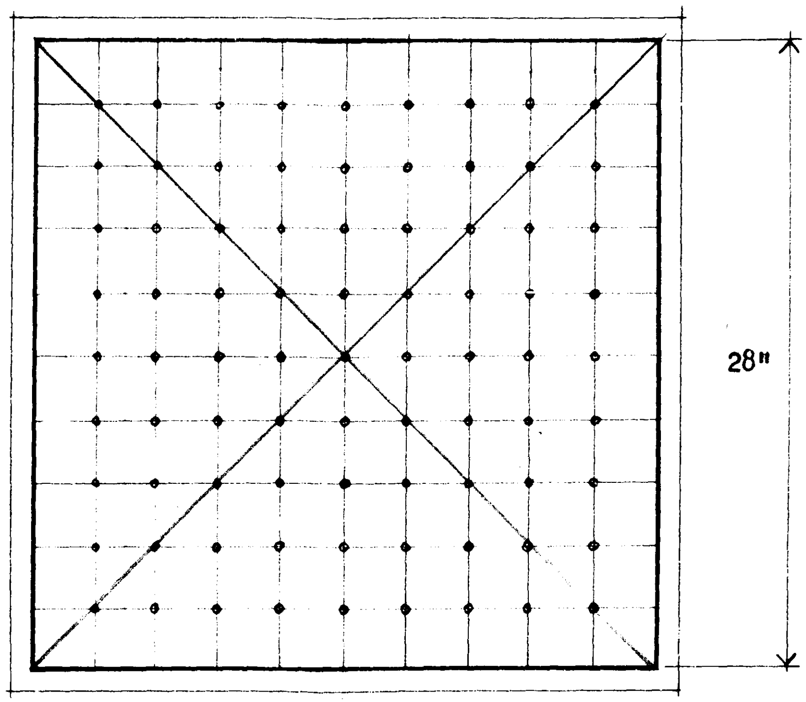
The rigid edge of lines BC, CD, DE, EF, etc. were bowed in due to the action of the upper and lower membranes pulling on its surface. The same type of action is happening in the rigid arches, for if it were not for the rigid purlins that provide a compression strut, the entire vault would greatly foreshorten. The buckling on the lower membrane is due to air pressure tending to reduce the membrane curvature, putting this membrane into compression while the upper surface is put into extreme tension. As the lower membrane is forced from a flat surface to a lesser curvature under air pressure, it will force the material to occupy a smaller area and obviously produce the resultant buckling.

The tendency for the entire vault to flatten out is due to the unequal tensile stresses in the upper and lower membranes. As there is far greater tension in the upper than in the lower membrane, the edges AG, BF are being pulled up, while the center of each arch is being pushed downwards.

3. Conclusions - This structural system is completely dependent upon the rigidity of a stabilizing frame to keep the vault from greatly deforming and then failing. The use of a separate structure between which an air inflated structure would span, showed disadvantages in lack of structural clarity and portability.

A barrel vault with unsupported ends is not an ideal solution for a structure using only air inflated units whether of large units as an arch or smaller units forming the vault. This vault is only of single curvature and a double curvature is required to eliminate shear and bending stress. Due to these many problems of structural inconsistencies, it was proposed that the next test be made with a surface of double curvature. In such a surface it was felt that many of the problems that were found in this vault would be overcome, and the need for a rigid frame would be eliminated.

TEST 5- FIGURE IX



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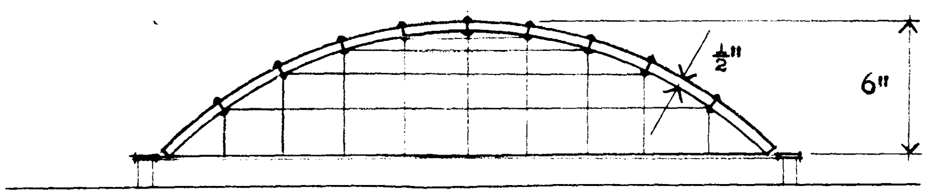


SECTION

DESCRIPTION

"Pucha" surface, 8 divisions patterned to form surface, connections between upper and lower membranes at points

MATERIALS

Rubberized fabric with vulcanized joints
Nut and bolt spacers
"Celotex" rigid tension frame

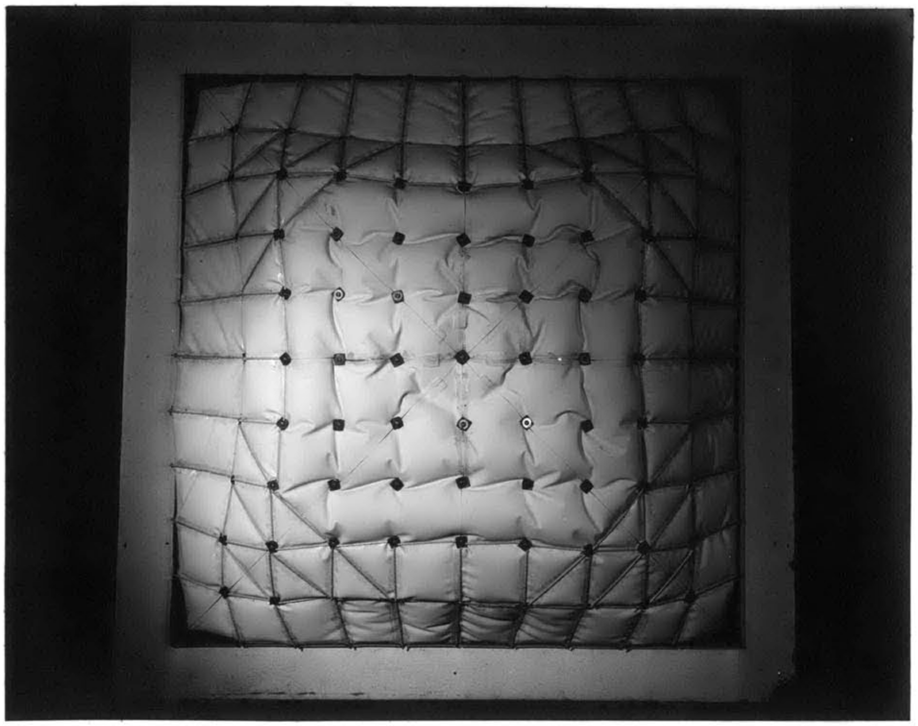


FIGURE X, PHOTOGRAPH OF MODEL, TEST 5

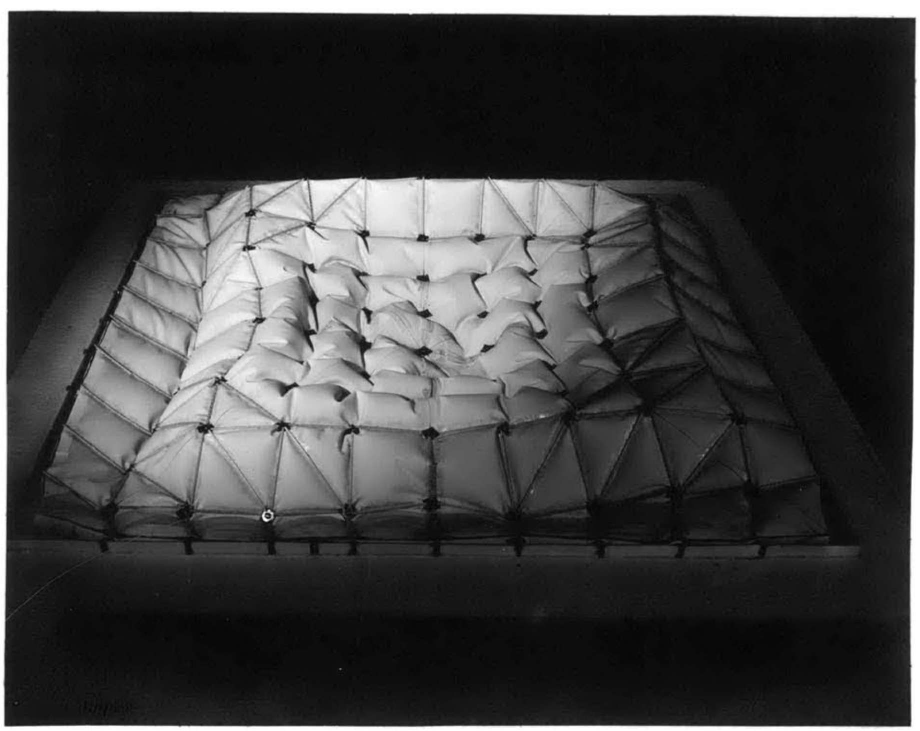


FIGURE XI, PHOTOGRAPH OF MODEL, TEST 5

TEST 5

1. Intent of Test - To construct a doubly curved surface that when inflated, could be studied regarding internal and external forces acting on and within such a structure.

2. Observations - The material was pre-patterned to take the form of a "pucha" and the upper and lower membranes were connected together at points over the surface of the form. By introducing air into the system it was to be determined if the form would naturally take its shape.

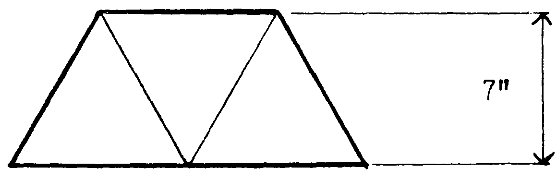
As air was induced into the system the material between point supports began to be put into tension, and as there were no restraining members other than the point connections, the material continued to billow out. This action continued across the entire area of the model so that the resultant appearance and form of the model was similar to an air inflated mattress that was exerting a continuous pull on the rigid frame. The action of air inflation is the simple matter of air pressure working on the least surface of resistance, forcing the membranes apart and causing local buckling in the material and an overall foreshortening of the structure.

