INFLATED ELEMENTS
AS FORMS FOR A CONCRETE
STRUCTURE

by

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Dear Dean Belluschi:

In partial fulfillment for the degree of Master in Architecture I hereby submit this thesis entitled, "Inflated Elements as Forms for a Concrete Structure."

Respectfully,

L. Gene Zellmer

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ABSTRACT

Studies were made of several different systems of forming a concrete structure with inflated elements. These studies included investigations of various types of shapes that are possible with air inflated membranes. One system was developed, including the design of the inflated element and the erection proceedure. The inflated element with its necessary connection details was constructed. A concrete structure was poured using this unit. In these test pours the connections made and the removal of the unit from the resulting concrete simulated job conditions.

INTRODUCTION

Architecture

Architecture, as almost everything in our world today, is developing an attitude of continual change. Much of the change is being brought about by advances in science and technology. The pace of change in architecture and building technology has been relatively slow but the pace is increasing and the demands of the world for shelters of all types will give it even greater acceleration.

The construction technique of today which has not changed basically for hundreds of years, is reaching maximum limits in production. In housing, for example, contractors have been forced to apply mass production techniques to the standard 2x4 stud framing system. Entire walls are trucked to the site and a house can be erected in one day. But, because the technique is not totally adaptable to mass production, much of the finishing work and other aspects are still done on the site. Unfortunately the workmen are forced to produce more...faster and quality workmanship has been all but completely sacrificed. The construction techniques used today developed toward one objective...to provide shelter at a minimum cost. For economic reasons the mechanical, electrical and structural systems avoid any integrated inter-relationships. As an element of flexibility the modular unit is actually as small as a 2x4 or a brick. A freedom in a sense, but the results have been buildings so loosely inter-related that no order is apparent. Buildings also have little relationship to each other or to their general environment. Our cities exist as chaos as seen by the square mile or by the square foot. Very few buildings have resulted in what can be called "architecture". Little more than 10% of the buildings constructed today are designed by architects. Perhaps this is so because our society is more interested in economy than in a visually satisfying environment. But, primarily it is because the architect does not have sufficient understanding and control of the construction technique to be able to create beauty with the use of it and at the same time meet such demands of society as economy. The necessity of this kind of understanding and control is even more important in the light of the newly developing techniques of construction.

The physical demands of society for shelter can be met by indistrialization and mass-production. Science and technology, the primary elements of these new techniques, not only need to be studied, but their entire sense of order must be understood and applied. Industrialization, itself, depends on such a sense of order to operate at its maximum efficiency. A building must be thought of as a system of inter-related sub-systems. All the systems must be interrelated and function together with a refinement similar to that found in the parts of the human body. An architect must understand the science and technology of these systems in order to be able to put them together in an harmonious totality. The physical world, society and human psychology are all a part of these systems and must all be studied. The education of the architect must be changed so that the profession will be prepared to meet the demands of each of these areas. Greater specialization will be required and the design of a building will depend on the coordination of larger teams of men. To keep abreast of new developments research must also be established as a primary area within the profession of architecture.

Science has developed many new products and techniques that have already been absorbed into the construction industry. Some of these new developments if better understood and properly applied could have significant potential in providing shelter for the activities of our changing world.

One of the new developments of recent years is the use of air as structure. Air structures can provide large spaces at a minimum cost of both labor and material, and they will be put to use by our society. But air structures should not simply be viewed as a way to provide large economical spaces....it is a totally new system and all of its potential should be explored.

Air Structures

An air supported structure was first suggested in 1946 and prototype erected in 1948 by Walter Bird of the Cornell Aeronautical Laboratory. They were developed and used as enclosures for large radar antennas. Since then air structures have been put to many applications. NASA and other groups have done considerable research on inflatable satellites, and re-eentry vehicles. The military has applied them to personnel shelters, hospitals, and aircraft hangars. Private industry has developed and sold them as warehouses, gymnasiums, and swimming pool enclosures for the private home owner. Some of the most ingenious conceptual ideas as well as technology for applications of inflated and membrane structures has been presented by Frei Otto in his book, Zugbeanspruchte Konstruktionen Goodyear Aerospace has investigated such applications as inflatable aircraft, continuous pipe forming techniques and tanks for liquids. Also, Goodyear was the developer of an inflated membrane called the "Air Mat" that maintains the shape of a slat slab with constant thickness.

Basically there are two types of air structures. Air supported structures are a single membrane having air pressure in the usable space, requiring air locks at the entrances. The air simply holds up the membrane. Air inflated structures have the pressure contained within a double membrane which becomes structurally rigid when inflated.

