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FABRICATION AND TESTING OF PRESSURIZED RIB TENTS

by

Earl C. Steeves

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April 1979

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NATICK RESEARCH and DEVELOPMENT COMMAND
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Aero-Mechanical Engineering Laboratory

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The use of pressure stabilized structural elements in tentage support structures has been under investigation for several years. The work reported here culminates the exploratory development phase of this investigation with a description of the fabrication and simulated snow load testing of several prototype concepts. In addition, some preliminary study of the fabrication of pressure stabilized structural elements is reported, including weaving and air retention techniques. The test results clearly demonstrate that building stable tent support

20. Abstract (cont'd)

frames using pressure stabilized structural elements is possible and that the design of such a tent to meet the operational snow load requirements is also possible. With regard to fabrication of the structural elements, further work is needed on the weaving to provide additional strength so that higher inflation pressures can be used and on providing additional air retention.

PREFACE

The work reported here culiminates an investigation to develop design procedures for and establish the feasibility of using highly pressurized structural elements for tentage support structures. The work was carried out under task 62723A 1L762723AH98AE entitled "Studies in the Mechanics and Materials of Tentage Structures" as a combined in-house and contract effort. The contract portion of the effort was carried out by Woven Structures, Inc., of Compton, California, under Contract No. DAAK03–C–0103 and consisted of weaving the contoured tubes used for arches in the support frames. In doing the weaving they used a patented three-dimensional weaving technique which results in a naturally curved tube. The prototype tents were fabricated using these contoured arches by the Shelters Prototype Branch, Aero-Mechanical Engineering Laboratory, under the direction of Ernest Saab and Kenneth Christopher with the actual fabrication being done by Leo Zink assisted by other members of that Branch. The simulated snow load testing of the prototype tents was carried out by Jack Lupien and Jack Buckley of the Experimental Analysis and Design Division, AMEL. The author was also assisted by William Crenshaw of the Tactical Shelters Branch, AMEL in the design of the tents and in the monitoring of the contract effort.

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INTRODUCTION

An analysis of the Army's needs for tents has been conducted. This analysis, which is presented in reference 1, considers the factors of mobility, habitability and cost to evaluate a number of structural support concepts for tents. The results of this evaluation reveal that the pressurized rib concept is one of the most promising for meeting the Army's needs for large sized, highly mobile field shelters. The pressurized rib concept consists of a pressure-stabilized frame or support structure covered with a lightweight environmental barrier, as shown in Figure 1. The number and size of the support structure elements has been reduced over the current double-wall air-supported tents. This is made possible by using pressures in the range from 300 to 500 kPa in contrast with pressures of less than 5 kPa used in double-wall air-supported tents. The pressure stabilized structural elements are made of a flexible material such as fabric so that it can be folded when not inflated. This gives a low bulk or volume in the transport configuration. This concept retains the rapid erection and striking which is characteristic of all air-supported tents and it is envisioned that the dedicated air supply required by current air-supported tents will be eliminated by greatly improved air-retention capability.

To support the development of the pressurized-rib concept, a series of investigations of the behavior of pressure-stabilized structural elements have been conducted and are reported in references 2, 3, 4, and 5. In referenences 2, 3, and 4, investigations of the behavior of pressure-stabilized beams and arches are reported. These investigations include the development of theory to predict the behavior of these structural elements under

[1] Johnson, Arthur; Comparative Evaluation of Concepts for Modular Tentage; US Army Natick Research & Development Command, Technical Report NATICK/TR–78/009, 1978.

[2] Steeves, Earl C.; A Linear Analysis of the Deformation of Pressure Stabilized Beams; US Army Natick Laboratories; Technical Report 75–47–AMEL; 1975 (AD A006493).

[3] Steeves, Earl C.; Behavior of Pressure Stabilized Beams Under Load; US Army Natick Development Center; Technical Report 75–82–AMEL; 1975 (AD A010702).

[4] Steeves, Earl C.; The Structural Behavior of Pressure Stabilized Arches; US Army Natick Research & Development Command; Technical Report NATICK/TR–78/018; 1978.

[5] Steeves, Earl C.; Pressure Stabilized Beam Finite Element; US Army Natick Research & Development Command, Technical Report NATICK/TR–79/002; 1978.

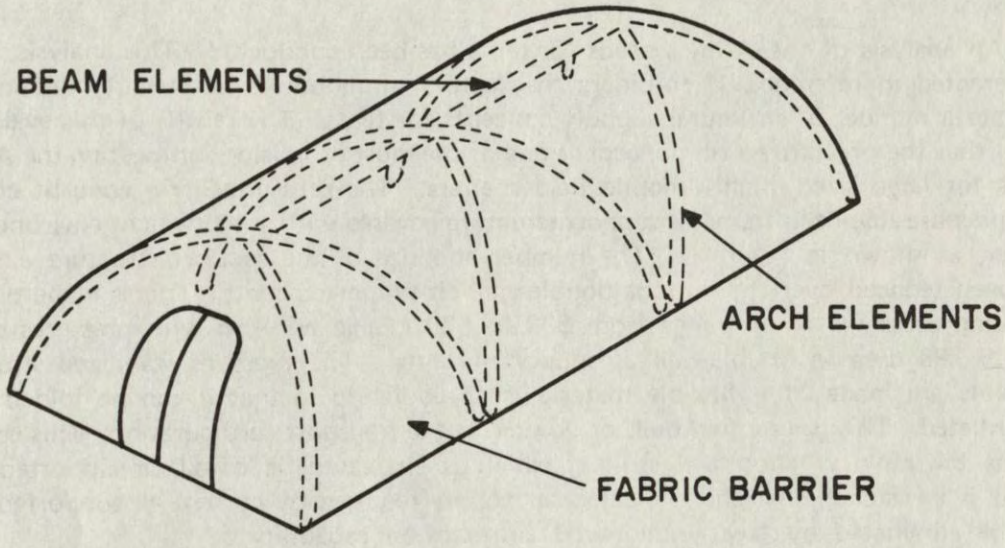


Figure 1. Tent Concept Using Pressure Stabilized Structural Elements

load and experimental verification of these predictions. The prediction of both the deformation and the load-carrying capability are verified by the experiments. In reference 5 the development of a finite element for pressure-stabilized beams is described along with its adaptation to a computer code for the analysis of frame-supported tents. This computer code is described in reference 6. The results of these investigations provide a basis for the design of pressure-stabilized structural elements and frame assemblies using these elements and allowed us to establish the feasibility of the concept. In all this work the parameters involved in the design are the element cross-section radius, the inflation pressure level, and the frame assembly configuration. These are chosen based on the wrinkling load failure criterion. As described in reference 2, 3, and 4, this criterion requires the above design parameters to be selected so that the applied load does not cause wrinkling of the fabric skin of the support structure elements.

A previous experience with a tent using this concept resulted in its collapse under a very light snow load. As a result, the stability of frames using pressure-stabilized structural elements was questioned by other investigators and tent designers, and the concept was at that time eliminated from further consideration. The tent involved was 15 m long by 7 m wide and the support structure consisted of four pressure-stabilized arches separated by about 5 m. The only connection between these arches was the fabric environmental barrier. Such a configuration is inherently unstable regardless of the nature of the arches, be they pressure-stabilized or not. The arches used were approximately 0.3 m in diameter and were made of a woven material much like fire hose. An inflation pressure of 690 kPa was used. These tubes were naturally straight; they were inflated and the ends drawn together with a winch to form arches. This made assembly very difficult and complicated the anchoring problem because the ends of the arch had to be restrained to keep the arch form.

It is the author's belief that the difficulty with this tent was the result of the inherently unstable support structure configuration used and was not related to the presence of pressure-stabilized structural elements. It is further believed that inherently stable frame configurations can be conceived and successfully utilized with pressure-stabilized structural elements. An investigation was conducted to substantiate these beliefs and the results of this investigation are the subject of this report.

The investigation included the development of three concepts, the fabrication of 4.9 m x 4.9 m prototype tents using each concept, and the simulated snow load testing of the prototype tents. In carrying out this aspect of the investigation we used designs and fabrication techniques with which we had high confidence of obtaining prototype structures to test. Some of the designs and fabrication techniques would not be desirable

[6] Remington, Paul J., John C. O'Callahan and Richard Madden; Finite Element Analysis of Scale Model Frame Supported Tents; US Army Natick Research and Development Command; Technical Report 76–21–AMEL; 1975 (AD A028837).

in a field item but were not detrimental to this investigation. Of particular note in this regard is the use of metal end caps and polymer film bladders. While fabricating the arches to be used in the prototype tent using these high confidence designs and fabrication techniques some studies to advance the state-of-the-art for fabrication of pressure stabilized structural elements were undertaken. These studies included: use of fabric coatings to provide air retention, the development of fabric ends to replace metal end caps, and the attachment of the fabric end caps to the arches to form a complete closed fabric pressure-stabilized structural element. None of these lower confidence techniques were used in the prototype tents.

This report describes this investigation including a description of the frame concepts, fabrication of the structural elements, assembly of the prototype tents and the simulated snow load test. The results of the simulated snow load tests are presented and used to evaluate the frame concepts.

FABRICATION OF PROTOTYPE TENTS

To demonstrate that stable frames can be designed using pressure-stabilized structural elements, we undertook a program of selecting frame designs, fabricating prototype tents using the selected designs, and subjecting these tents to simulated snow loads to evaluate the tent stability. A tent having a length and width of 4.9 m was chosen for this work because a tent of this size, the Tent, Frame Type, Expandable, 16′ x 16′ (FSN 8340–782–3232), is currently in the system and would provide a basis for comparison. The selection of frame designs was based on the criterion of the inherent stability of the basic frame element. In this section the chosen frame concepts are described and the details of the fabrication of the tents including the structural elements are presented.

Frame Concepts

The three arch concepts chosen for this work are shown in Figure 2 and are designated as the crossed-arch, leaning-arch, and arch-and-purlin concepts. For each concept the basic structural module which was selected on the basis of inherent stability is shown along with single- and multi-module tents.