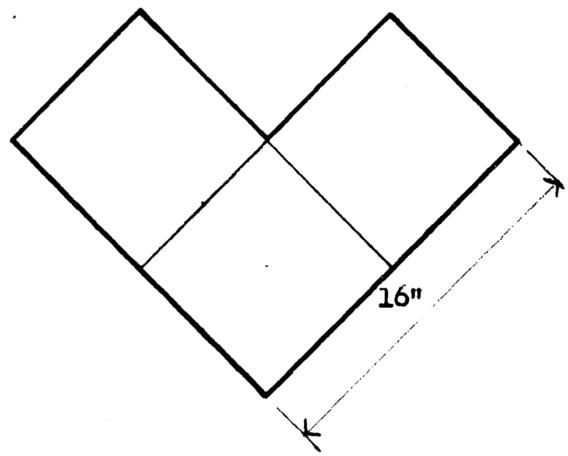
To assist this model in taking its form, rigid struts were applied to the surface of the membranes between each point support. As these were placed at the peripheral edge of the structure and extra supports applied at the four corners of the model, it was conjectured that this control over the buckling and bending in the system would be sufficient to make the model take its form. This proved itself to be fallacious, for the restraint of the membranes in the peripheral area of the structure had little to no effect upon the central area. This central area of the model (Ref., Figure XI) continued to buckle, so that instead of rising into the patterned curvature, this area tended only to pull inwards on the more rigid edge area. The excessive weight of the model should be considered out of scale to the model, but the basic reason for structural failure is the structure's inability to resist shear and bending stresses. Due to a flat curvature along the edge of the form and a reverse curvature that exists in the corners of the "pucha", there is considerable bending and shear stress acting in these areas. This beam action of the structure along the edge can only be handled by additional re-inforcement, in order that the structure can be considered stabilized with all forces resolved.

3. Conclusions - What has been observed in this experiment is that a structural system cannot be considered stable and in equilibrium, if the individual units are not also in equilibrium. If reinforcing struts are introduced between point supports on the

surface of the membranes, buckling and deformation of the surface are controlled when air is induced into the system. However, reinforcing struts do not necessarily create an equilibrium condition in the structure as a whole; bending and shear stress must be resolved. The possibility of creating an air structure within this frame of reference exists, but it would be desirable from the standpoint of portability and the development of an ideal or pure air system to create equilibrium without the need for compression members. To further this ideal it seems that further study must be given to the individual units. Factors of shape, stability, spacing and size appear extremely vital to the design of the structure. With this in mind the proposal was made to construct a series of small units that could be studied by themselves and in tandem with other units.

TEST 6 - FIGURE XII





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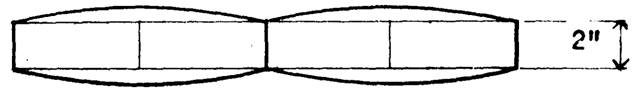


TYPICAL SECTION

DESCRIPTION

Two models - one executed with equilateral triangular units - the other with square units - both maintaining a 2" web - Units are glued to each other

MATERIALS

Rubberized fabric
Stitched and glued seams

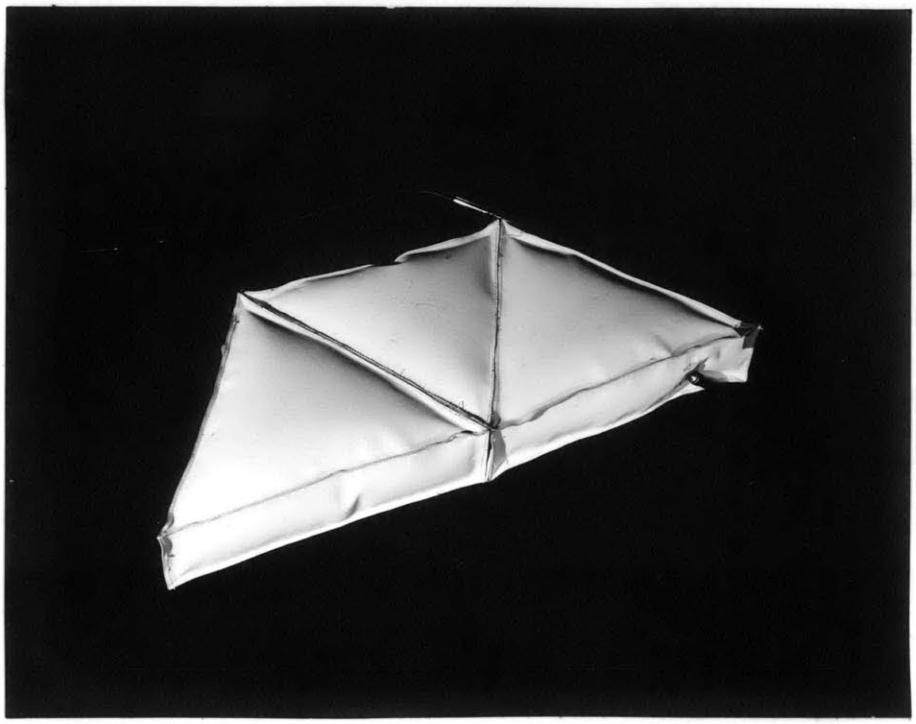


FIGURE XIII, PHOTOGRAPH OF MODEL, TEST 6

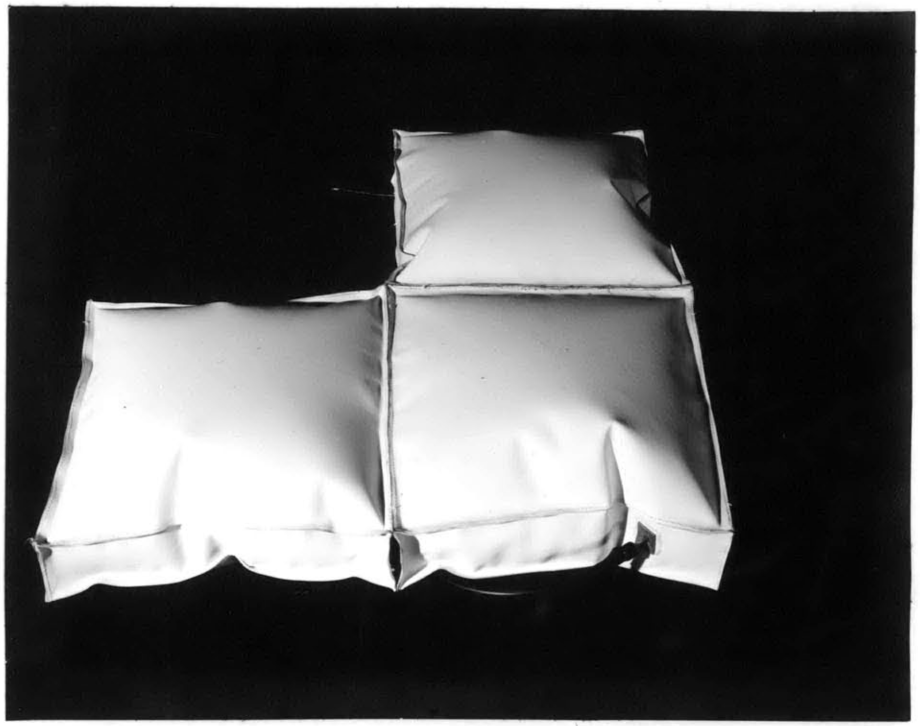


FIGURE XIV, PHOTOGRAPH OF MODEL, TEST 6

TEST 6

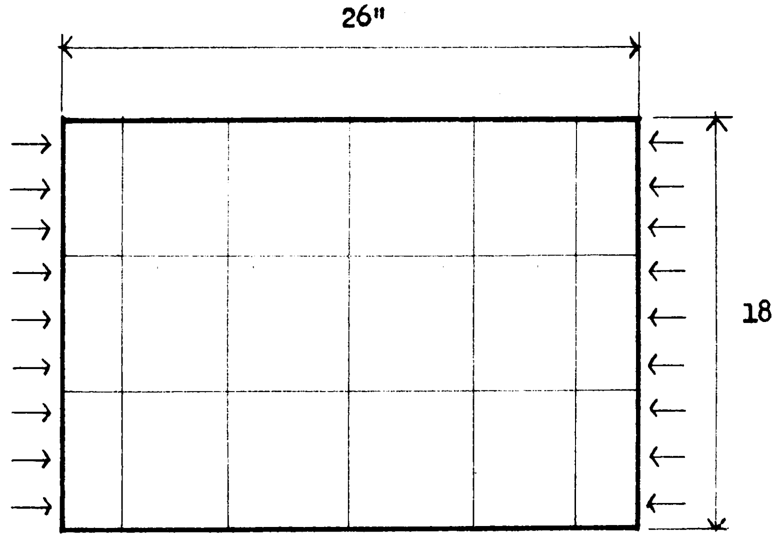
1. Intent of Test - The construction of units of two different geometries in order to re-evaluate the structural characteristics of air inflated units.

2. Observations - The reactions to air inflation were similar to the reactions that we had observed in previous tests on units, except for the problem of buckling. Where the joint between units previously showed considerable concentration of tensile stress causing noticeable buckling of the edge, only a slight amount of this action was observed in these models. As this buckling condition was considerably improved, it was reasoned that the increase in depth of the units was largely responsible.

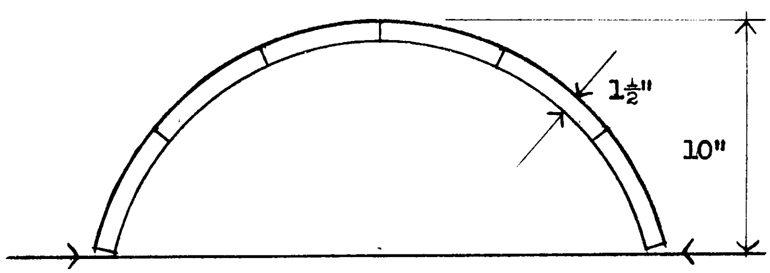
3. Conclusions - If these units gained greater stability by an increase in depth it was proposed that a simple vault of single curvature be constructed employing a greater depth to each unit, plus proportioning of the units to more closely approximate a cube. The vault, being of single curvature, would not be an ideal form for an air system, but it would present the reactions of one unit in regard to another unit. The geometry also presents a simple construction technique using identical units. Since the flatter the section of each unit, the greater the tensile

stress in the upper and lower membranes, it was proposed that the barrel vault be composed of units with a greater depth.