Air structures have several desirable characteristics. They are light weight, when deflated can be easily transported to the site, can be erected with a minimum of labor, are easy to repair, and provide large unobstructed spaces. They can be manufactured and erected at a completed cost as low as $1.50 per square foot. With an internal pressure of 0.65 psi above the atmospheric pressure they have withstood winds up to 200 mph. A pressure as low as .054 psi is sufficient to withstand a 75 mph wind. In case of excessive leaks or power failure the skin settles very slowly. An air inflated structure with a span of 35 feet and a height of 24 feet can be supported with a power plant no larger than a household vacuum cleaner. This same structure develops enough strength to lift the weight of a small automobile. Air supported structures are inflated with about the same volume of air that is supplied by a typical evaporative cooler.

The size and application of inflatable structures is limited only by the tensil strength of the membrane. The development and study of different types of fabrics has gone hand in hand with the development of air structures. Fabrics of nylon, cotton, and dacron with calendered neoprene coatings have been used as forms for concrete. Weights up to 60 ounces per square yard and tensil strengths up to 600 psi have been developed. Lighter weight fabrics in Goodyear's "Air Mat" structural panel have been subjected to pressures up to 60 psi. The development of plastic coatings are making lighter and stronger fabrics possible; however, their costs are still relatively high. With the proper demands put on technology, it will be possible to develop fabrics to meet the needs of any application.

Concrete and Inflated Forms

The air inflated structural system has many potentials. The idea of its use as forms for concrete is not a new one. The approach that has already been explored uses an inflated dome as a form upon which concrete is sprayed. This has had limited success because of the limited use of this type of structure. The objective in this thesis was to apply the air inflated system of forming to structures that would have a wider range of use. However, to gain a basic understanding of how the inflated structural system works was also a primary objective. The inflatables in this thesis will be used to construct a particular type of structure. A great deal of work is being done at the present in an attempt to develop a structural floor system that provides an ordered framework in which the mechanical services can be rearranged or removed and replaced. The floor slab acts as the top cord. The bottom cord exists four to six feet below the slab, allowing a space for mechanical and electrical services. Structurally there is an advantage because the effective depth of the structure makes total use of the space that exists between the ceiling and the floor above it. There are other advantages to this system and for the purposes of this thesis its validity has been assumed.

Attempts are being made to construct this type of structure with precast units, and this may prove to be the best approach. However, this system does require extensive use of a large crane and although the units are precast, scaffolding is often required to hold the units in place until they are post-tensioned. The latter, in some cases, has been eliminated with lift slab techniques, but this is also an expense. After the units are all in place, welding, bolting, or post-tensioning are required to make them act as one structure. Also, precast plants are often not near the site, which makes the units more costly.

The problems of precast units mentioned above often make cast in situ concrete the only practical solution. It does have one advantage, which is inherent in the nature of concrete, of being able to act monolithically with out requiring any mechanical connections.

Cast in situ concrete for the type of structure being considered here also has its disadvantages. The size of the voids and the number of openings connecting them would require a very complicated wood form. Also, the re-use of wood forms is limited. Steel has some advantages. However, to form voids the size of five foot cubes would require very thick steel plates or attached bracing to make the sides rigid. Fiberglass would also have this problem. In addition, forms of these materials would tend to become heavy and awkward to remove and transport on the job. With these considerations it seemed practical to develop an inflated unit for this particular forming problem. Even though inflatables tend to dictate certain basic shapes, the structural requirements of the concrete, the need for a minimum number of elements, and the ease of erection and removal were each given their appropriate amount of consideration. The objective was not only to develop the purest possible pneumatic expression but also to slove a problem of forming in a way that could be used in the building market as it exists today. In other words, by using available equipment and labor, to erect the forms simpler, faster, and more economical than it can be done at the present. The resulting form was also influenced by the process of manufacture.

DEVELOPMENT STUDIES

Several diverse approaches were investigated in an attempt to find the best solution to the problem as it has been stated. However, before presenting these, there are two basic principles of inflated membranes that should be pointed out.

One of these fundamental principles is that any container filled with an internal pressure will tend to become circular or spherical. As in the case of a soap bubble, since the membrane is elastic, a sphere is actually formed, and it is known that this is the smallest surface capable of enclosing a given volume. The spherical shape can be altered by restraining the membrane. This can best be imagined as in the case of rubber balloon with a string tied around it. If the string is tied short enough to have a definite restraining effect on the rubber membrane, the balloon will appear to be two spheres joined together. Note that the string will be forced into the shape of a circle. A spherical shape tends to develop, even if the inflated membrane is not elastic. However, if the pattern of the rigid fabric is not cut and joined based on this principle, ripples and wrinkles will occur on the surface of the inflated unit. The inflated cell actually attempts to reshape itself into a minimal surface.

This becomes a controlling factor when attempting to design inflated shapes using available commercially manufactured fabric that has a negligible amount of elasticity. It soon becomes apparent that some shapes are not possible.