Crossed Arch Concept

The basic structural module for the crossed-arch concept is formed by crossing two arches at their center point and securely joining them at that point. In this concept the planes of both arches are vertical and intersect at an angle determined by the tent width and the module length. The layout of this concept is shown in Figure 3 where the dimensions are given for the double-module tent used in this investigation. Also shown is a sketch of the arch used for this concept. The rather large area between the modules which has no support caused some concern, so two techniques for adding structural support to this region were conceived and are shown in Figure 4. The midspan beam spans the gap between the two modules and does not provide any additional load paths to ground

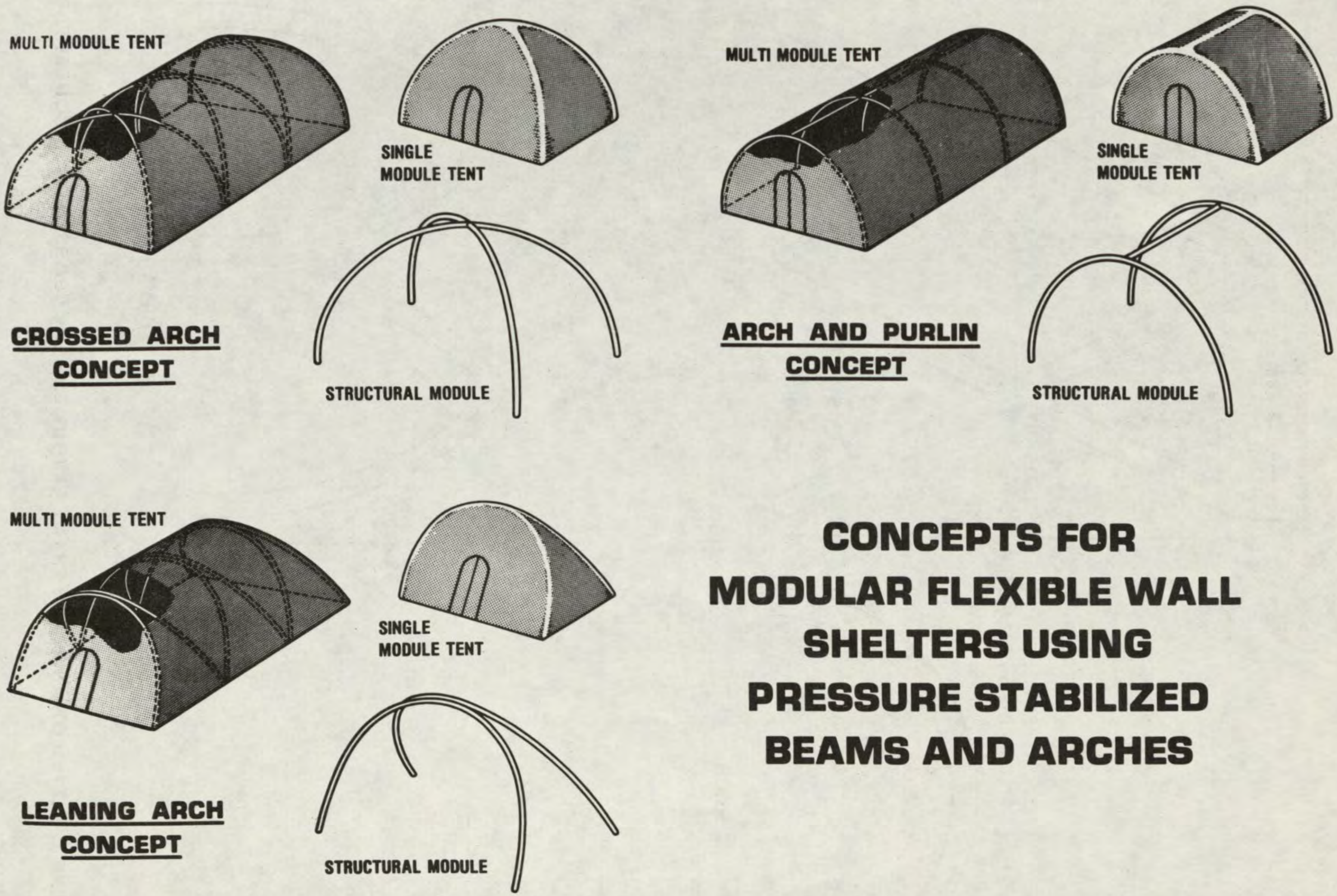


FIGURE 2. FRAME CONCEPTS FOR PRESSURIZED RIB TENTS.

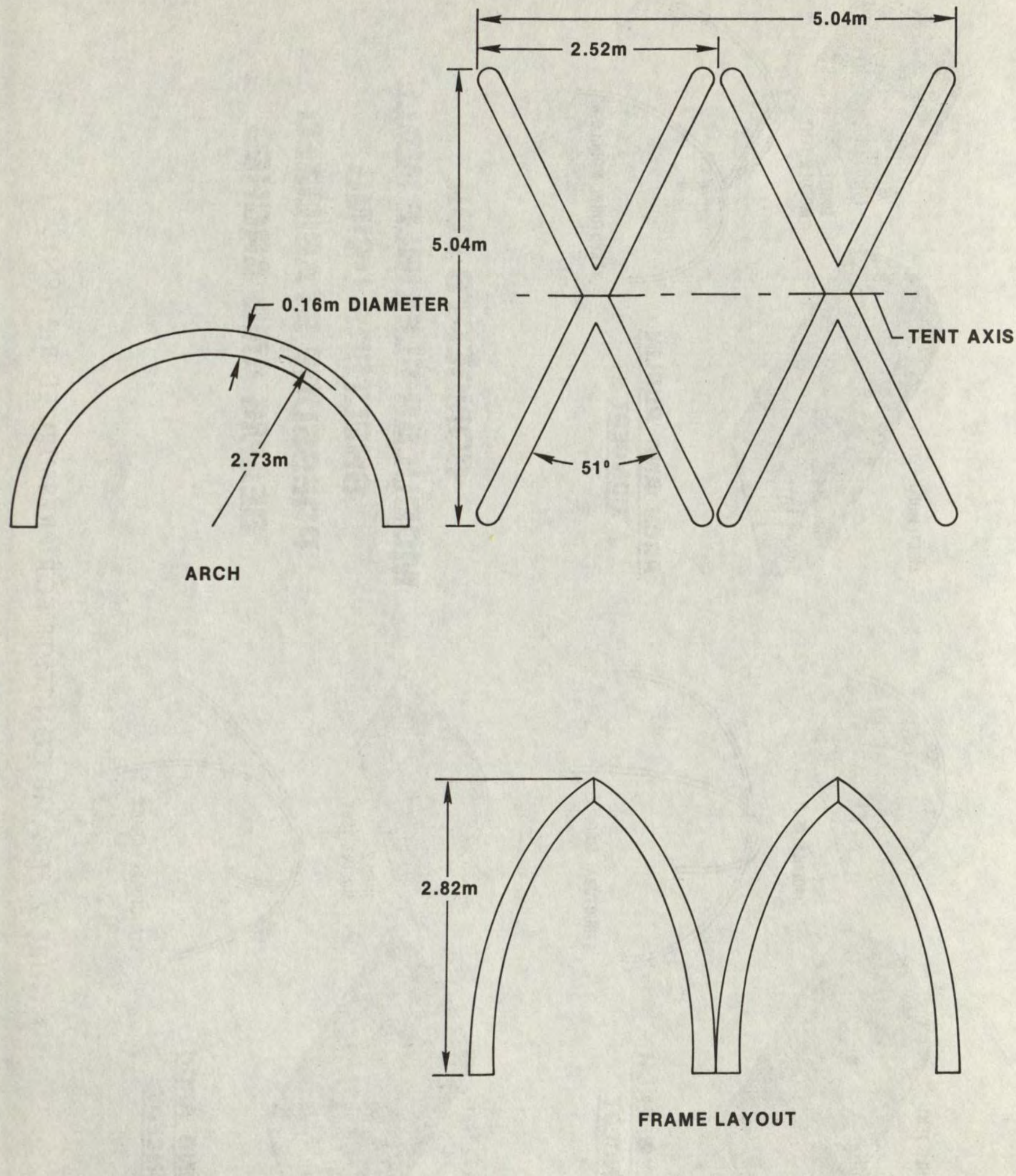
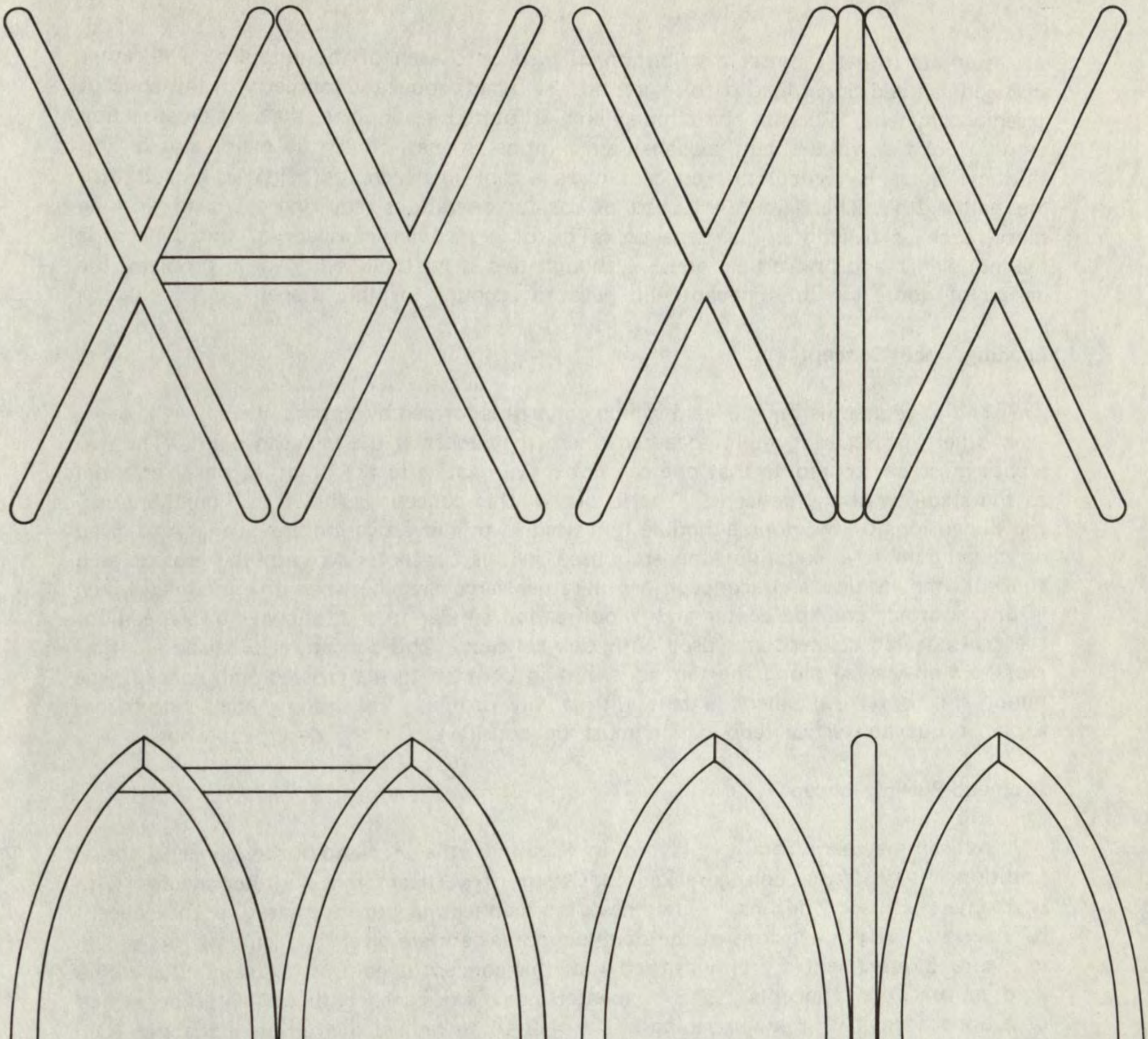