TEST 7 - FIGURE XV



PLAN



SECTION

DESCRIPTION

Simple barrel vault, composed of square inflated units, patterned to form vault, glued together - containing equal pressure through valving

MATERIALS

Rubberized fabric, stitched and glued seams
Rigid base support

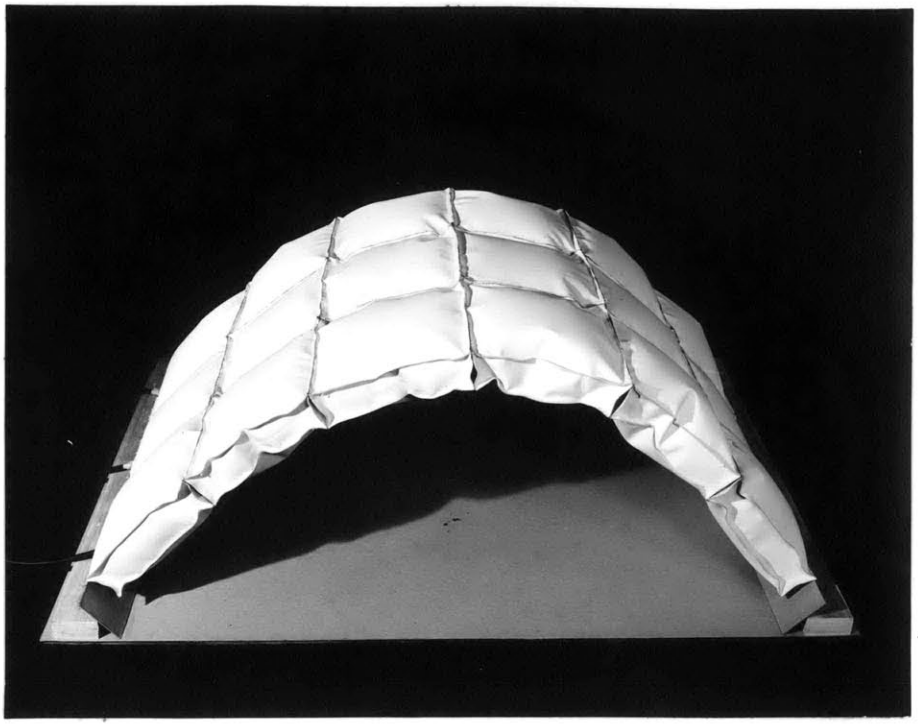


FIGURE XVI, PHOTOGRAPH OF MODEL TEST 7

FIGURE XVII, PHOTOGRAPH OF MODEL TEST 7

TEST 7

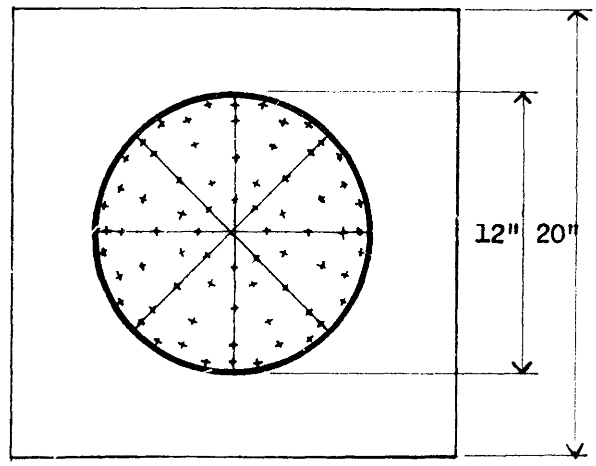
1. Intent of Test - To study the effect of air pressure upon units of a greater depth when joined in tandem and patterned to form a simple barrel vault.

2. Observations - The units had less of a tendency to pull together, due to the increase of depth. Some local buckling was observed at the area around the corner joint of each unit, but the effect was not great enough to force a failure of the entire structure. The unsupported edge of the vault also showed buckling upon an increase in air pressure within the structure. This action was similar to all other previous tests, for whenever there is an unsupported edge to a unit, the tensile forces in the membrane are not equilibriated, and the material buckles.

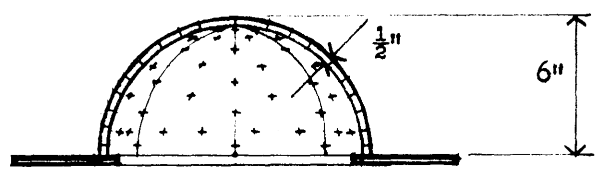
3. Conclusions - It was readily seen that by the conclusion of these tests on the individual units, the increasing depth had a direct effect upon the equilibrium of each unit and gave a resultant stability to a series of units. It must not be overlooked that a scale problem exists with the thickness of material and excessive rigidity of joinery due to the weight and stiffness of material, yet it was concluded that the greater stability was primarily due to the change in proportions of each unit. If an inflated unit becomes more stable when the depth is increased

and the other dimensions remain constant, it was reasoned that the closer each unit came to approximating a sphere, the greater the stability of each unit. Tensile stresses on the membrane would then be equalized, and tendencies for deformation or buckling to occur are minimized under uniform loading conditions.

TEST 8 - FIGURE XVIII



PLAN



SECTION

DESCRIPTION

8 equal divisions patterned to form
a hemispheric dome - point connections
between the two membranes

MATERIALS

Rubberized fabric
Stitched and glued seams
Polyetholene tube spacers
Thread connections
"Celotex" rigid base

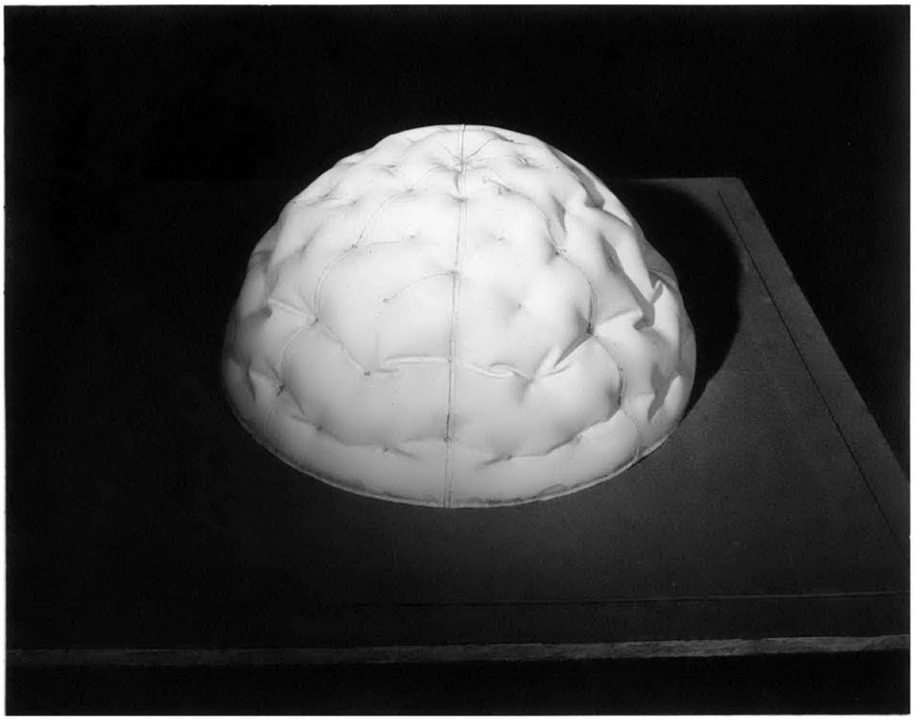


FIGURE XIX, PHOTOGRAPH OF MODEL TEST 8

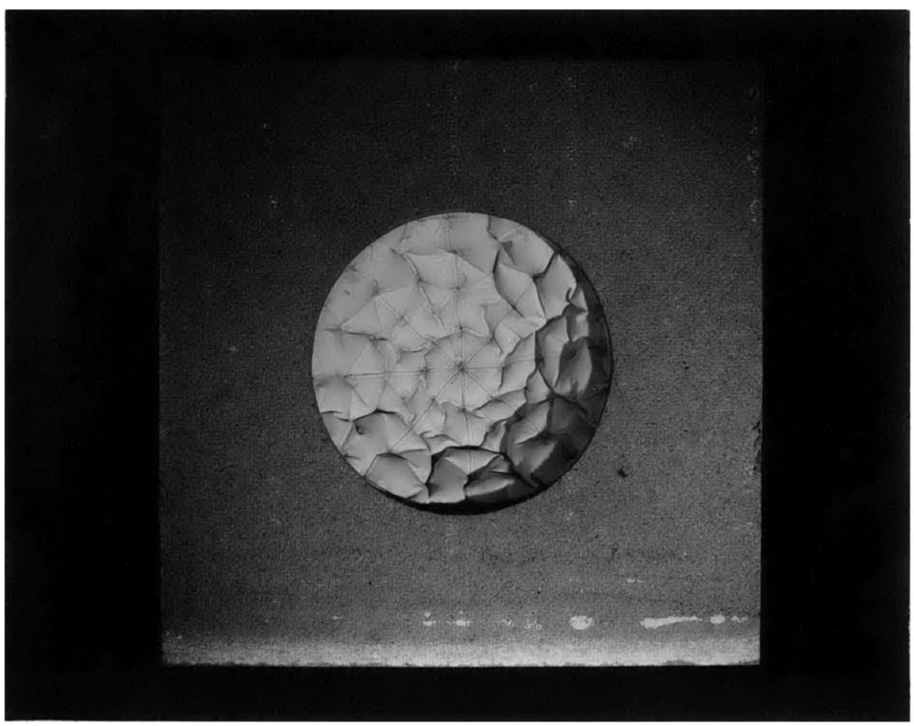


FIGURE XX, PHOTOGRAPH OF MODEL, TEST 8

TEST 8

1. Intent of Test - To observe in a doubly curved surface the effect that buckling has on the overall shape. It was conjectured that such a structure would not only stand by itself when inflated, but that local buckling would not be sufficient to cause a collapse of the structure as long as the depth is properly proportioned to the span.

2. Observations - Previous to inflation of the structure it was observed that the dome stood easily by itself and was considerably rigid. This rigidity was attributed to the double curvature of the structure, and to the material which was thought to be oversized for the model's scale.

When air was introduced into the structure the entire surface and shape of the dome changed. The extent of this change was not sufficient to cause a collapse of the structure, but the reaction was completely normal to the results of previous experiments. The surface of the dome inflated and became rigid with distinct bulging between the point connections of the upper and lower membranes. Greater buckling was observed on the lower membrane, this being attributed to the fact that pressure was working inward on the curvature of the shape and also due to the pressure differential. The resultant action on the structure was a foreshortening of the membranes. The local bulging and buckling of the material and the local tendency for the material to draw together resulted in this decreasing height of curvature.