Another fundamental principle is that the tension in the surface of an inflated cell is directly proportional to the internal pressure and the radius of curvature. An interesting phenomena arises as a result of the proportional relationship to the radius of curvature. Consider a section through an inflated cylinder lying on its side with flat plates attached at top and bottom. As a force is applied to the flat surfaces, the radius of the membrane is reduced. As a result, the stress in the membrane is decreased. In other words, when a load is being supported the stresses in the membrane providing the support are actually reduced, which seems to be contrary to the nature of structures we are accustomed to working with. From this also follows another apparent inconsistency. Normally, as in the case of sheet metal, a corrogated sheet will deflect less under a given load than a sheet of a single arch. However, in the case of inflated forms, a series of smaller radii will be under less stress and therefore will deflect more than a larger radius, given equal pressure. This can also be understood from the point of view that a larger radius will displace more volume with less of a deflection than will the smaller radius.

The studies that are presented on the following pages demonstrate the effect of these principles. In order to pass on to the reader any thoughts that may be of value, the material is presented in the sequence in which the ideas developed through a greater understanding of inflatables as here applied. Much of the work was trial and error and each method attempted was done to study advantages and disadvantages.

These are the approaches that are presented in the following pages: The sphere as a basic unit, a shape controlled by rigid planes joined together with flexible fabric, concrete used as the inflating material, an inflated cylinder which is removed horizontally out of the remaining structure, and the final proposal of restraining the inflatable form with webbing.

The sphere, being the natural shape of an inflated form, was considered first. If shperes are placed adjacent to each other, spaces are left between them. These spaces could be filled with concrete and when the spheres were removed a floor system would result. These spheres could be arranged in different wasy as shown in Fig. 2A. The primary problem is that too large a quantity of concrete remains and the holes that connect the voids are too small. The next step then is to push the spheres together. The results would then be something like that shown in Fig. 2B. The resulting structure is desirable but now the sphere has actually become a cube. The pressure exerted by these spheres pressing against each other would be difficult to restrain at the edges of the floor system. Consider restraining the shape of the sphere by making the sides that are pressed together out of a flat rigid material with a flexible fabric joining their edges together. To control the distance that the sides would be forced apart, wires could be connected internally to opposite sides. At this point it appeared that this approach could be made to work. To take it a step further and since a triangulated truss results in more economical use of material, the possibility of using this technique for that type of truss was investigated.

From the photographs you can see the shape of the deflated form. Also note the location of the steel. The system for erecting this could be as follows. The steel reinforcing is hung into place, supporting itself with the use of temporary post. From below the form is slipped into position. Each form is supported on a post. The form is then inflated, the diagonal steel being enclosed in pockets between the inflated units. The concrete would then be poured into these pockets from above at the same time the slab is poured. What has actually happened is that an enclosure has been created that completely surrounds the concrete. The concrete is filling the pocket as the air fills the inflated form. This is almost like pouring concrete into a sock, which is approximately what happens in conventional forms. However, if we make the form light and flexible so that the concrete inflates it to its ultimate shape, we have a new approach. The next group of drawings and photographs indicate one way in which a triangulated floor system could be constructed with this technique.

A scaffolding system is erected first. The post have special caps that provide connection for a horizontal member. This provides a place for workmen to walk when placing the form unit. Two men can carry and install the unit. It is attached to the top of the post and adjusted to receive the steel. The steel is lowered into the form in weld units that are later welded or wired together. The bottom portions of the form unit are then raised into position and the unit is clamped around the steel at all points. A plate is then placed on the horizontal members providing a walking surface for the pouring of concrete. After the concrete is set, the system is removed in the same order as it was placed, beginning first with the post. The form unit unclamps and drops away. The disadvantages here seem to be the over complication of numerous elements and the necessity of all of these elements to remain until the concrete is set.

Another approach is to consider the use of inflated cylinders. A cylinder can be produced by taking flexible fabric with low elastic characteristics, joining opposite edges, closing the ends, and inflating it with air. This would be a very economical shape to manufacture. If cylinders were placed adjacent to each other, allowing a small space between each, and concrete was poured over them, a one-way hollow core structure would result. The cylinders could be removed by reducing the air pressure in them and sliding them out and into position for casting the next day.

If the space in between the cylinders was also properly shaped, a two-way structure could be developed. That approach was attempted by restraining the shape of the cylinders as shown in Fig. 2E (which was later found to be very difficult) and inserting up side down pyramids between them. Also an inflatable the shape of the cylinders was placed between the pyramids in the other direction.

The pyramids could be designed as an umbrella-like folding fabric. It would be inserted after the steel was placed. Once the concrete was poured and set, the tubes would be slid out and the pyramids would be removed from below. The results would be a two-way plate with the pyramid shaped concrete making the top and bottom cords act together.

With the difficulty of making a cylinder of the shape mentioned above, an attempt was made to use a cylinder with a circular cross section.

A steel form work was developed which when placed between the cylinders would develop a result as shown in Fig. 2F.