FIGURE 3. SKETCH OF ARCH AND FRAME LAYOUT FOR THE CROSSED ARCH CONCEPT.



MIDSPAN BEAM

CENTER ARCH

FIGURE 4. MODIFICATIONS OF THE BASIC CROSSED ARCH CONCEPT.

but attempts to get a better distribution of load onto each of the modules. The center arch adds an additional load path to ground. Two facts about the geometry of this concept deserve comment. Because the circular arch is rotated in its plane, the tent cross-section as one looks down the tent axis has an elliptical shape. Since the major axis of this elliptical shape is vertical this concept gives a tent in which the height is greater than the half-width. This feature may be of use for operations requiring overhead working space, such as helicopter maintenance. The other geometric aspect of this concept is the nonplanar and nonvertical end. Although this is not believed to be a problem, the design of doors for this concept will have to account for this shape.

Leaning Arch Concept

The basic module for the leaning arch concept is formed by tipping two arches towards each other and securing them together where they meet at the midspan point. The two arches must be secured so that one can not move relative to the other, as this is essential to the stability of the concept. The layout of this concept is shown in Figure 5 where the dimensions of the double-module tent used in this investigation are given. Also given on this figure is a sketch of the arch used in this concept. As with the crossed arch concept, the leaning arch concept has a rather large area between the modules which is unsupported, and the center arch modification similar to that shown in Figure 4 for the crossed arch concept was used with this concept. This concept also has an elliptical cross-section viewed along the tent axis, but in contrast to the crossed arch concept, the minor axis is vertical, giving a tent with a low profile. The leaning arch concept has a planar but nonvertical end which must be considered in the design of doors.

Arch-and-Purlin Concept

As can be seen from the layout in Figure 6, the arch-and-purlin concept uses a traditional tent frame configuration consisting of vertical arches interconnected with horizontal beams or purlins. It is these interconnecting purlins that give the concept its stability. The dimensions of the double-module tent are given in Figure 6. As shown in Figure 6, a segmented arch was used with this concept in contrast to the circular arches used in the other concepts. This segmented arch is designed with its centerline as half of a dodecagon having an inscribing circle of 2.44 m radius; the radius of the arch used in the leaning arch concept. The motivation for using the segmented arch resulted from questions concerning fabrication and cost rather than structural stability. The weaving of circular arches is rather costly and available from only a single source, so alternate fabrication techniques are desirable. The segmented arch which can be fabricated from straight tubes is one such alternate. The objective here was to examine the techniques for fabrication of segmented arches and assembling them in a tent structure. The details of the design and fabrication of these segmented arches will be discussed later in this report.

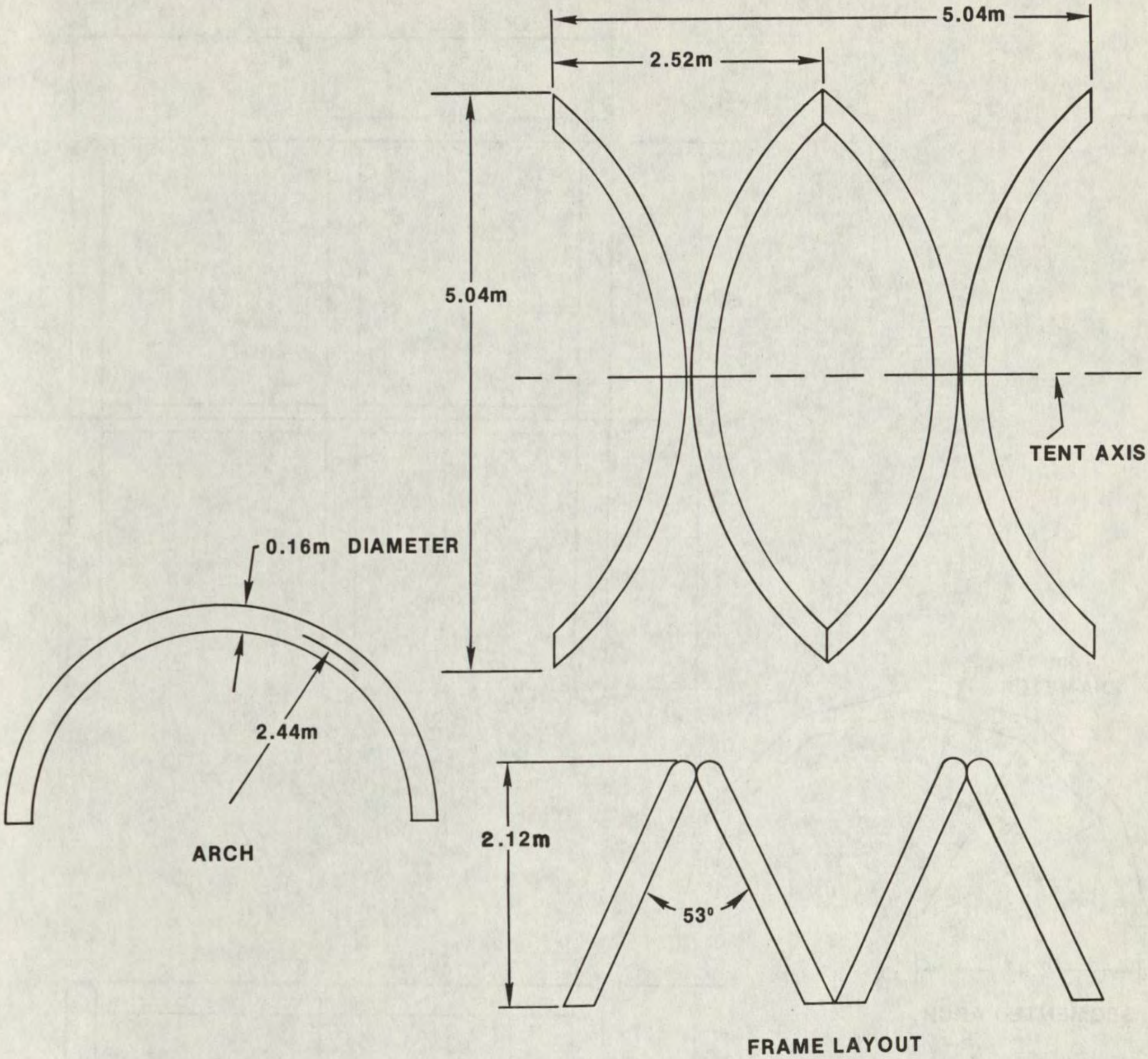


FIGURE 5. SKETCH OF ARCH AND FRAME LAYOUT FOR LEANING ARCH CONCEPT.