3. Conclusions - As all tests to this time have resulted in forms tending to decrease in size, it was felt that the construction should be improved to where this action no longer existed. All surfaces of single and double curvature will maintain their shape when inflated, providing proper depth and curvature requirements are satisfied. The change in curvature through local buckling is considered undesirable, and instead of an action of reducing the structure in size to reach stability, it would be far better that the structure expand to reach its state of equilibrium. The proposal for the next experiment was to use a unit that was known to expand to reach maximum rigidity. A unit that most closely approximated a sphere was the selection which would be used in a geometric division of a surface of double curvature.

SUMMARY OF TESTS IN WORKING MODEL FORM OF AIR INFLATED SYSTEMS

These tests were initiated in the belief that a working model of an air inflated system would provide a better understanding of how an air inflated system works. Tests 1, 2, and 3 provided a graphic example of the forces at work within inflated units that required external restraint for them to maintain equilibrium according to a pre-patterned geometry. Test 4 examined a system of single curvature composed of linear elements patterned in an arch form, which described problems involved in the single curvature, and in the use of rigid members combined with an air inflated structure. Test 5 was the investigation of a surface of double curvature that required special consideration for shear and bending forces in an air inflated system. Test 6 dealt with an investigation of the proportions of an air inflated unit, while Test 7 combined these units with greater depth into a singly curved arch form. Test 8 dealt with the problem of buckling through the use of a hemispheric domical form; a problem that has been observed in all previous experiments and needed further consideration before a summary of work could be completed. These experiments greatly aided in the authors' understanding of the problems and characteristics of air inflated systems. There is a danger in approaching a research project through these means, however; for there can exist a lack of structural scale of materials and joinery of materials. With a lack of materials technology there is a possibility of reaching conclusions from observations that are not exact. These experiments are only rough approximations, but it was found through observation that the most successful inflated unit is one that geometrically approaches a sphere and the most stable structural system is a form of double curvature. From these two conclusions a design proposal was made for an air inflated structure.

PROPOSAL FOR AN AIR INFLATED STRUCTURE

PROPOSAL FOR AN AIR STRUCTURE UTILIZING THE PRINCIPLE OF AIR SUPPORT THROUGH INFLATED CELLULAR UNITS

A. Selection Of Form

Functional requirements

The general functional use that has been stated has well defined program requirements. A spectator sport activity requires a plan that organizes a stadium type of seating around an arena. A square or rectangle in plan lends itself to this type of activity if optimum seating requirements do not include the ends of the arena but only the sides.

The volume of the space is determined by code in regards to volume per person, but in general, space which is graduated from low at the edge to high in the center is desirable.

Structural considerations

The air structure acts structurally as a thin shell, and according to thin shell theory a curvature is required to eliminate bending and shear stress. Forms of double curvature are especially appropriate, for if the resistance of very thin sheets depends upon its curvature, the double curvature becomes its maximum expression.

If by program requirements or preconception the plan of the structure is designated a square or rectangle, then in order for the form to be of double curvature it must be translated or more properly transformed from straight lines.

Adaptations of domes to square plans in history produced the "squinch" and the more sophisticated pendentive. If the dome were not required as the surface of double curvature, it would be possible to create a surface of double curvature emanating from a square plan by simply continuing the "squinch" according to a pre-established geometry.

One type of surface that is evolved this way is a "pucha". It is a surface of transformation of a plane curve (generatrix) similar to itself when rotating or translating. This is a surface of similar section. The "pucha", specifically, is a cloister vault without edge on a square plan (Figure VIII) where the directrix is a straight line and the generatrix is a variable circumference.

There are a number of surfaces of translation that produce a projection to a square plan but that have not been considered due to mechanical requirements (see section H).

B. <u>Membrane Theory In Relation To Form.</u>

Theoretical analysis for thin shell construction is well documented[2,3] but this is for surfaces of the same curvature. A domical surface as a thin shell can be theoretically determined with accuracy but a surface that is not of the same curvature produces difficulties in analysis.

This is an objection to the design of a structure like a "pucha" because of the apparent complicated calculations that are necessary to derive its relatively simple form. It is convenient to remember that very few surfaces of double curvature can be mathematically analysed and that approximate methods are generally used for most practical applications.

Static determinations of a "pucha" in relation to membrane theory are possible. In general these would be the same for a spherical surface[4], except that static conditions would vary at

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[2]Norris, C.H. (Prof. of Civil Eng., M.I.T.), "Analysis of Shells," Unpublished Notes.

[3]Timoshenko, S., <u>Theory of Plates and Shells,</u> New York McGraw-Hill, 1940.

[4]Kobayashi, A.S. and A.J. Durelli, <u>Feasibility Studies For Air-Cellular Featherweight Housings,</u> Phase Report ARF No. K103, Contract No. AF 30 (602)-1952, Armour Research Foundation of Illinois Institute of Technology, Chicago 16, Illinois, March 1957, Section III.

the edge because of greatly reduced curvature. The greater surface of the "pucha" would act in pure tension or compression except at the edge and corners where reduced curvature would introduce bending and shear stress.

C. The Air Inflated System And Its Static Analysis.

Theory

The static conditions of a structure will not change whether the system is of concrete or of air inflated cells. Membrane theory of thin shells is held equally valid for air structures. This premise is true if the individual air inflated unit is equilibriated and the membrane is pre-tensioned sufficiently so that compressive loads do not exceed the tensile stress that is applied to the membrane by the air pressure.

Geometry of Individual Units

From the previous studies in this report it has been empirically determined that the geometry of the individual unit is of great significance if the total structure is to be statically in equilibrium. The inflated sphere has been determined as the ideal individual unit shape. The geometry of spheres over a surface of double curvature is quite complex, though, and further complexity arises if the surface is of a varying curvature. Problems of joinery are increased and solutions for water integrity are complicated.

Additional problems of geometry arise due to solutions involving static considerations. In order to solve the problems of bending and shear stress introduced in the "pucha" at the edges and corners, some degree of reinforcement is necessary. It is possible to establish a geometry which introduces smaller inflated units at the edge and corners that graduate to larger units over the greater surface. The theory behind this geometry is that a greater number of units at the edge and corners would substantially increase the web action in these areas, counteracting the bending and shear stress. A system of spherical units that satisfies this geometry seems difficult to establish, primarily because points of tangency occur in a complex manner.

The use of a unit that approaches the sphere in a volume and external surface area relationship could better provide a system that satisfies the geometrical requirements in relation to static solutions. A cube or a shape that approaches a cube is a geometric form that would create nearly equal stress patterns over its surfaces when inflated. The combination of these units in a reticular system would then provide a more satisfactory answer to joinery and water integrity problems.

Static Stability and Erection Principles

The geometry of an individual cell establishes the erection principles of an air cellular system. When pressure acts internally on the surface of a cellular unit, the forces resolve themselves into a state of self-equilibrium. From geometry it is obvious that the resultant force acting on the surface ABCD is larger than the resultant force acting on A'B'C'D' (Figure XXI). A net force then acts in the outward direction. This force is balanced by the forces which are acting on the sides of the unit. If the sides are completely restrained then the inflation of the unit will form a uniform tension field over the upper and lower surfaces.

The radial distance between the two membranes varies as pressure is introduced into the unit. The curvature introduced into the upper and lower surfaces resolves the restraining force on the edge into 2 components which establish a uniform tensile membrane force on the unit.

When several of these inflated units are joined together to form a structural element, the resultant forces acting on the sides of two neighboring units will balance each other (Figure XXII).

(This above statement presupposes that the equilibrium condition of a unit is not greatly altered by the joinery. If it is altered, then under inflation resultant forces acting on the sides of two neighboring units will not balance each other. The