The angle of the plates take care of the shear in one direction, the width of the plates take care of it in the other direction. The steel form has outer wings that are rigidly fastened to the base frame. The center wings are moveable and have a fold flap that connects their upper edges. They are put into position with center flaps fastened together. After the reinforcing steel is placed, the flaps are released and the air inflated cylinders are slid into position. Note the heavy line on the photograph of the steel form indicating the edges that come in contact with the cylinder. After the cylinders are in position, it is inflated pressing against the edges of the steel form and making a seal. The concrete comes in contact with surfaces of the cylinder not exceeding 8" in the lower portion of the form. Therefore the possible defelction of the cylinder is held to a minimum. The air pressure could easily be attained that would keep the seal from being forced open.

One of the advantages of this system over the one previously mentioned is that the mechanical equipment would occupy the space in the structure not exposed to the room. This may be considered significant in certain applications.

There are a number of difficulties that would have to be overcome in these two systems. However, the most serious problem is that the cylinders could not be slid out from certain positions because of the columns.

At this point, it is necessary to evaluate what has been discovered and decide exactly what approach should be taken. All of the approaches investigated so far have brought out some interesting points about inflatables and each have had some problems that would have to be overcome. Considering the use of these forms for use in the commercial market of the United States as it exists at the moment, the most important aspect is keeping the cost of labor at a minimum. This implies that the best system will be the one that can be simply inserted, inflated and removed without need of crane or complex scaffolding. This means a minimum number of attachments and accessories. The size of the unit should be light weight and small enough so it can be moved easily. The system must be developed so the columns are not interfered with. Ideally if it is going to be inflated it should be totally a flexible inflatable form. This is a practical consideration in that metal parts as a major part of the form would tend to wear the fabric which could greatly reduce the life of the unit. Trying to develop a forming system for triangulated structure becomes overly complicated. It is doubtful that the savings in material is worth the complications.

Considering all the above factors, a waffle plate system with openings between the top and bottom cord would permit the simplest solution. The form units could be similar to the spheres pressed together as mentioned in the first part of this section, but it must solve the difficulties that arose there. The problem is to contain air under pressure in such a way that it will logically form a cube.

PROPOSED SYSTEM

The Shape of the Inflated Unit

As we know, the cube is not a natural shape for an inflated element. From the previous sections we have acquired an understanding of certain basic shapes that are practical. Cylinders, for example, could be used as edge members of the cube with connecting cylinders radiating from the center to give support, Fig. 3A. A membrane would then be attached to the edge cylinders to make the side surfaces of the cube. This membrane would also need some air support to keep it from sagging under the pressures of fresh concrete. Being able to make the edges of the cube and at the time maintain the stability of the flat surfaces is a serious problem. If the unit is inflated with enough air to support concrete the intended flat sides would actually tend to make the unit become spherical.

One way of controlling such surfaces can be done with the use of webs. The edge of the web can be cut in different shapes which will control the shape of the membrane along the edge of attachment. The membrane between webs, however, will develop as archs of minimal surfaces. In Fig. 3B there is indicated a combination of webs and cylinders. The cylinders create a problem in that to function as a cylinder they must be inflated separately. This would mean an additional complication of having to make separate tubes and valves to supply them with controlled air pressure.

It was found possible to locate webs in such a way that the curved edges could be formed without cylinders, see Fib. 3C. These webs can be arranged in many different ways and the accompanying drawings show some of the possibilities.

The most serious difficulty that begins to arise is the complexity of the internal connections necessary to achieve the final shape. To reduce the webs in one section another technique was considered. The horizontal webs were removed and replaced with a cord which is attached to and restrained by the vertical webs. This helped, but did not sufficiently reduce the number of elements converging on the center.

As often happens in the development of a design, the most obvious solution is the hardest to find. Let us look at Fig. 3A again, the cube with cylinders at the edges. The outer part of the cylinder is stressed in a particular way because of the forces induced by its other half. If these forces can be simulated, the other half of the cylinder could be removed.

If we observe a section through the unit without showing the internal parts of the cylinder or webbing, we see what is shown in Fig. 3D. The solution is obvious when we consider how soap bubbles would make such a shape. A web would develop between them, Fig. 3E. It could not be simpler. All twelve edges of the cube could be developed in the same manner. The web actually simulates forces on the sides of the cube which make them act as if they were parts of a sphere. Even though the edges of attachment are numerous, they are not complex. Only one edge is attached to a given position. Therefore, it can be easily attached and easily aligned.

The intersection of the partial cylinders at the corners would form a spherical surface. The sphere would have the same radius as the cylinders. This shape is disciplined and ordered, it approaches the shape of a cube and yet it is totally expressive of an inflated form.