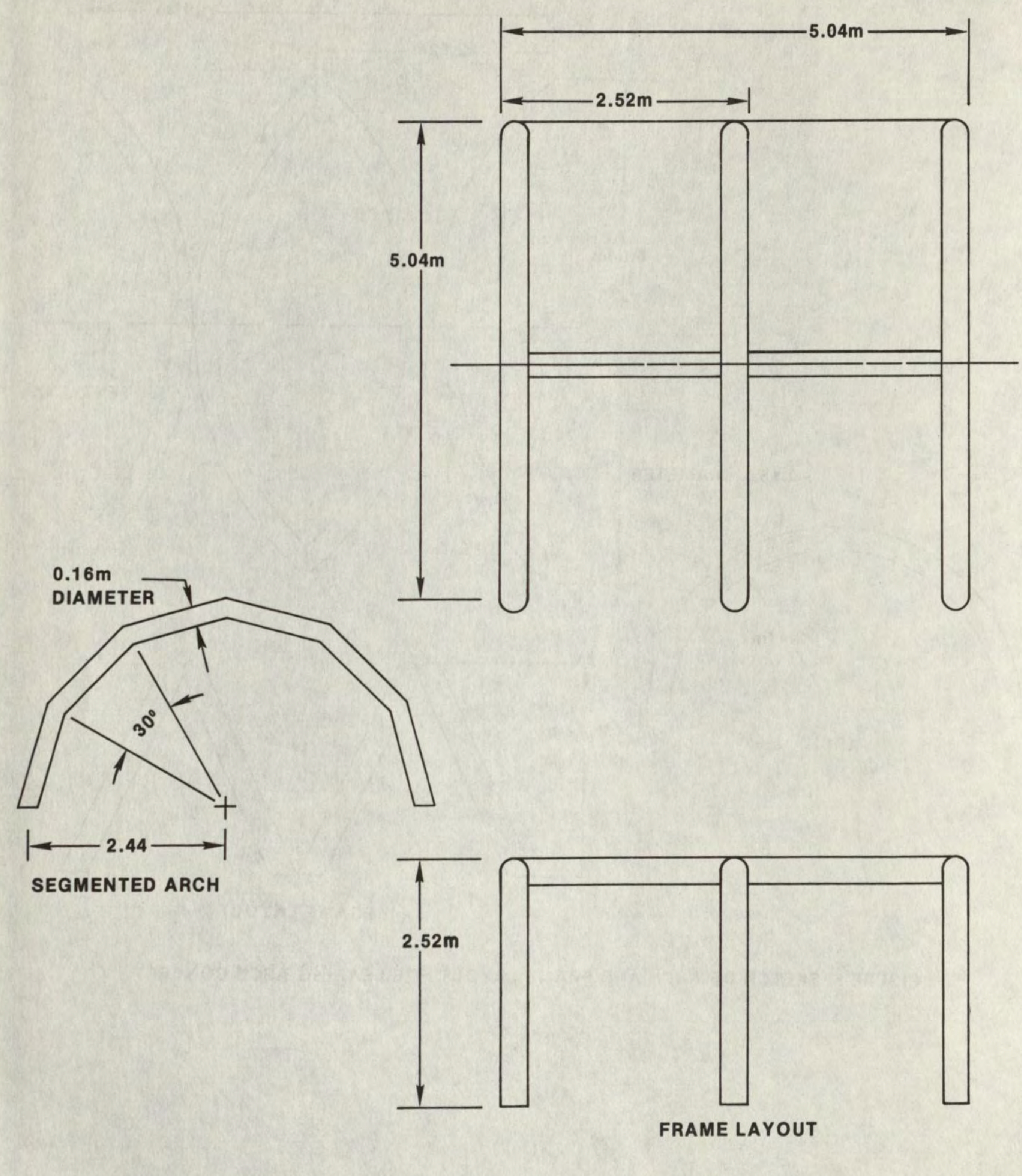


FIGURE 6. SKETCH OF ARCH AND FRAME LAYOUT FOR ARCH AND PURLIN CONCEPT.

Arch Fabrication

The circular arches were woven using a unique three-dimensional weaving technique that gives a natural circular contour. In undertaking this project we had confidence in this weaving technique and in providing air retention with the use of polymer film bladders. However, the use of coatings to provide air retention was also tried as a part of the effort. On the arches with which polymer film bladders were used, the end closures were accomplished with metal end caps of the design reported in reference 4. In an attempt to reduce weight, the coated arches were fitted with woven hemispherical end caps. The use of this coating technique and woven end caps provided a preliminary look at some of the fabrication problems associated with the making of pressure-stabilized structural elements.

Weaving

As has been indicated, the weaving of the arches is done with a three-dimensional weaving techniques that gives a natural curvature to the arch. Thus, when it is inflated, it has the shape of a segment of a torus and an extremely small tendency to become straight. This contoured weaving is accomplished by using a shaped roller to pull the warp yarns through the loom. As shown in Figure 7 this roller is shaped so that its diameter smoothly decreases from its maximum, D, to its minimum, d, in moving along x–x axis. Since the roller is rotated at a uniform speed about its x–x axis, the yarns in contact with the larger diameter part of the roller are pulled through faster than those in contact with the smaller diameter part. Because of this yarn speed differential there results a variation in the fill yarn count which gives the contour. The faster moving yarns correspond to the outer radius of the torus or arch. The contoured tube is woven flat and a complete circumferential yarn takes two passes of the fill yarn shuttle, as shown in Figure 8. To do this the shuttle must be stopped and the direction reversed. This results in a crease or fold on both edges which corresponds to the inner and outer radii of the arch. Because it is not possible to keep the shuttle tension constant there results a nonuniformity in yarn lengths in the crease region, which is believed to be related to some strength problems to be discussed later. Straight tubes are woven using the technique described with the use of a cylindrical roller. It was intuitively felt that the weaving of the straight tubes in this manner would be straightforward. However, it turned out that the tubes so woven had some curvature; typically on the order of a rise of 0.2 m in 5 m of length. This was not a problem in their use so it was not corrected. This curvature is caused by a pull-through speed differential between the upper and lower fabric layers. This speed differential is caused by the upper layer being pulled through on a radius equal to the roller radius plus the fabric thickness while the lower layer is pulled through at a radius equal to the roller radius. It is believed that this unwanted curvature could be removed by using a double roller, one in contact with the upper layer and the other in contact with the lower layer.

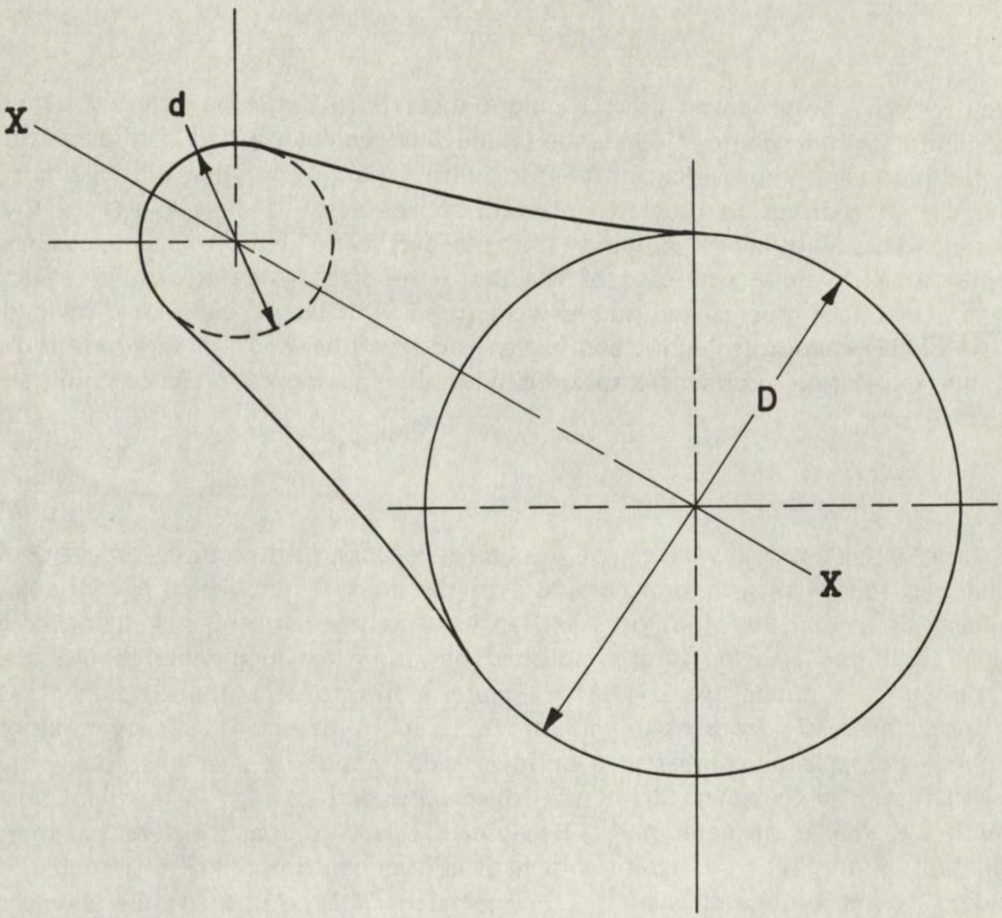


FIGURE 7. CHARACTERISTIC SHAPE OF THE ROLLER CAM USED IN THREE DIMENSIONAL WEAVING.

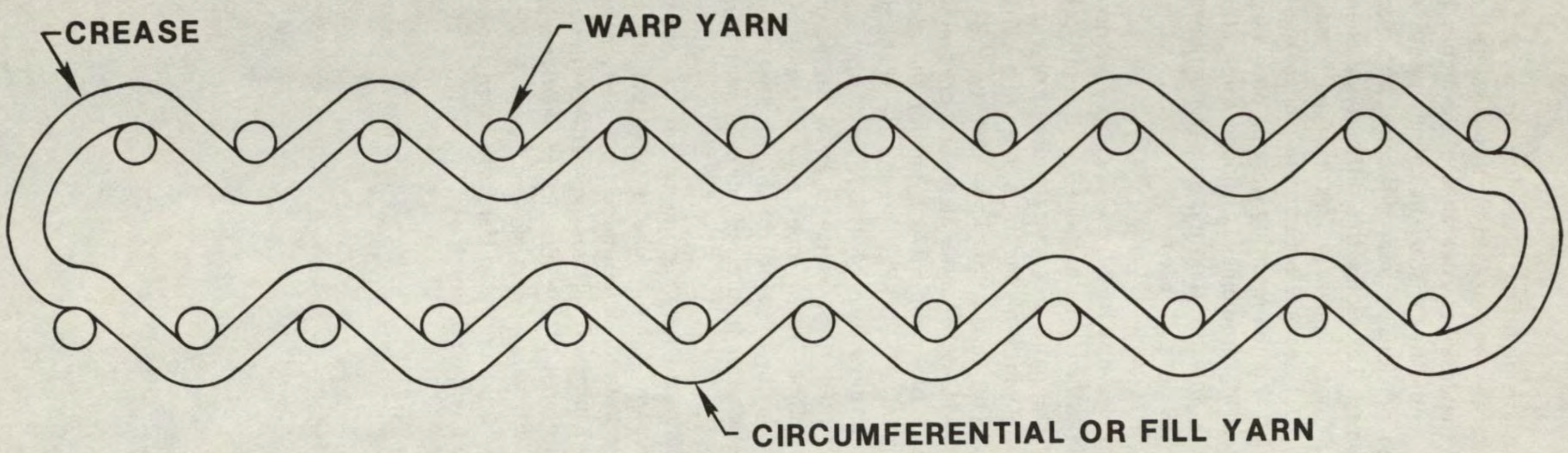


FIGURE 8. WEAVING OF TUBES IN FLAT CONFIGURATION.