FIGURE XXI
INFLATED UNIT CELL UNDER HYDROSTATIC PRESSURE

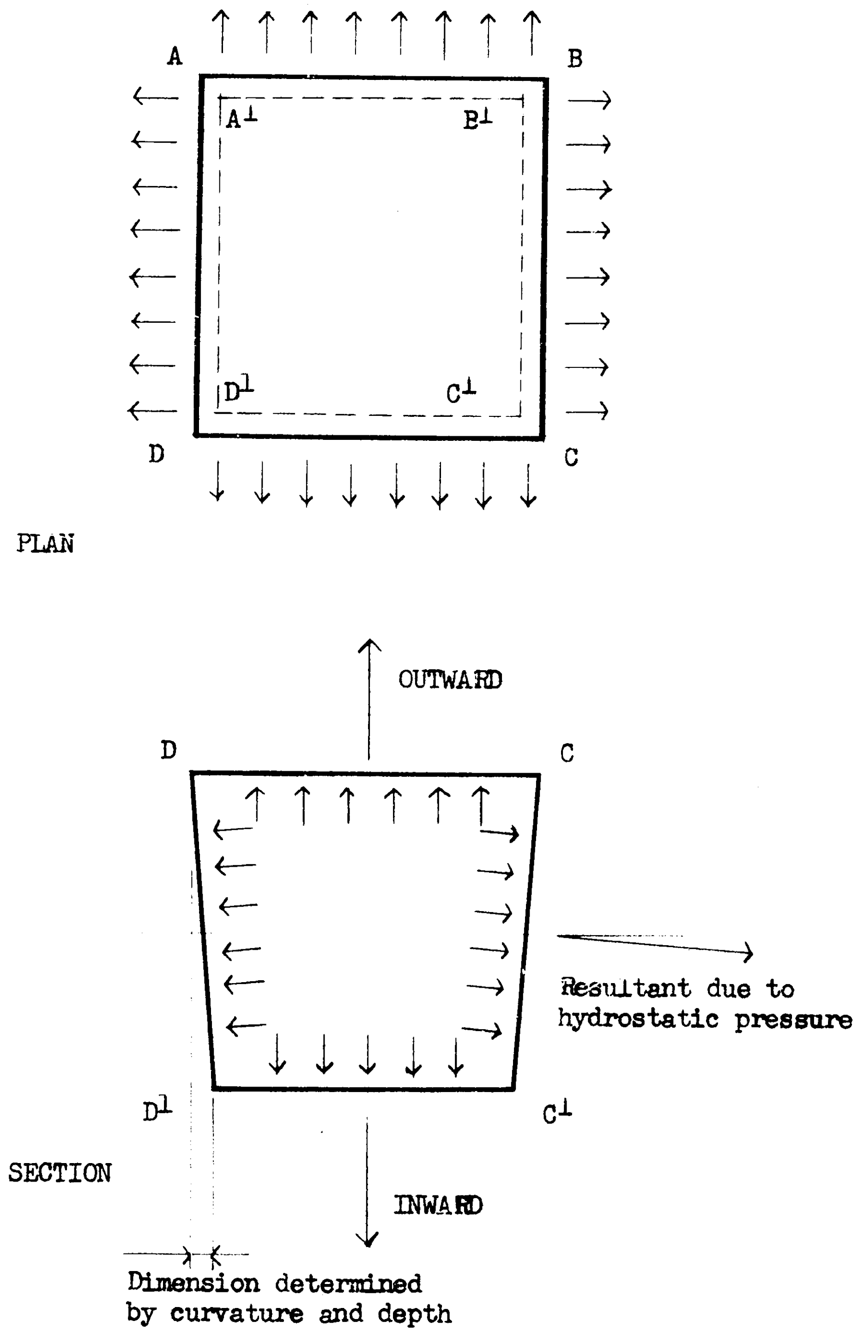
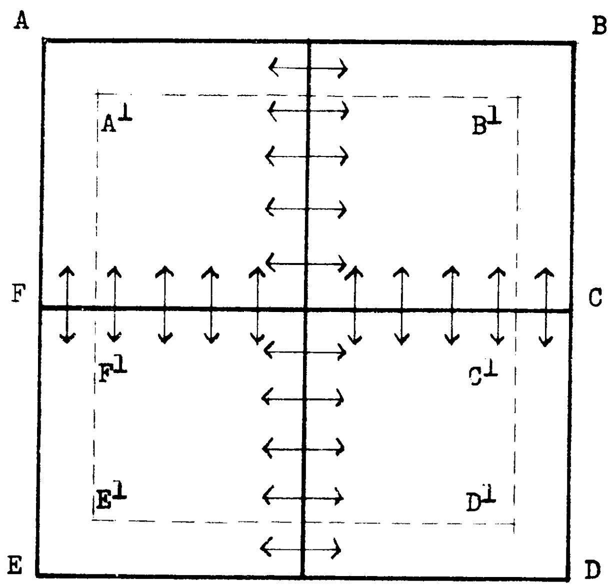
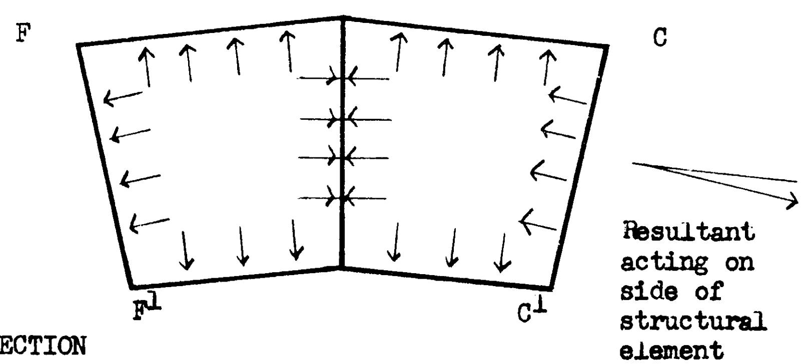


FIGURE XXII
STRUCTURAL ELEMENT OF INFLATED UNIT CELLS



PLAN



SECTION

balance can only occur in this situation if a compressive stress can be taken along the line of joinery between units, or it will resolve itself in a buckling of material along this line. This action will tend to reduce the curvature of any surface if the radial distance between two surfaces of a unit is less than the distance across a symmetrical unit. This relates back to the sphere or a volume geometrically close to a sphere as being the most ideal unit, where the tensile stress across the surface of a unit is relatively equal.) Authors' note in parenthesis.

Assuming the outside forces on this group of units to be equilibriated, then the differential resultant force of the inside and outside surfaces now tends to push the center of the group outwards. This force is balanced by the uniform tension field applied by the forces acting on the sides of the unit. The net effect of all such forces is similar to an equivalent membrane with a thickness which is equal to the sum of the upper and lower membranes, loaded hydrostatically and under a uniform tension field. The hydrostatic pressure which contributes to a rise in the center of the equivalent unit is equal to the inflation pressure in single wall air supported structures.

The above paragraph provides a base for the theory of cellular air systems and can be expressed for the total system as well as each unit or a group of units.

Size of individual units

The size of any individual unit cell is a function of the tensile strength of the membrane material. This can be visualized by the construction of two units of different size using the same fabric surface. The smaller unit obviously is stiffer and will deform less than the larger unit when an external force is applied. The specific size would have to be determined in relation to deformations that would not render the air structure unstable.

D. Edge Conditions In Relation To Tension Ring.

Any shell structure, if the curvature is less than a hemisphere, requires an edge member. This is equally true for an air structure although the size of the edge member would be smaller due to the reduced dead load of an air system. Continuous support in the form of a tension ring would be required to resolve the latitudinal tensile stresses that exist at the edge of the system.

The design of the edge member is primarily a structural consideration, but must also be thought of in terms of the structure's mechanical requirements, and in its relation to the esthetics of a doubly curved shell structure's transition to the ground (see Section H).

E. Forces Due To Wind Load

Additional forces exerted on surfaces of double curvature due to wind loading have been determined theoretically[7] and empirically through wind tunnel tests.[8,9] In general it may be said that wind loading tends to exert a negative or lifting force on a doubly curved surface (air-foil action). In a surface of low silhouette the compressive force that may be exerted on one side would be minimized.

The above statements are generally correct, but they oversimplify the action of wind loading and the true stress distribution would be quite complex, depending upon wind conditions.

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[7] Op. Cit., Timoshenko, p. 374.

[8] Op. Cit., Kobayashi and Durelli, p. 28.

[9] Catalano, E.F., Student Publications of the School of Design, "Two Warped Surfaces", North Carolina State College, Raleigh, North Carolina, Vol. 5, No. 1, 1955, p. 13.

Empirical data gathered in wind tunnel tests on scale models would provide stress distribution patterns of a specific nature.

An effective method of counteracting unequal loads due to wind on the structure is the provision of an edge member of sufficient dimension to dissipate and "spoil" the full force of the wind. The edge member serves as a baffle to wind loads which are most effective in producing a negative or air foil action on the structure. The air, instead of striking the surface and flowing over the membrane in an even line, is broken into small turbulences which have less of a tendency to create highly negative force components on the surface of the structure.

F. Joinery, Connections Of Individual Units Together

In the previous section on the geometry of individual units, it was established that a cube or a form in geometry approximating a cube would give a fairly equal stress pattern over the surface. The selection of a planimetric volume rather than a curved volume facilitates the joinery of units together within a geometric order. Joinery would be accomplished by connecting two units along the upper and lower edges with a zipper. A zipper that is watertight and would resist the membrane tensile stress is desired. The only additional problem in the connection of units together occurs at the closing of four corners. A seal would be created here, by the use of a gasket of neoprene or some similar material that would be secured by anchorage at the top and bottom surfaces.

G. Mapping Of Surface

The mapping of the surface according to a pre-established geometry could be accomplished through direct projection. From the geometry established in plan, projection to the curved surface is accomplished by the location of points on that surface in relation to their distance from the plan of projection (Figure XXIII).

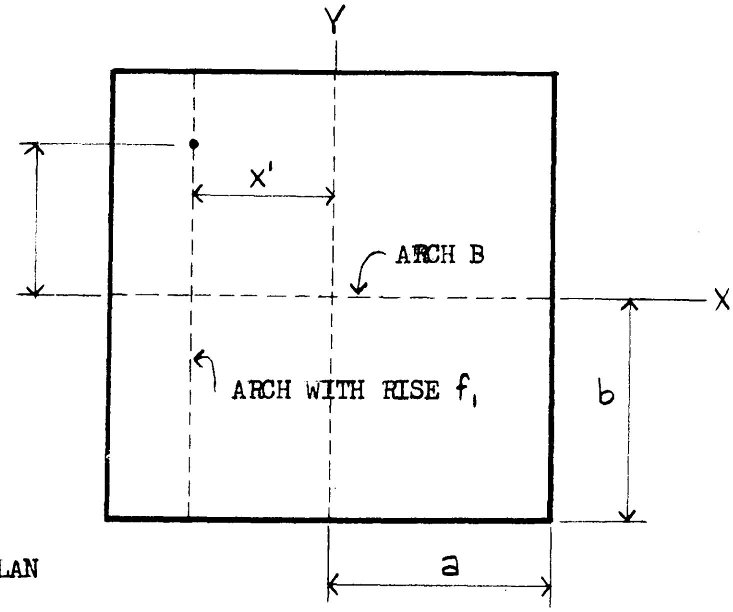
H. Mechanical Considerations

Recent construction of air inflated structures has generally accepted a requirement for continuous air supply to maintain structural equilibrium. This is one solution that solves many of the practical problems of maintaining positive control over air pressure within the system. Conditions such as changes in temperature causing expansion or contraction of the air molecules, and the possibility of small openings existing in the surfaces of the structure, indicate that a continuous supply of air can satisfy practical considerations of the system.

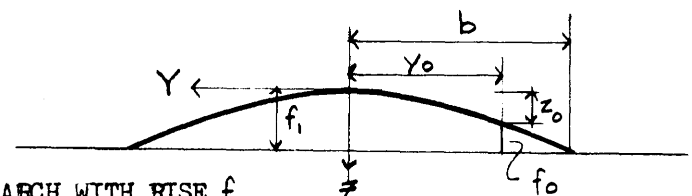
The amount of air pressure required to sustain an air

FIGURE XXIII

MAPPING OF A "PUCHA" SURFACE THROUGH LOCATION OF ANY POINT ON ITS SURFACE



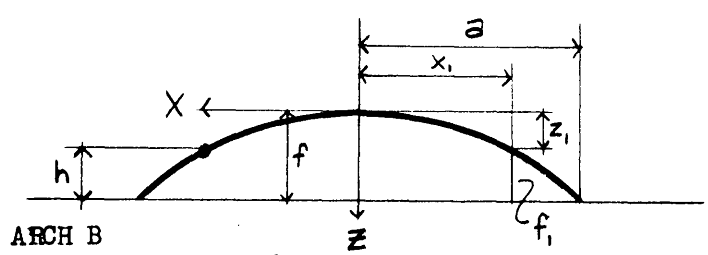
PLAN



ARCH WITH RISE f_1

$$f_o = f_1 - z_o = f_1 - \left(\frac{y_o}{b}\right)^2 f_1 = f_1\left(1 - \frac{y_o}{b}\right)^2$$

$$= f\left(1 - \frac{x_1}{a}\right)^2\left(1 - \frac{y_o}{b}\right)^2$$



ARCH B

$$z = \left(\frac{x}{a}\right)^2 f$$

$$f_1 = f - z_1 = f - \left(\frac{x_1}{a}\right)^2 f$$

$$= f\left(1 - \frac{x_1}{a}\right)^2$$

$$h = f\left(1 - \frac{x}{a}\right)^2\left(1 - \frac{y}{b}\right)^2$$

inflated cellular structure is a function of the geometry of individual units and the distance between the upper and lower membrane surfaces. In general this is reflected by the concept of "effective pressure" (Ref. Section C). In previous air inflated structures, air pressures have varied from 1½ psig for single membrane structures of impregnated nylon to 50 psig for a "drop stitch" unit (continuous internal support of a patterned form). An air pressure that perhaps more closely approximates that which would be proposed for the structural units that have been studied in this report, would be a pressure of 5 psig. This pressure was used in calculations for an inflated cellular system investigated by the Armour Research Institute.[10] An air pressure of 5 psig was used in calculations of a system employing Mylar 500-A film, and though this material is far more rigid than materials considered in this report, the air pressure would not be greatly different.