Details and Erection Procedure

After development of the basic inflated unit, it is necessary to find a way by which these units can be connected to produce the open structural frame desired. To keep labor cost at a minimum this connection should be a part of the unit. In other words it should not be an element that has to be installed separately. The openings made by the connectors must vary in size; they must be made as large as possible to allow for maximum duct size. However, they are required to be relatively small near the columns where the shearing stress is high. This means that variations in the sizes of the connectors are necessary. The connectors must be of a soft flexible material so that the unit can be easily collapsed without causing damage to the membrane. If they are inflated, as the last statement seems to require, they must not exert forces on adjacent units great enough to affect the alignment of the forms.

A connector that could meet these requirements and be used with the inflated unit thus far developed is shown in figure 3F. It is composed of a tube which is inflated separately from the primary unit. Tubes from adjacent units would be brought together by their own internal pressure. The seal, however, does not depend solely on this so the force between the tubes need only be great enough to bring them into continuous contact. The seal is actually achieved by a flap that is attached to one of the tubes and acts as a plug between them. The inflated tubes would become rigid and simply provide support for the plug which keeps the concrete from wedging between them. The elements are designed so that inflating of the tubes creates tensil stress in the plug and therefore it can not be pushed out of position by the depositing of concrete. As the depth of the concrete in the forms increases, the static pressure presses the plug more firmly into position.

Another connection that must provide a seal occurs at the bottom edge of the cube. This is where the cubes become attached to each other and form the bottom cord of the truss. The connecting element is a channel with its legs sloping in and facing downward, figure 3G. However, if it proved more economical the channel could be replaced with wood members which would be shaped and fitted on the job. The element attached to the cube is a flap made of a steel plate encased in fabric. In its installed position it provides a continuous edge upon which the inflated unit rests. The membrane fabric is reinforced at the edge of the steel to prevent wearing. By cutting the flat steel plate and letting the fabric be continuous a hinge action is developed which allows the flap to be easily collapsed when the form is deflated. The steel flaps are attached to each other with clamps. The channels are factory made units with an overall dimension of 10' by 10', figure 3H. Adjacent units are bolted together. They are supported by a scaffold tree which allows space for circulation of workmen and equipment while the scaffolding remains in place. The scaffold has four arms that are attached to a base plate which distributes the load over a large bearing area. The angle of incline and the length of the arms are adjustable to allow a maximum range of use.

A special tool was developed to aid the workmen in pulling the flap into proper relationship with the channel. A small lip on the bottom edge of the flap fits into one jaw of the tool. A notch in the other jaw is pressed up against the bottom edge of the channel. The elements are brought into position as the jaws close. The tool automatically locks closed in the same manner that vice-grip pliers lock. The workmen then secure the elements with a device similar to a "C" clamp and the tool is removed.

To reduce further labor cost, the required scaffolding

While this is nearing completion for a given section the reinforcing steel is lowered into position from above. The dimensions of the steel lifted into position would be limited primarily by the capacity of the crane on the job. As the section of steel installed and necessary wiring and welding is completed the inflated units are distributed near their respective locations. The fork lift then begins lifting the units into position and inflating them to the required pressures. At the same time the inflated units are secured to the channels and the connections between the units are accomplished automatically. When this is completed the concreting can then be accomplished in a single pouring process.

The inflated units contain enough pressure to sustain workmen and basic equipment during the remaining construction of the slab. After the concrete has been in place for twenty-four fours the inflated units are removed and are ready for use in the next bay. This enables a minimum number of units to be put to maximum use on a single project. The steel channel units and "scaffold tree" remain in place until the concrete reaches minimum required strength.

Models and Manufacture

The only way to understand and test shapes of inflated elements is to build models and inflate them. Many aspects of the manufacture proceedure can also be planned with the use of models. The final shape of the cube developed from this project was arrived at after numerous test models. It was soon found that the nature of fabric used had as much effect on the resulting shape as the pattern of the fabric and the shape of the form.

Woven fabrics generally stretch on the bias and are rigid in the two directions of the woven threads. The bias is at a 45° angle to the directions of the weave. The first models that were constructed in the development of the cube were made of pattenns cut parallel to the edges of the fabric as it came off the roll. Consider an upper edge of the cube and regard it as a portion of a cylinder. These first models had the rigid direction of the fabric perpendicular and parallel to the axis of the cylinder. There was no stretch in these directions and when inflated the 45° stretch at the corners caused ripples to occur at the points where the webs attempted to control the shape. By simply cutting the pattern at a 45° angle with the edges of the fabric as it came of the roll this problem was eliminated. The stretching occured so the tension distributed itself in a way that differences in surface tension were balanced.

However, it should be noticed that the direction of the cutting the pattern must depend on the way in which surface tension will occur in the resulting form. It will not be the same for different shapes and may even be different for parts of the same shape. In the latter case, parts of the pattern would have to be cut separately and the angle of the cut changed to accomodate the shape.

There as less problems with the use of elastic fabrics as far as ripples are concerned. However, shape in elastic fabrics are less easily controlled. Some test models could be built of elastic material and patterns for rigid woven fabrics could be cut based on the resulting inflated surface area.