The high strength of Kevlar and the resulting possibility for weight reduction led us to choose it for weaving the structural elements needed for this investigation. Kevlar–49 was initially specified, and because of the desire to coat some of the arches, it was ordered in the unfinished condition; that is, with the twisting finish removed. Although this material had been successfully woven previously, great difficulty with yarn pilling was experienced and could not be overcome. To resolve this difficulty, a change was made to Kevlar–29 with the twisting finish not removed. This involved some risk involving adhesion of the coatings to be used, but seemed a better risk than the possibility of yarn damage during a scouring operation and the resulting weaving problems. The change to Kevlar–29 seemed to solve the weaving problems. Although some pilling continued to occur, it was not significant. It is thought that this may be reduced further if a higher twist is used, perhaps up to 0.9 turns per cm.

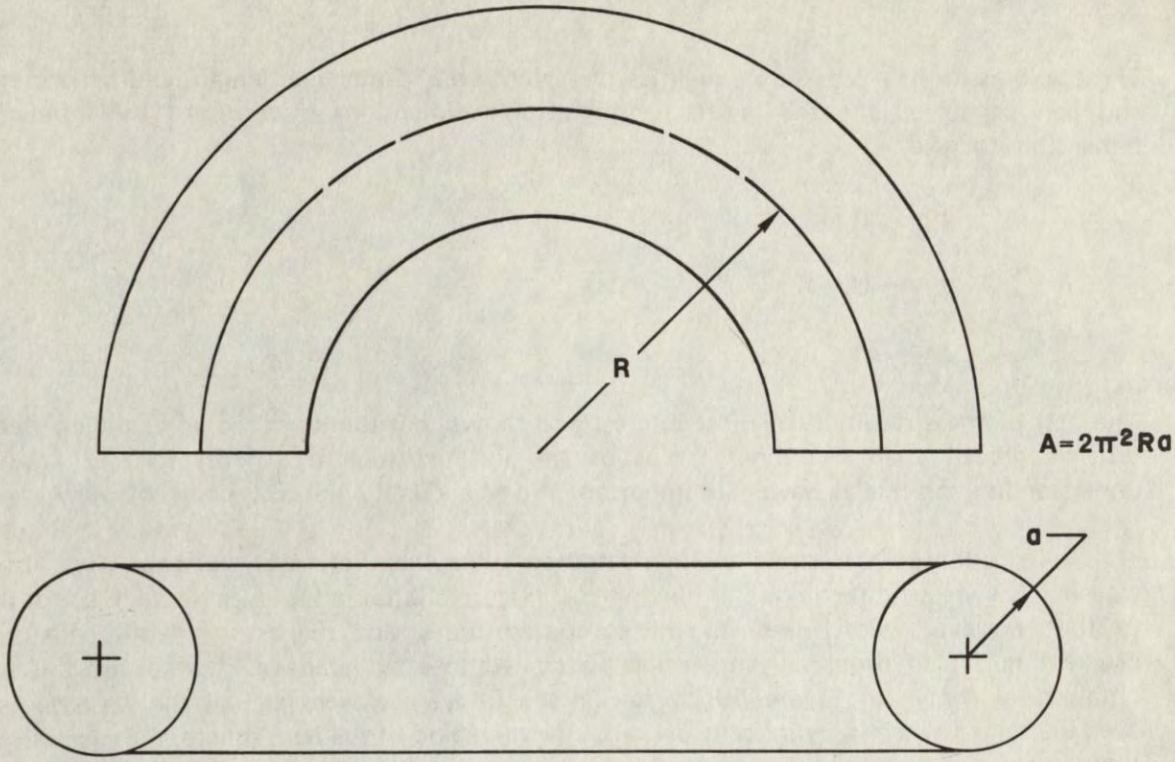
The weave design used is a plain weave with 44 tex single ply yarns having a twist of 0.5 turns per cm. The straight tubes had a yarn count of 18 x 18 per cm, and the contoured tubes a count of 16 x 16 per cm. For the contoured or curved tubes, the fill yarn count is the average over the width of the tube since the yarn count varies over the width due to the curvature. This gave a tube linear density of 82.2 kg/m. The Kevlar breaking strength is given as 1.94 N/tex, thus the theoretical or ideal fabric breaking strength is 1540 N/cm for the straight tubes and 1370 N/cm for the contoured tubes. The design pressure for these tubes is set at 520 kPa, an estimate of the pressured need to provide the strength to support the snow load of 479 N/m^2. The design stress for this pressure loading is the circumferential stress which is equal to the product of the pressure and the radius of the tube. Since these tubes have a radius of 0.08 m, the design stress is 416.0 N/cm, giving a factor of safety of 3.7 for the straight tubes and 3.3 for the curved tubes, based on the ideal or theoretical fabric strength computed above.

Another interesting problem relates to the measurement of the dimensions of the tubes, in particular the radius of curvature. If the tube is taken off the loom and laid out flat and the radius of curvature measured, one obtains a number very different from the radius of curvature of the inflated tube. A relationship between these two radii can be established by equating the surface area of the tube in the lay-flat and the inflated configuration. To illustrate this, we make reference to Figure 9 where these two configurations are illustrated. Accounting for the differences in angular length of the two configurations we obtain the following relationships:

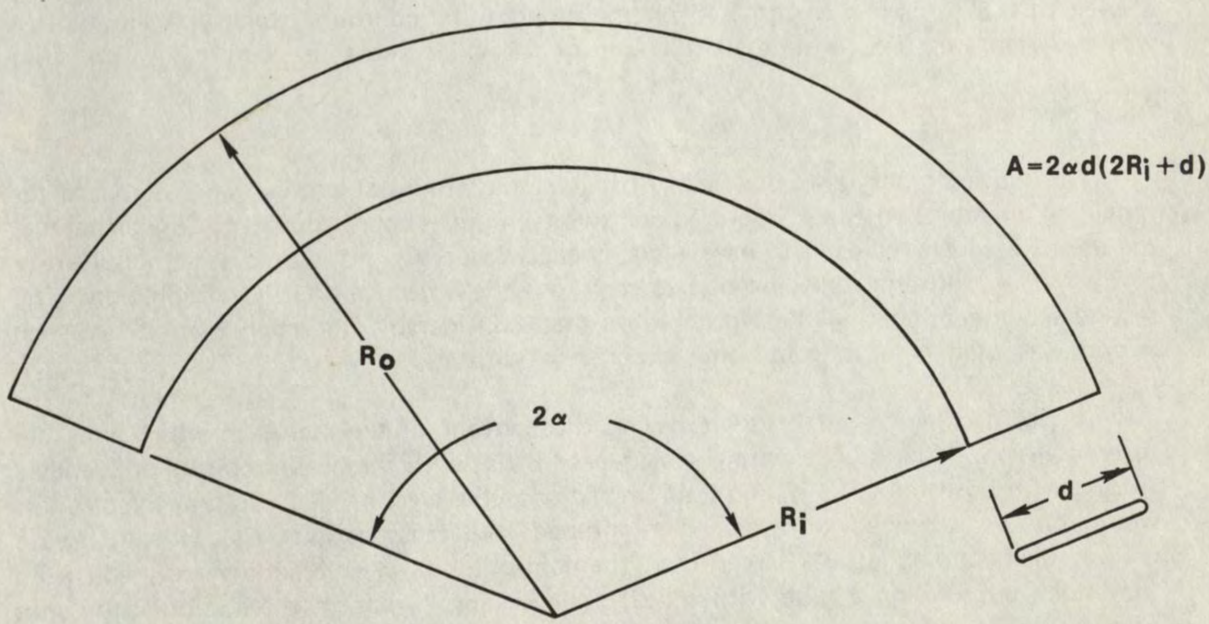
$$2\pi^2 RA = 2\alpha d \ (2R_i + d)$$

$$\pi(R - A) = 2\alpha R_i$$

$$2\pi a = 2d$$



INFLATED CONFIGURATION



LAYFLAT CONFIGURATION

FIGURE 9. LAYFLAT AND INFLATED TUBE CONFIGURATIONS.

These expressions in order are equalities of surface area, center line length, and perimeter and can be solved for the lay-flat configuration dimensions in terms of the inflated dimension to give

$$R_i = \pi(R - a)/2$$

$$\alpha = 1 \text{ rad}$$

$$d = \pi a$$

The first of these results is of most interest and shows that the inner radius of the lay-flat tube is greater than the inner radius of the inflated tube by the factor $\pi/2$. An understanding of this behavior is important from a quality control point of view.

In addition to the straight and contoured tubes, hemispherical end caps were also woven. The weaving technique as illustrated in Figure 10 uses a six-layer weave in contrast to the two-layer weave used for the contoured tubes, and shapes the hemisphere by programing thread drops. A hemisphere attached to a cylinder was desired and this is obtained as shown in Figure 10 by having the fill yarn woven into all the warp yarns over the region where a cylinder is desired. In the region of the hemisphere, the successive fill yarns are woven into fewer of the warp yarns, leaving drop yarns and making the fabric narrower as the weaving proceeds until it comes to a point which forms the apex of the hemisphere. A complete cycle of a fill yarn requires six passes of the shuttle. When this six-layer fabric is unfolded, as shown in the photo in Figure 11, it forms a hemisphere attached to a cylinder. The drop yarns are also quite evident in Figure 11. The hemispherical end caps were woven with the same 44 tex, single-ply yarns having a twist of 0.5 turns per cm as used on the straight and contoured tubes. Again, a plain weave design was used with a yarn count of 14 x 22 yarns per cm.