The total span of an air structure can be created merely as a function of the tensile stress characteristics of the membrane material. In this relationship the air pressure

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[10] Op. Cit., Kobayashi and Durelli, Section III.

is not a variable and will theoretically remain constant for any span.[11]

It is proposed that sufficient fan and duct equipment be provided to supply a constant air pressure within the structure. As air pressure within the system must be constantly maintained, the most positive control is supply of air continuously along the perimeter.

The possibility exists where certain climatic controls can be maintained over the area covered by the structure through the temperature of the air induced into the system. This possibility suggests that the structure would act as a radiant panel which could cool in the summer and heat and melt snow and ice in the winter.

I. Acoustics

A detailed explanation of the mechanics of sound within an air inflated structure can only be an approximation, due to the relatively small amount of research that has been done with this type structure. The basic laws of acoustics show fairly accurately what will happen under these conditions, so that proposals can be made to produce a good acoustical environment.

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[11] *Ibid.*, Section III

As materials involved in the construction of air structures are so light in weight and relatively transparent to sound, it is easy to suppose that the fabric membranes have little effect acoustically. Through empirical experiments, however, it is discovered that an air inflated system has an excellent potential for reflecting sound. The high frequency range of sound is effected by the material, producing a sharp staccato overtone to sounds reflected off the structure's surface. The air inflated structure, acting as a drum, also has the ability to transmit directly the sound of impact noise created by rain or hail.

The problem of reflection, which is magnified by the doubly curved shape of the structure, can possibly be remedied by an articulation of the surface. As each air inflated unit has a considerable convex curvature, it is surmised that this articulation to the doubly curved surface would correct for problems of echo, flutter, and focusing of sound waves. It is also possible to further control these problems by suspending sound absorbent baffles from the lower membrane of the structure. This could conform to the geometry of the air inflated units. These baffles would have the qualities of preventing the "creep" of sound along the structure's surface and would absorb high frequency sound that is reflected off the convex surface of each air inflated unit.

The problem of transmission of impact noise through the structure can only be slightly dampened by applying a "fuzzy" material to the membrane, much the same as the undercoating of an automobile body. There not only is a question as to the effectiveness of this procedure for sound reduction, but the problems of applying such material to a membrane and the resulting additional weight to the structure makes this solution seem impractical. This one acoustical problem which has not as yet been successfully solved sets an important limitation on the use of an air structure. Functions that require an acoustical environment of good hearing conditions would require special solutions to these acoustic problems.

J. Lighting

The development of a lighting system for an air inflated structure can only be evolved from functional requirements of use, consideration of low and high light intensities, and special regard for the geometry and structural characteristics. As the general building type considered is related to spectator sports activities, a higher intensity of light is required over the arena than over the spectator area. The spacing of lighting units could conform to the geometry of the cellular structural system. One possibility is the suspension of fixtures from the lower membrane at the points for connection of the air inflated units. Wiring for this system could be handled along the webs between the cellular inflated units, and the surface mounted fixtures could be easily attached at the time of erection. The fixtures should be designed to supply the required footcandles on the area below, provide illumination to the structure, and generally reflect the form and character of the air inflated structure.

K. Membrane Materials

As noted in the bibliography, the authors sought information on possible surface membrane materials from many sources. The information received did not offer data on any new developments in material for air structures, but did supply information on fabrics and film materials in current use. Film material such as "Polyethylene," "Mylar," "Teslar," etc. are used for relatively small air structures that provide shelter for swimming pools, green houses, etc. Fabrics composed of vinyl coated nylon or neoprene coated nylon have proven serviceable and structurally feasible for larger structures, especially those designed for military service.

There is no special reason why a membrane material need be completely air tight. As long as a continuous supply of air is moving through the system, the main consideration for structural stability is the maintenance of air pressure. This has been dramatically proven by the Army Quartermaster Corp. This group constructed a dome of common Army "duck" normally used for tenting fabric, and introduced air under pressure continuously. The dome reached and maintained its patterned shape, even though air was constantly escaping through the porous surface. The escaping air was found to resist the leakage of rain water through the porous surface, which provided an excellent solution to the problem of water integrity.[12]

If we can assume that fabrics and films are available that have sufficient tensile strength for use in air structures, and that development of new strengths in materials is possible for extremely long spans, then the most significant factor about fabric and film is the usable life of the material itself. Fabrics and plastics tend to deteriorate and have a very uncertain duration of useable life. The most optimistic reports give a vinyl coated nylon fabric in air structures a useable life of 10 years. Until materials for membranes are developed that have a greater serviceability and life use, the air structure must still be thought of

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[12]This information was gathered from a trip the authors made to the Army Quartermaster Corp., Natick, Mass. to observe installations of single membrane air inflated structures that are tested there.

as a temporary system that requires constant maintenance and eventual replacement.

L. Erection Procedure

The erection of an air inflated cellular system is accomplished through the act of inflation. Formless uninflated units are joined together on the ground and when inflated the system takes its patterned form if the required edge restraint is applied (as in Test 7 of this report).

A problem arises if the edge member or tension ring is raised off the ground. In this case erection masts would have to raise the joined units to a height where connection could then be made to the tension ring. Once this connection is completed, the inflation of the system would allow the structure to take its patterned form.

This suggestion may appear to be the most feasible, but the proposed solution is made with reservation, and much thought should be devoted to this stage of construction.

CONCLUSION

To formulate a conclusion to a thesis project of a subject that has had a relatively small amount of previous investigation and research, it is necessary to make a careful analysis and estimation of the work completed, with a definite direction given for further investigation. There can be a more complete understanding of this project through: a statement of the motives preceeding the investigation; general approach for study; methodology of investigation; logic behind a design proposal; an ellaboration of the esthetics of an air inflated structure; and a proposal for areas of further investigation.

One of the primary motivations behind this study is the recent acceptance of a new technique and use of materials in the field of construction. The development of air structures has been one basically directed towards a specific use, and though structural and practical problems of construction have been solved, little thought has been given to the esthetics and further possible uses for such a system. As industry rarely accepts the responsibility of research and regard for esthetics, it was felt by the authors that the purpose of this project should deal with these aspects in the development of air inflated structures.

Since there has been very little investigation into systems of air cellular structures, and since the authors of the project believed that this type of air inflated structure offered the most architectural possibilities, the major portion of the study has been devoted to a development that includes structural and practical considerations of this type of system. It is only through a complete understanding of the purely practical and functional characteristics of this structural system that an esthetic can be derived.

The process of experimental testing, with some of its advantages and disadvantages, has already been described. The attempt has been made through these tests to find the most structurally satisfactory unit and system of units possible. As it was found that a spherical unit and a surface of double curvature met these requirements most exactly, it then became a matter of adapting these ideal conditions to a practical realization.

Conditions such as structure, shape of structure, lightness in weight, economy of material, and material durability immediately set limitations to a design proposal. The most attractive proposal that appeared to the authors at this time, was the possibility of a long span structure to be used as a spectator sport facility. The greatest difficulty in the development of this proposal was the coordination of the geometry of inflated units within a geometry for the structural system. Problems of joinery of units are extremely critical, so that it becomes a matter of either revising the most ideal structural unit for the most ideal joinery condition, or accepting the spherical form, and adapting a more complex solution for insuring water integrity of the structural system.

This brief study has perhaps discovered more problems than solutions, but this may well provide direction for future study. Direction for further work should include the following considerations:

A thorough study of materials and technology of joinery. The scale of materials must be understood, so that the results of any further tests and models can be considered more accurate.

A complete understanding of the mechanics of air acting within an air structure.

Specific structural analysis of individual units in relation to the structural form considered.

Erection procedures that satisfy various design considerations.

A thorough investigation should be made into all types of surfaces of double curvature with particular consideration given to the possible geometric subdivision of such surfaces.

All further work should pay particular attention to the esthetic of such a structure, for not only must there be a straightforward simplicity in a solution to structural requirements, but it is strongly urged that an honest visual expression be made of all structural and mechanical elements.

This study has been developed in essentially the time of three months; the span of time provided for the Master's Thesis during the summer term. In this respect the work completed is only preliminary. While this is true, the authors believe that the benefits from this study have been numerous.

The authors have been greatly interested in this relatively new and exciting facet of architecture. The solutions to problems that arose during this study were not easily perceived and the resulting polemic between the authors stimulated a greater interest in the study. It is hoped that the resulting work has provided a development in the field of air structures that could benefit further research.

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APPENDIX

List of Correspondents

During the course of this study we made inquiries to the sources whom we felt had experience with some facet of air inflated structures. Those who responded are listed below.

Much of this correspondence served a useful purpose in revealing the degree of interest and development in air structures. As noted previously the air structure concept is relatively new and the majority of manufacturers are in the development stage.

The names and addresses of these correspondents are presented as a guide for others wishing to research this field.