If models are to be made to test ideas a quick construction technique is a necessity. Generally, the cements that adhere to coated fabrics take 24 hours to achieve any strength. And, after they are secure they are not easily removed to permit minor changes that may be necessary. A technique found to be of value during this project was the use of a tape with high adhesive qualities. A pattern could be cut, taped together and inflated, changed and re-inflated in a relatively short time. However, tape does not hold pressures greater than 1 $\frac{1}{2}$ psi, which is sifficient to see what happens. This can be achieved orally which is very convenient and economical for quick test. A balloon cut in half, taped into position and tied in a knot to contain the air was used to eliminate the need for any special valve-stem.

Another technique which has been used for building inflated models makes use of liquid latex rubber. The desired shape is carved out of polystrene and liquid latex is painted in thin coats over the entire surface. Reinforcing fabric may be applied. If webs are desired, threads can be stitched between the necessary points. About ten or twelve coats of latex are required. A slit is then cut in the latex and toulene is poured onto the polystrene. The polystrene is dissolved and can then be poured out. The slit is then resealed and the unit is ready for inflation.

The technique selected to construct the final shape in this project makes use of a hypoln coated woven nylon fabric. This material was used in attempt to simulate the way in which the actually forming unit would be manufactured. The fabric weighs 8 oz. per square yard, will contain air pressures up to 10 psi. The joints are laped on the inside with a strip of the same fabric which acts as a joint tape. The joints were cemented with 3 M Brand No. EC1357. Test strips were made with this cement and Utility Cement No. 503, Knowles Rubber Company, Inc.

and both proved to achieve a greater strength then the coating on the fabric. The former was selected because with toulene it could be thinned for painting on with a brush and removed if necessary. The corners are cut portions of a rubber ball. In the actual manufacture process the corners could be reformed of the same fabric as used in the other portions of the unit. In the early models several attempts were made using the flat coated fabric but the results were not satisfactory. At a large scale this approach would probably work. However, the preformed shape of the rubber ball greatly simplifies the corner problem at this scale.

The coated fabric was cut in the pattern shown on the drawings. This pattern has a minimum of joints and except for the corners has no joints that occur in the areas where concrete comes in contact with the unit. The elimination of joints on the edges of the cube also provides a continuous membrane and reduces the probability of ripples due to the joint tape. Notice that the joints that do occur are parallel to the rigid direction of the fabric. In this way the joint tape acts homogeneously with the fabric.

The internal webs which control the shape are made of the same fabric as the rest of the unit. The stresses which develop in them are substantial even at low pressures. The points of attachment are particularly critical

This detail has a double angle as can be seen in the drawings. Each angle helps to keep the other from gradually peeling away. The correct length and precise location of the webs are very important. If the web is attached only slightly out of line the results will be very unsatisfactory. The larger the scale the less effect this will have.

The tubes used to connect through the adjacent units are natural rubber. They are not inflated because the rubber had sufficient strength at this scale. In the full scale manufactured unit they would be made of a material similar to that used in the rest of the unit. However, this shape would probably be modified due to the use of this material. They would also be inflated. through the same valve stem as the rest of the unit but would have a lead off hose with a control valve that would regulate the pressure separately.

The metal flaps at the bottom edge of the model are attached with tape because it is more elastic and does not have to withstand any air pressures. The metal is broken at mid-point on each side and 3/4 inches in from each corner. This allows the unit to be folded when deflated. At full size this entire element could be more precise and create better edges.

To manufacture the unit at full scale would actually be easier than to build a small model. Reaching inside, glueing and sealing would be simpler and more accurate. On this type of work it is possible that the elements would be stitched together. In such a case the fabric is usually not cured on the inside until the unit is completed and inflated, then during the curing process the rubber which is actually soft would better conform to the shape and seal any leak holes in the unit.

To manufacture the cube shape developed here would require about 30 square yards of coated fabric. It is estimated that material of the required strength would be about 25 oz. per square yard which would total about 46 lbs. The steel flap at the lower edge would amount to about 15 additional pounds. The resulting 61 lbs. could be easily handled by workmen and raised into place by the fork lift.

The only limiting factor of such an inflated unit is the strength and durability of the fabric. Concrete has already been cast with coated fabric forms. The next step would be to build full scale units and conduct complete feasibility studies.

BIBLIOGRAPHY

"All Purpose Air-Supported Tents and Their Application for Global Military Use", U.S. Army Quartermaster Research and Engineering Command, Natick, Mass. (1961).

Architectural Forum, "Air Sandwich Wall Systems" (April 1957).

Architectural Forum, "Those Ballooning Air Buildings" (July 1959).