Air Retention

The woven tubes described above provide the structural strength, but a means for providing air retention is also required and two techniques appear possible. One technique, the use of bladders, was felt to have a high chance of success and assured us an opportunity to build the prototype tents needed to carry out the objective of this investigation. The second technique, coating the woven tubes, had considerable uncertainty associated with it and was used here to gain some experience with it.

It was decided to get bladders having the contour of the arches in which they are to be used, so, in addition to straight bladders for use with the beams, contoured bladders for use with both the 2.73 m and 2.44 m radius arches were needed. So that the bladders would not be subjected to stress when inflated, the cross-section was made to have a 0.17-m diameter, about 6% larger than the fabric tube. The bladders are made from film stock by forming a tube with a heat sealed seam. To form the contours, the ends of these tubes are sealed, and the tube is inflated to make it rigid. This rigidized tube

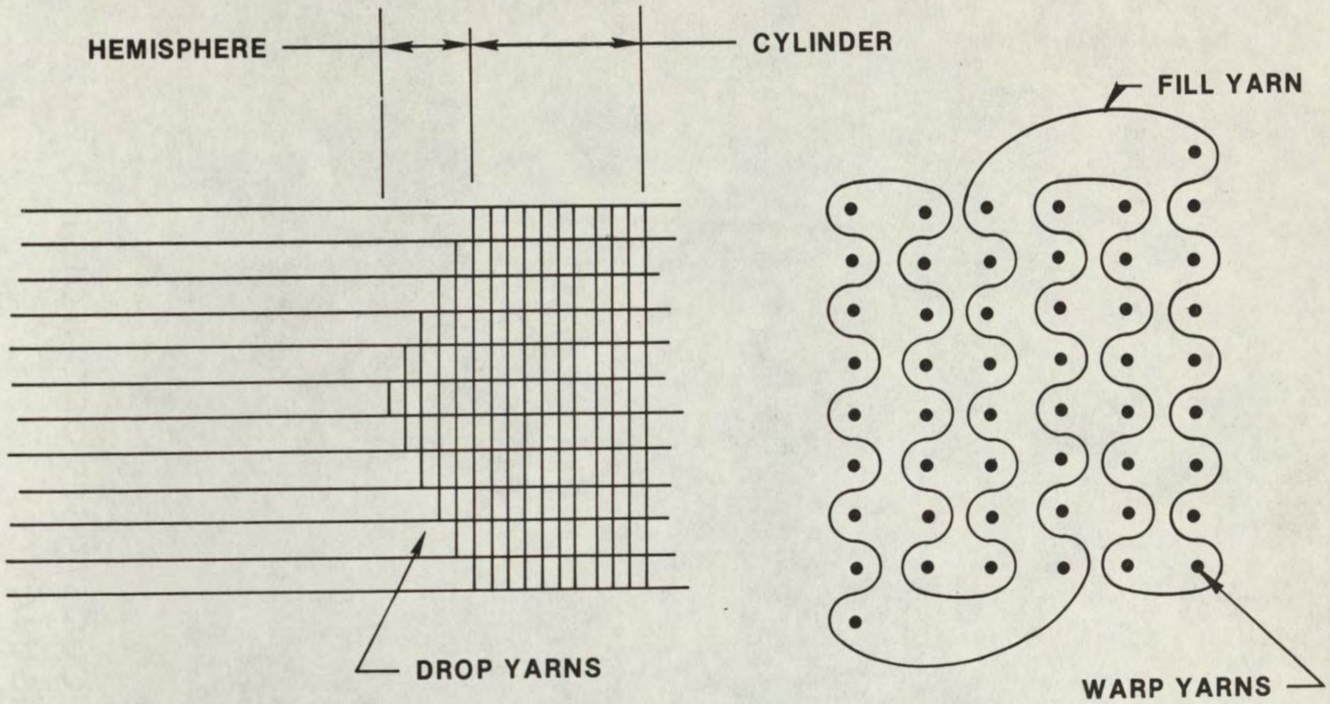


FIGURE 10. ILLUSTRATION OF THE WEAVING TECHNIQUE FOR THE HEMISPHERICAL END CAPS.

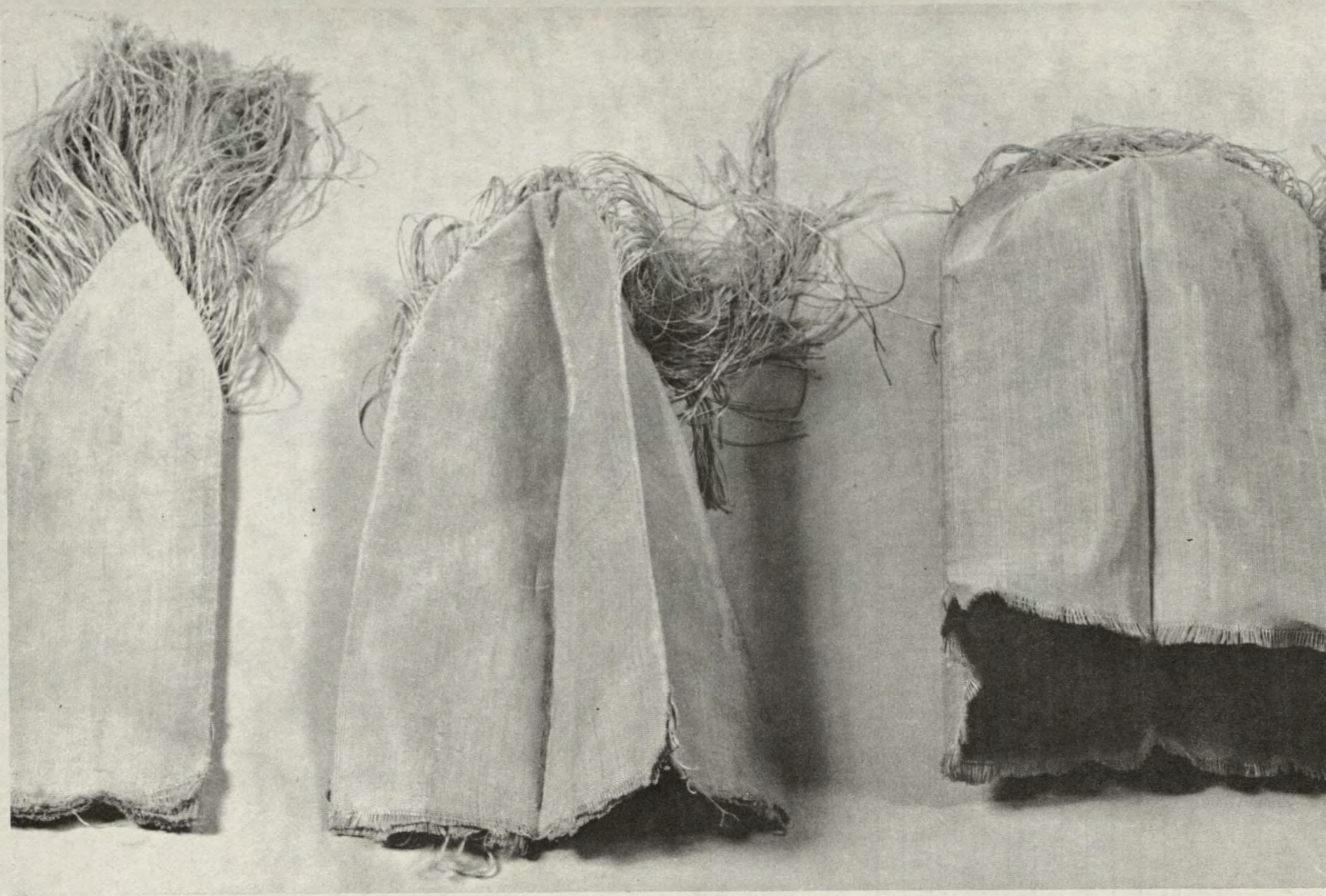


FIGURE 11. WOVEN HEMISPHERICAL END CAP IN VARIOUS STAGES OF UNFOLDING FROM WEAVING TO END USE CONFIGURATION.

was physically bent into an arch and restrained in the desired shape by a series of closely spaced pins. The inner radius where the excess material was located was heated until the appropriate shrinkage occurred. Once the bladder was smooth and wrinkle-free, it was allowed to cool while still in the restaining pins. These bladders were made with a 0.064-mm composite film of polyethylene terephthalate sandwiched between two sheets of polyethylene (this has the trade name "Scotchpak #77" of the Minnesota Mining and Manufacturing Co.). Because leakage developed during usage of these bladders, replacement bladders had to be obtained. Two materials were used, polyethylene film and 0.05-mm nylon-6 film (this has a trade name "Capran 80" of the Allied Chemical Co.). Both the polyethylene and the nylon were obtained in the form of lay-flat tube having a width of 0.25 m, thus no seaming was required. These were used straight; that is, without contouring or shaping them, and this caused no problem with regard to distortion of the fabric arch shape. Considerable trouble was experienced with cracking and development of leaks in the polyethylene film. In this regard the nylon film was superior to the two other films used. The cracking and leak development was an especially severe problem at the sealing point in the metal end cap.