Armstrong Cork Company
Lancaster, Pennsylvania

Birdair Structures, Inc.
Buffalo Industrial Park
1800 Broadway
Buffalo 12, New York

CID Air Structures Company
1501 East 96th Street
Chicago 28, Illinois

E.I. du Pont de Nemours and Company, Inc.
Wilmington 98, Delaware

Architectural Forum
Rockefeller Center
New York 20, New York

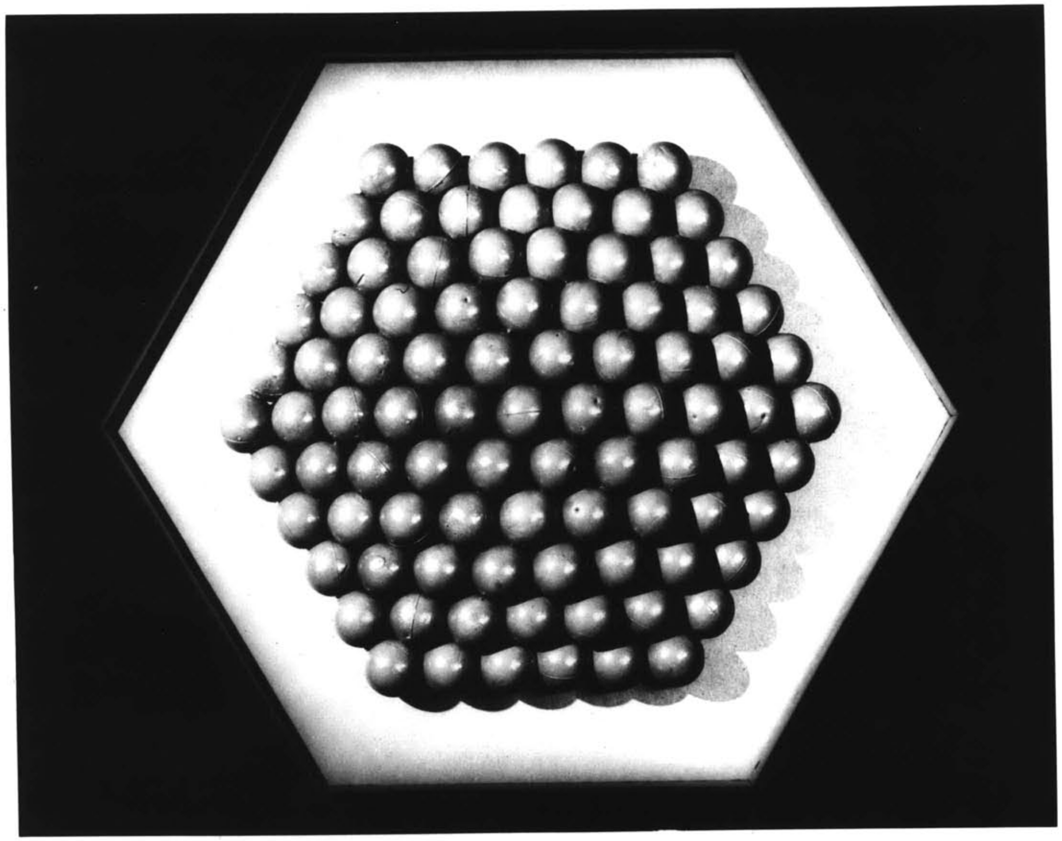
H.T. McGill, Manufacturers and Distributor of Film Materials
548 N. Milby Street
Houston 23, Texas

Monsanto Chemical Company
Plastics Division
Springfield 2, Massachusetts

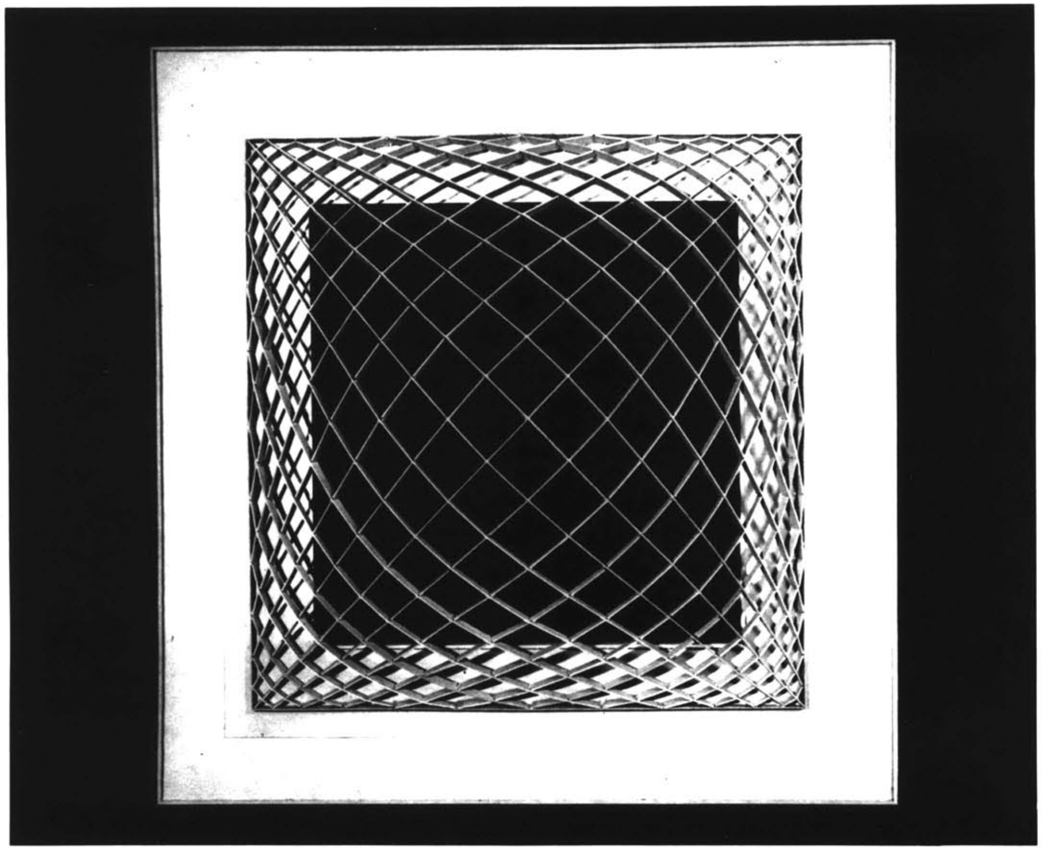
Raven Industries, Inc.
Sioux Falls, South Dakota

United States Rubber Company
Coated Fabrics Department
Mishawaka, Indiana

United States Department of Commerce
Office of Technical Services
Washington 25, D.C.

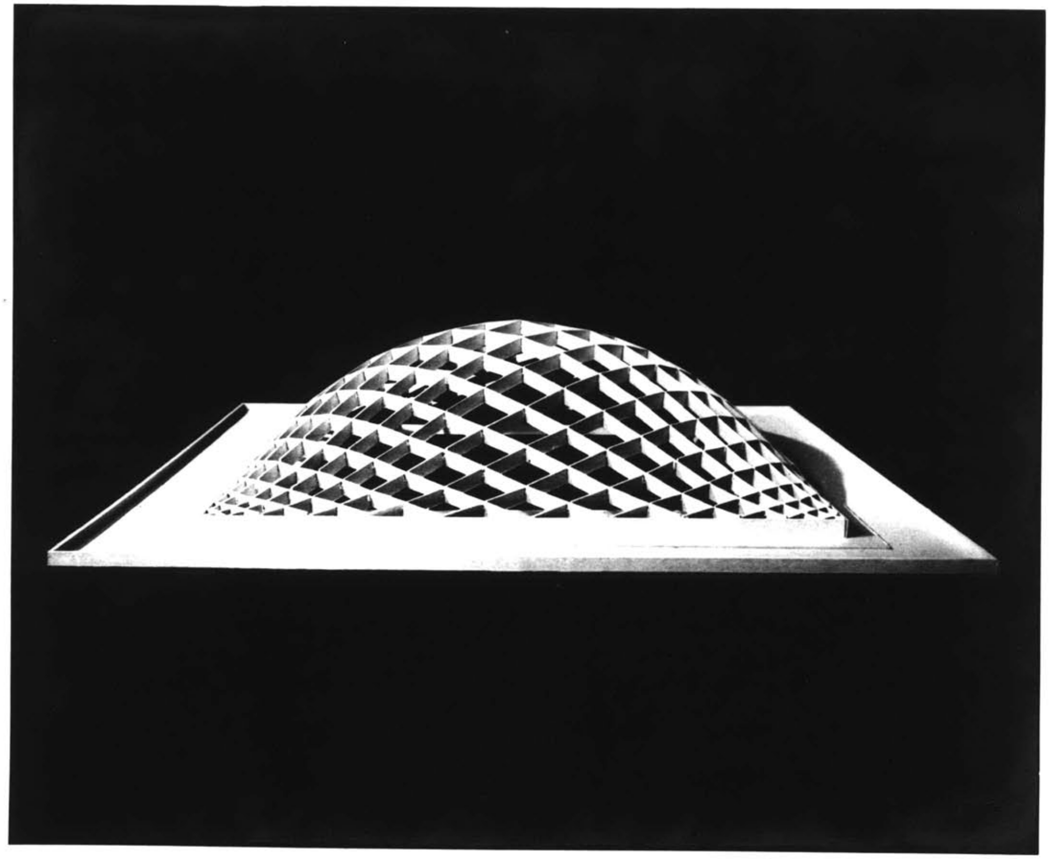


AN AIR INFLATED STRUCTURE
MODEL OF SURFACE WITH SPHERICAL UNITS
MASTER OF ACHITECTURE THESIS M I T
K M LOCKHART & R B MORRILL SEPT 1960