Bird, W. W., Jr., "Improved Materials for Air Supported Radomes," Cornell Aeronautical Laboratory, Report No. UB-765-D-4, (1953)

Hagen, Hans W. "Analysis of Inflated Cell Structural Elements," M.S. Thesis, MIT. (1961)

Kobayashi, A. S. and Durelli, A. J., Feasibility Studies for Air-Cellular Featherweight Housings, Phase Report ARF No. K 103, Contract No. AF 30 (602) Armour Research Foundation of I.I.T., Chicago 16, Illinois, (March 1957)

Monego, Constantin J., "Air Supported Tents for Military Use", U.S. Army Natick Laboratories, Natick, Massachusetts

Otto, Frei, "Shells and Membranes", World Conference on Shell Structures, National Academy of Science - National Research Council, Pub. No. 1187, (Oct 1962)

Otto, Frei, Zugbeanspruchte Konstruktionen, Frankfurt, Ullstein (1962)

Robertson, Nan., "Air Structures for School Sports", New York Educational Facilities Laboratories (1964)

Warner, Leo V., "Experimental Deflections and Natural Frequencies of an Inflatable Fabric Plate" M.S. Thesis, MIT. (1963)

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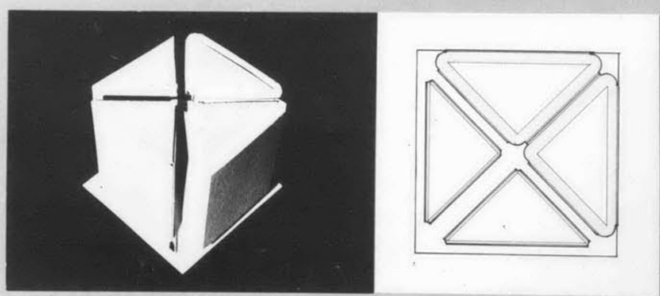

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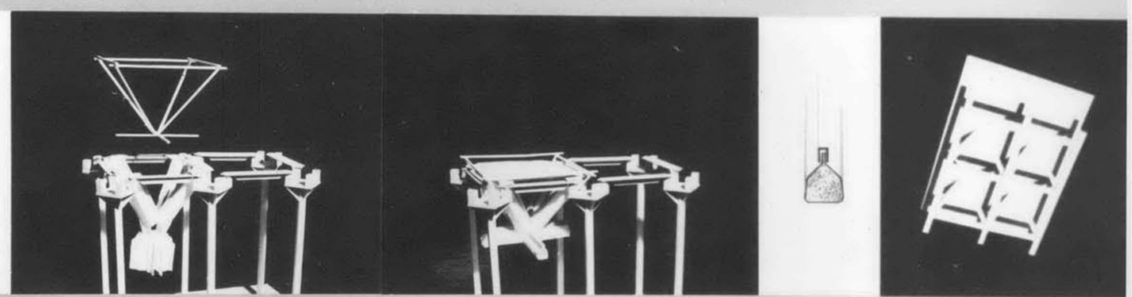

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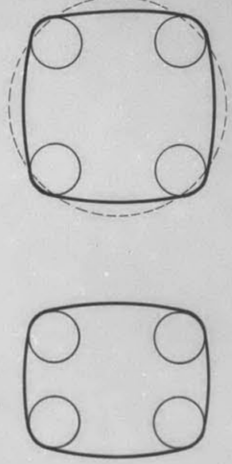