As indicated above, some of the arches and straight tubes were coated, and this was done with a neoprene latex coating designated as B. F. Goodrich material number 190X–63112A. In selecting this coating material, both urethane and hypalon coatings were considered but were rejected because of excessive stiffness of the finished material. To apply the neoprene latex coating, the tubes were turned inside out, the ends sealed, and the tubes inflated using a bladder and a pressure from 14 to 28 kPa. The coating was applied manually with brush and roller and given a room temperature cure. This method of coating was used for each of five to seven coats. Thin coats were used to avoid entrapment of moisture. The tubes were checked for leaks and any found were coated locally in the area of the leak. After coating, the tubes were turned right side out so the coating would be on the inside of the tube. While this technique of manual application was satisfactory for the small number of tubes coated in this work, it would not be satisfactory in large production quantities. The hemispherical end caps were also coated using the same material and application techniques but the coating was applied with the end cap on a shaped mandrel. Before application of the coating to the end caps, strips of Kevlar fabric were cemented to the drop yarn lines in the hemisphere. This was done not for strength reasons but to cover over the relatively large gaps between yarns in this region. This prevented the inflation pressure from forcing the coating through these gaps.

Assembly of Coated Tubes and Fabric End Caps

The coated tubes and end caps were assembled and fitted with an inflation valve to form a complete closed pressure-stabilized structural element. The main task in doing this was the attachment of the end caps to the tubes to provide sufficient strength and air retention. This was accomplished with adhesives and the technique used is shown in Figure 12. The adhesive bond area has a region in which Kevlar is bonded to Kevlar which gives the required strength and a region in which the neoprene latex coating on the end cap is bonded to the Kevlar fabric tube to make an airtight seal. The adhesive was cured under pressure by pushing the endcap up into the tube, inserting a wooden clamping plug and clamping the juncture with a metal clamp using a rubber cushion. The Minnesota Mining and Manufacturing Company adhesive No. 2141 was used for the joint. The inflation valve was installed in the tube by cementing the valve flanges to the fabric.

Tent Fabrication

In this section we describe the details of the fabrication of the prototype tents. Beginning with the fabrication of the frame assemblies for each of the three support structure concepts and, following that, the various aspects of the overall tent fabrication are discussed. Only the uncoated arches used with bladders are considered. No tents were fabricated using the coated arch assemblies. What was learned about this technique of providing air retention and fabrication is discussed in a later section.

Assembly of the Frame Concepts

The crossed arch concept is illustrated in Figure 3, with some modifications shown in Figure 4. For this concept two features of the frame assembly deserve comment: the end closure, and joining of the arches at their intersection point. The end closure was accomplished with a metal end cap that sealed the end and provided a means of inflation. This type of closure was used because we had higher confidence in this technique for use on the prototype tents than the fabric end caps described above. The design of the end cap is shown in Figure 13, and a photograph showing the end cap attached to one of the fabric arches is shown in Figure 14. These end caps have a mass of 3.57 kg. As is shown in Figure 13, the Kevlar fabric and bladder go through the inside of and wrap around the sealing ring. The sealing ring with the fabric and bladder is seated in the end cap on the rubber gasket. The sealing ring is captured by the retaining ring which is bolted to the end cap to hold the assembly together and apply pressure to seal the closure at the gasket. Inflation is accomplished through the port in the bottom of the end cap. One of the end caps was attached to each end of the arch spaced so as to give an angular span of π radians. The joining of the two arches to form the crossed arch module is an important aspect because it is the joining of the two arches into an integral structural that give it breadth and thus its inherent stability. The arches are joined with a harness which, as depicted in Figure 15, has the geometrical form of two intersecting cylinders, with their planes vertical and intersecting at an angle of 51°. This harness was cut and sewn from ordinary Kevlar fabric. The connection of the arches is made by passing each of the inflated arches through the harness and positioning them so that the harness is at their center point. The arches are then inflated simultaneously. The presence of the two inflated arches inside the harness, which provides space for only a single arch, securely locks the arches together and makes a very rigid connection. Photographs of the assembled and inflated juncture are shown in Figure 16. In these photos the sewn seams are visible and the bulging that occurs because of the constriction of the inflated tubes can be seen. This bulging put great stress on the sewn seams in the harness and these seams tended to come apart after the tent was inflated several times. This is then an area of concern in the design of this concept. The pair of assembled arches used in the prototype tent is shown in Figure 17.

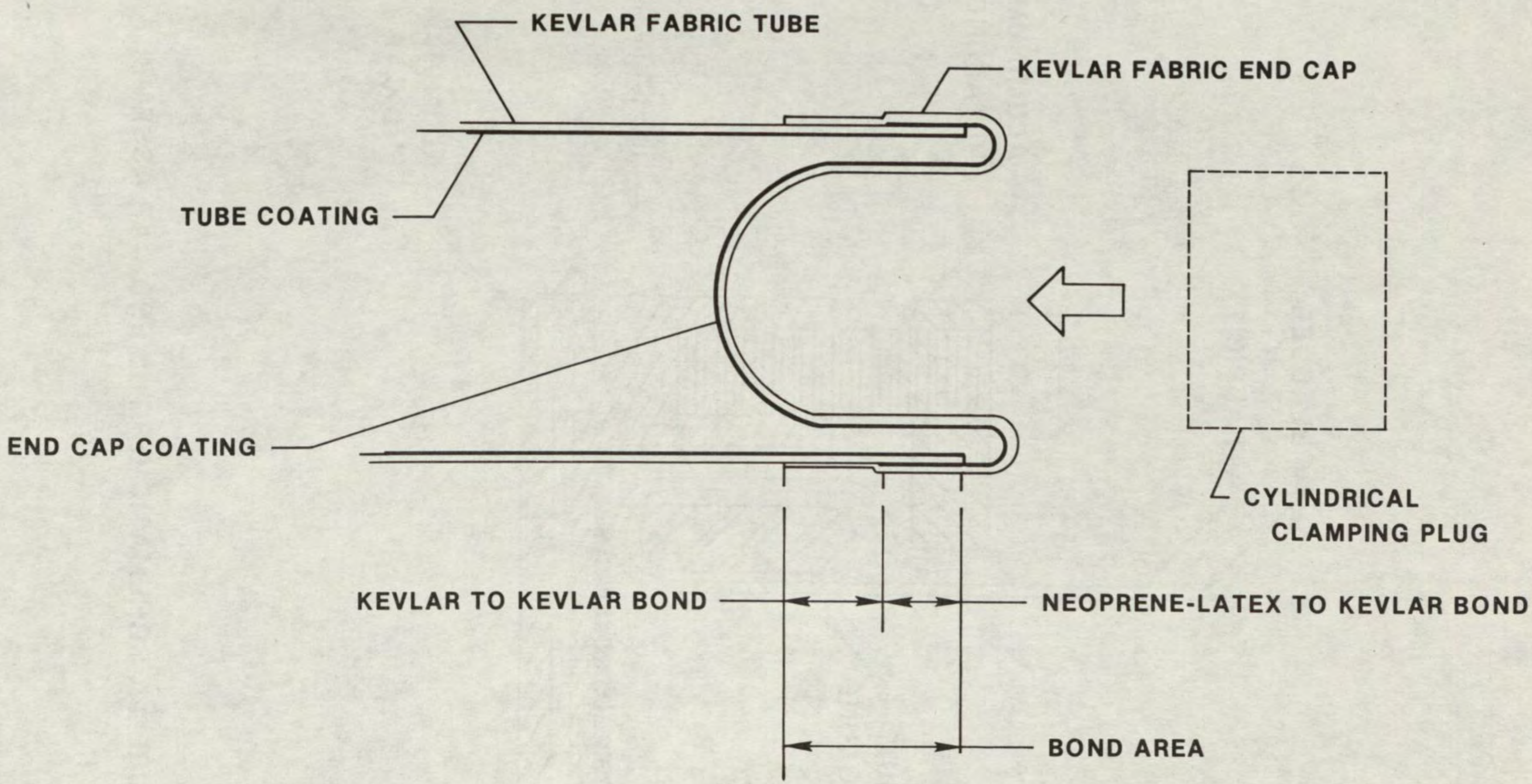


FIGURE12. ATTACHMENT OF FABRIC END CAP TO TUBE.