AN AIR INFLATED STRUCTURE
MODEL OF PUCHA SURFACE

MASTER OF ARCHITECTURE THESIS M I T
K. M. LOCKHART & R. B. MORRILL SEPT 1960



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MODEL OF PUCHA SURFACE
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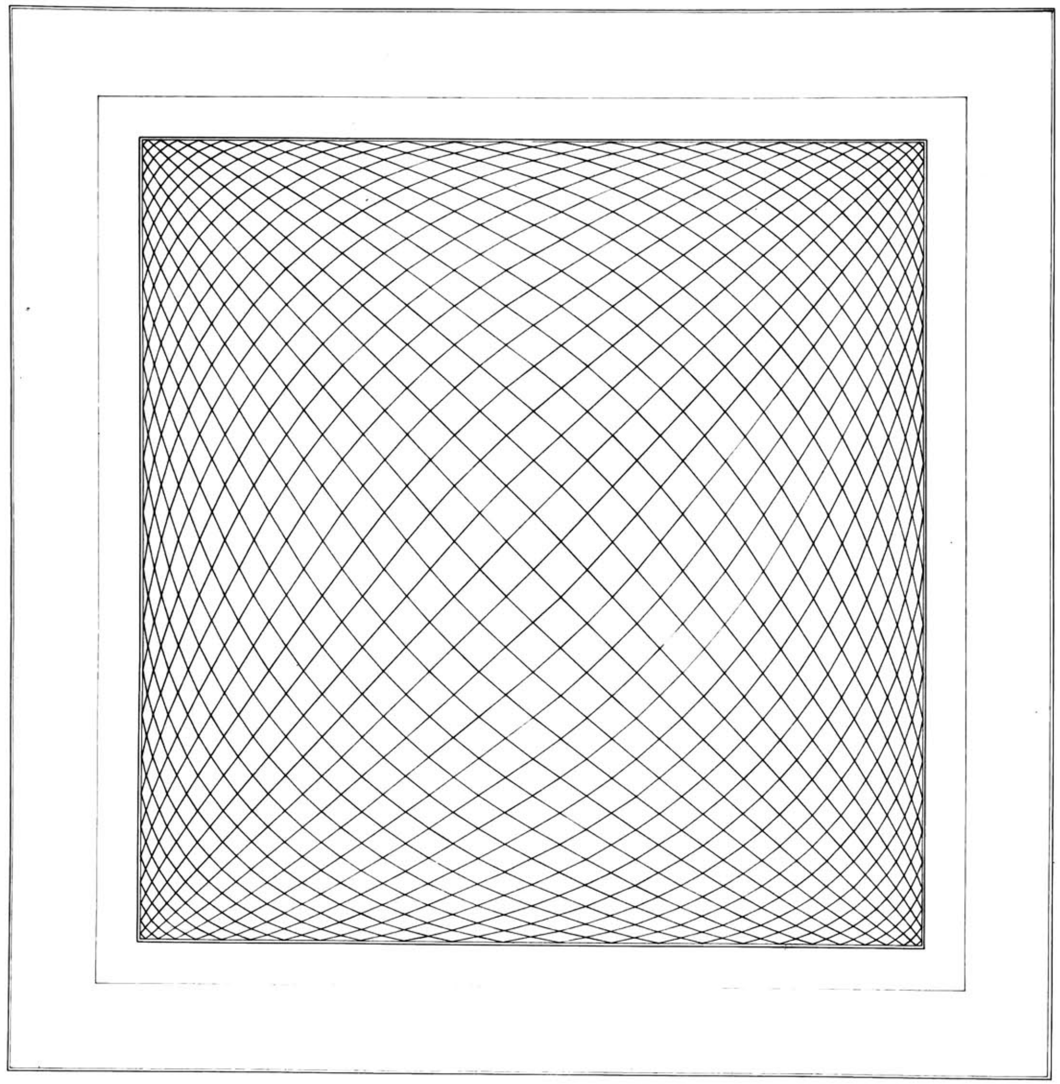
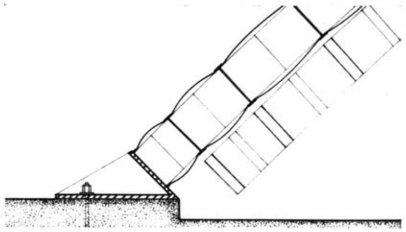
K M LOCKHART & R B MORRILL SEPT 1960



AN AIR INFLATED STRUCTURE
SCHEMATIC PLAN OF PUCHA SURFACE
MASTER OF ARCHITECTURE THESIS — M I T
K M LOCKHART & R B MORRILL — SEPT 1960

0 5 10 20 30 FT



AIR INFLATED CELLULAR UNITS

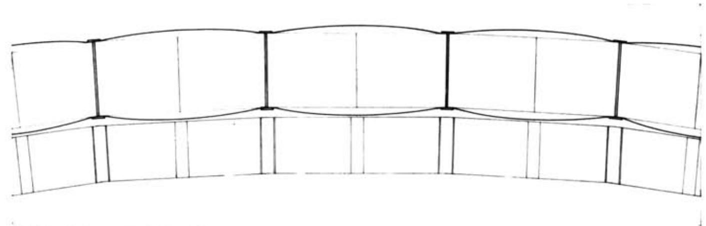
NEOPRENE CLOSERS AT CORNERS OF UNITS

ACOUSTIC BAFFLES

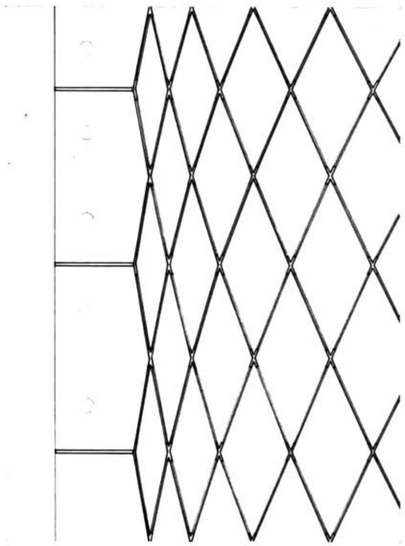
STEEL CONNECTING PLATE

CONTINUOUS CONCRETE EDGE SUPPORT

SECTION DETAIL OF EDGE AT MIDPOINT OF SIDE



SECTION DETAIL AT CENTER OF SPAN

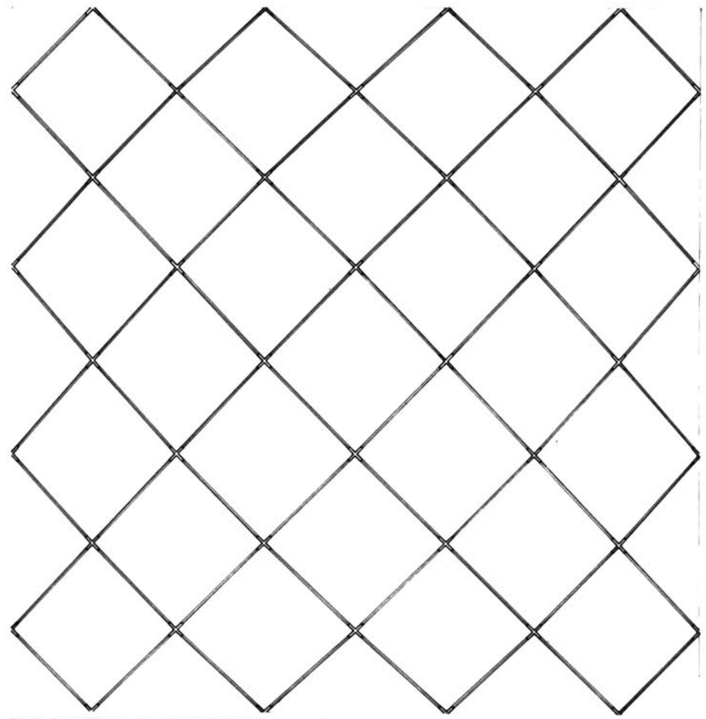


AIR INFLATED CELLULAR UNITS

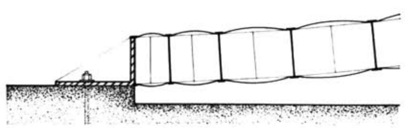
ZIPPERED CONNECTION BETWEEN UNITS

NEOPRENE CLOSERS AT CORNERS OF UNITS

ROOF PLAN DETAIL OF EDGE AT MIDPOINT OF SIDE



ROOF PLAN DETAIL AT CENTER OF SPAN



AIR INFLATED CELLUR UNITS

NEOPRENE CLOSERS AT CORNERS OF UNITS

STEEL CONNECTING PLATE

CONTINUOUS CONCRETE EDGE SUPPORT

SECTION DETAIL OF EDGE AT CORNER

AN AIR INFLATED STRUCTURE
DETAILS OF INFLATED UNITS, PUCHA SURFACE
MASTER OF ARCHITECTURE THESIS M I T
K. M. LOCKHART & R. B. MORRILL SEPT 1960

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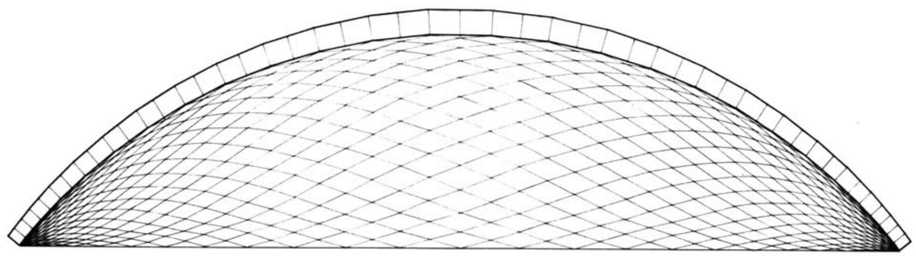

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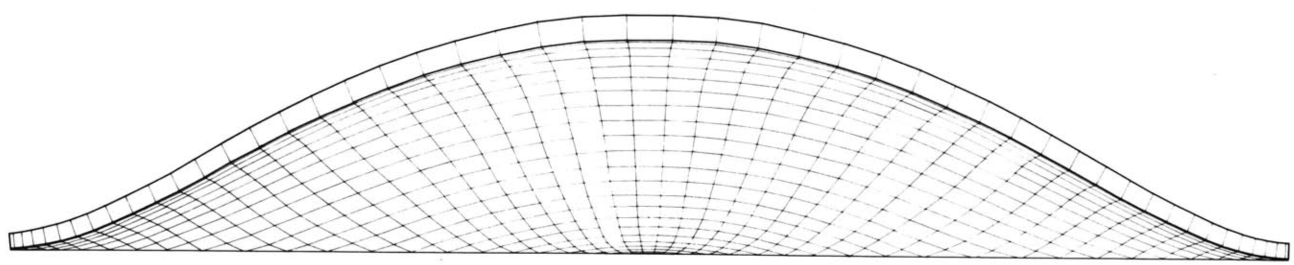

DIAGONAL SECTION

AN AIR INFLATED STRUCTURE
SCHEMATIC SECTIONS OF PUCHA SURFACE
MASTER OF ARCHITECTURE THESIS M I T
K. M. LOCKHART & R. B. MORRILL SEPT 1960

0 5 10 20 30 FT