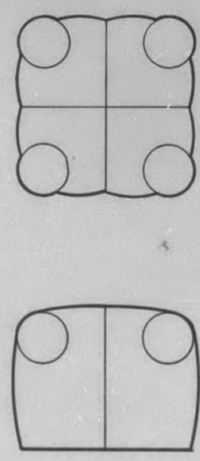

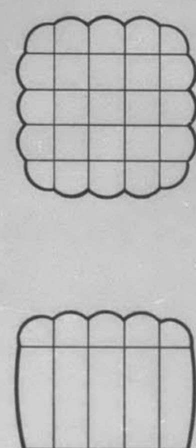

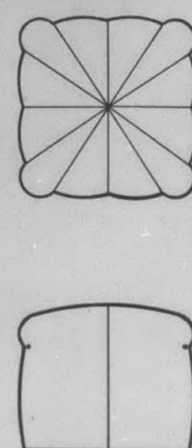

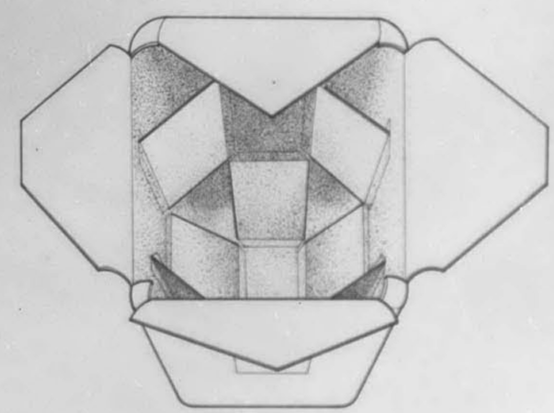

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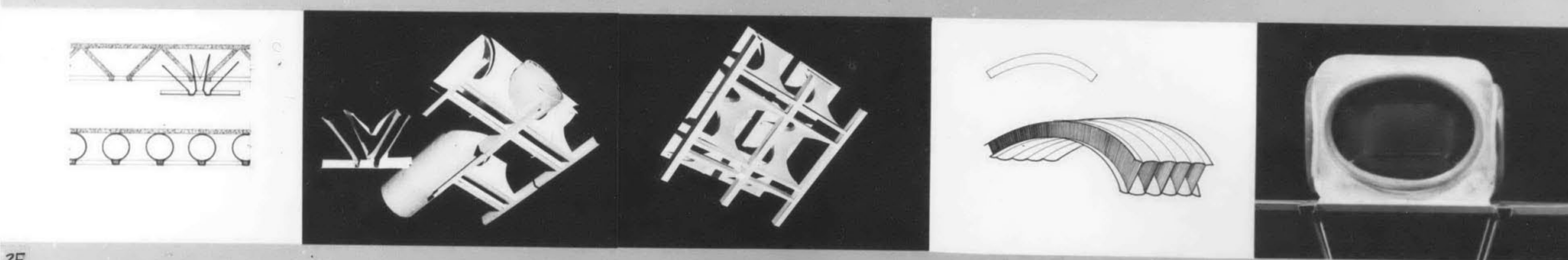

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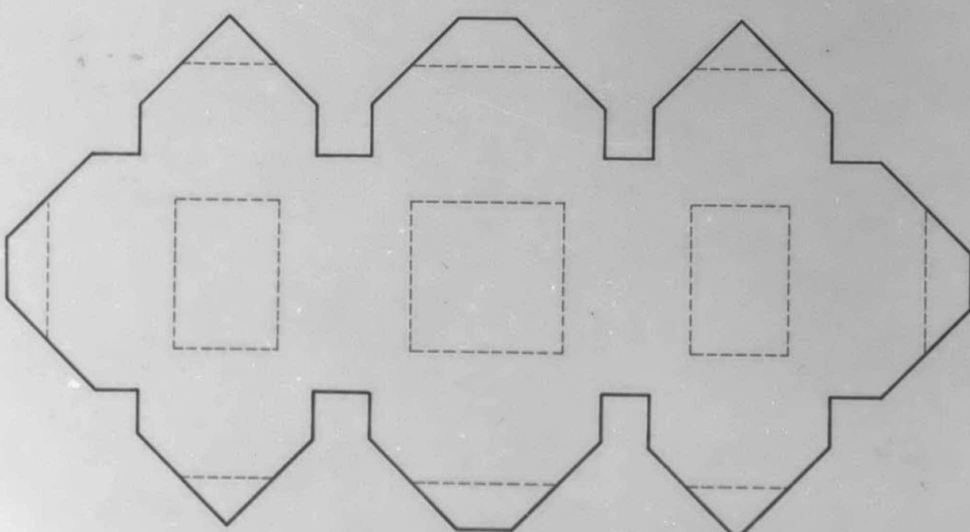

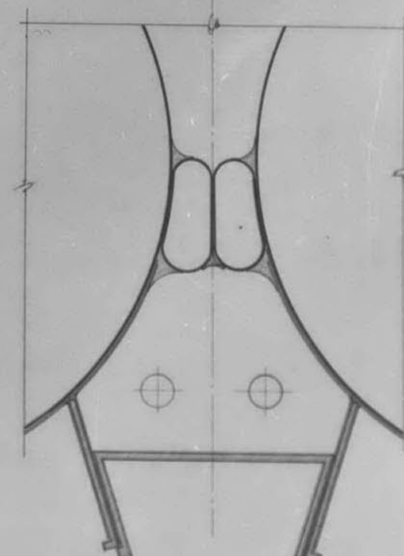

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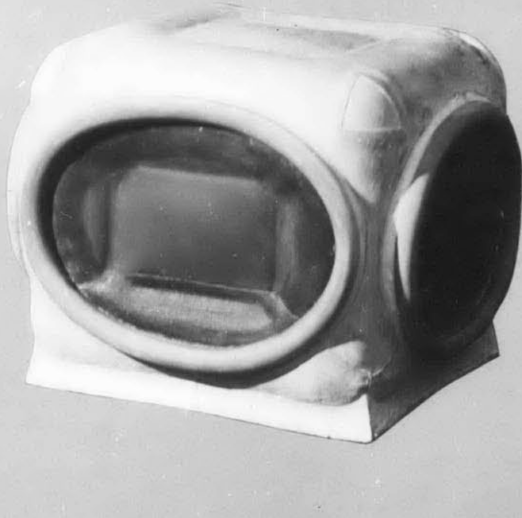

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