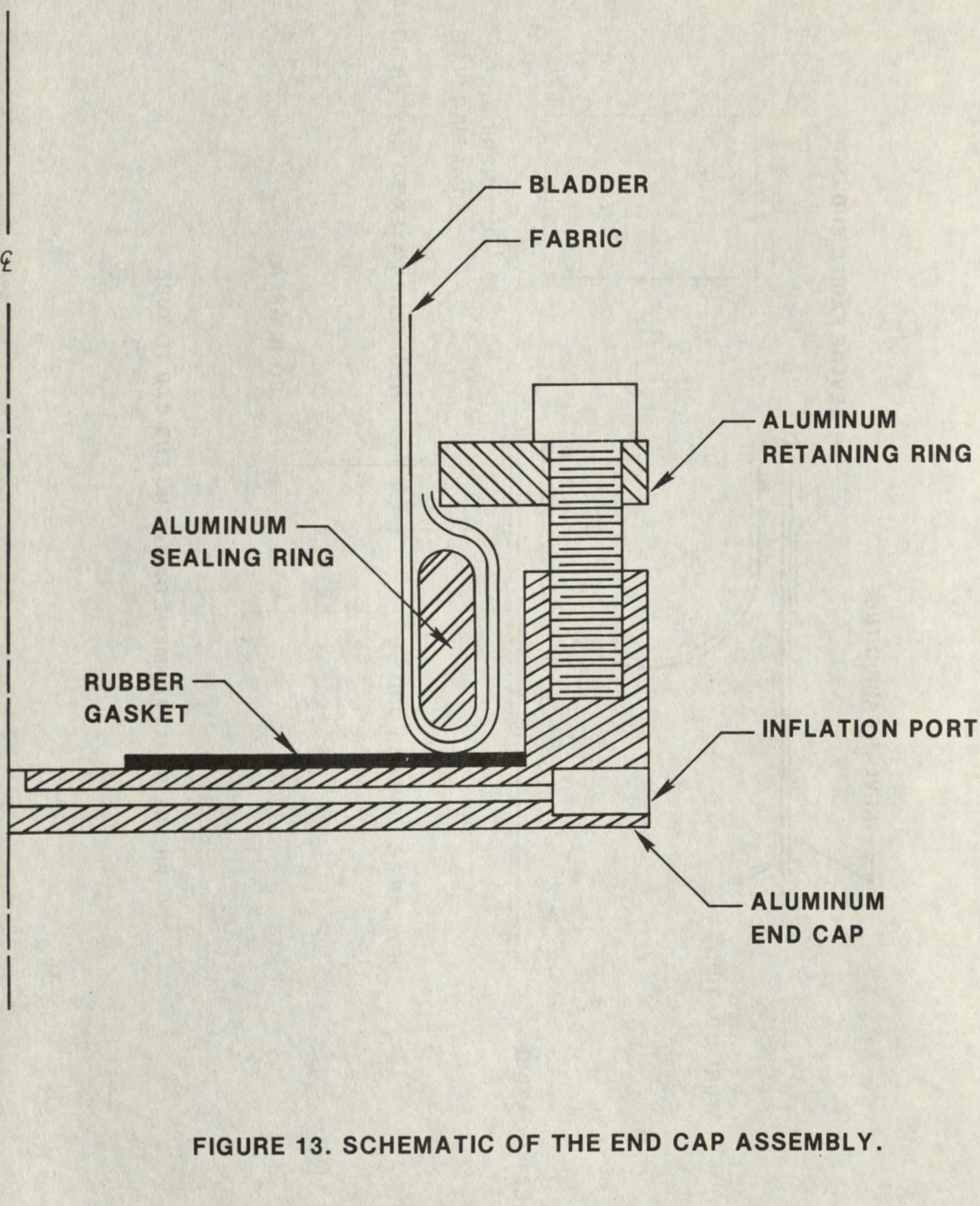


FIGURE 13. SCHEMATIC OF THE END CAP ASSEMBLY.

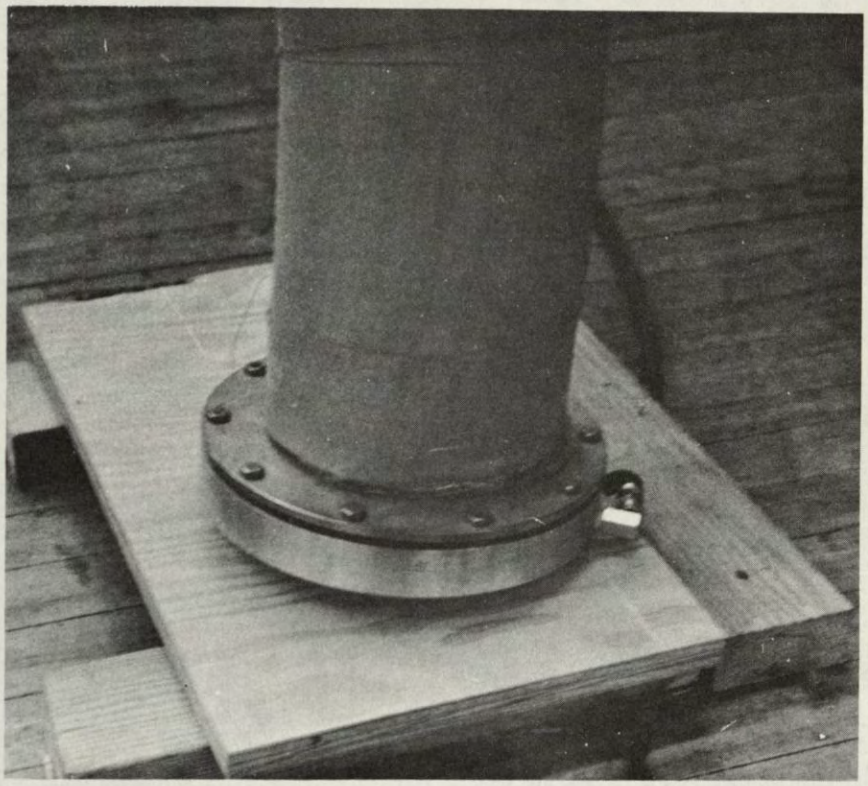


FIGURE 14. END CAP ATTACHED TO FABRIC ARCH.

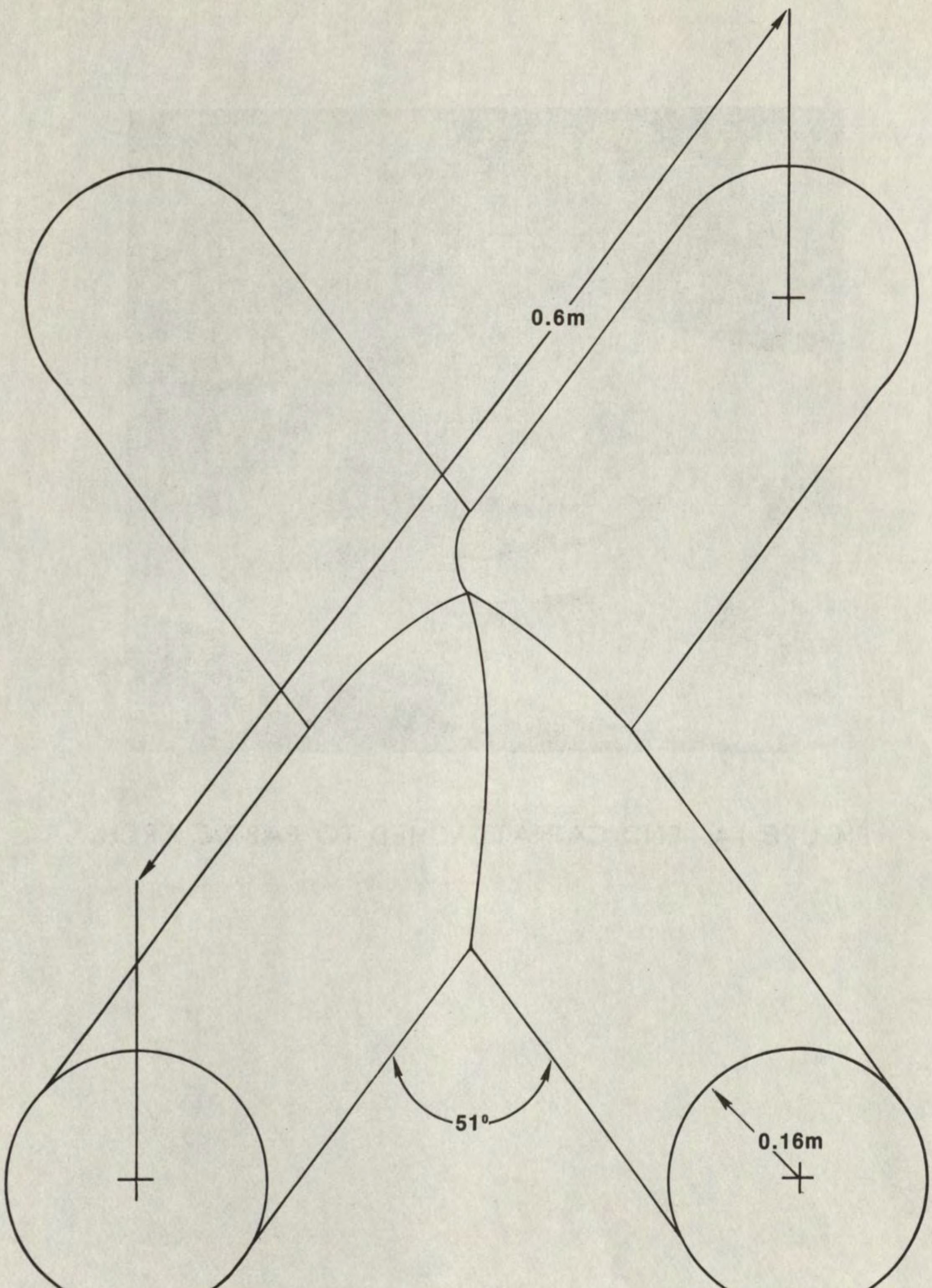
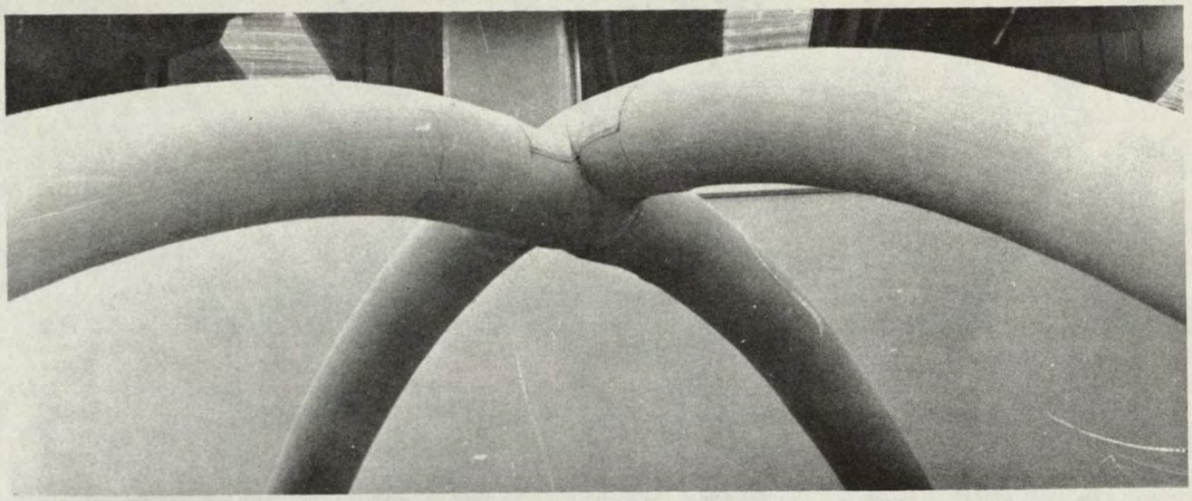


FIGURE 15. SKETCH OF JOINING HARNESS FOR CROSSED ARCH CONCEPT.



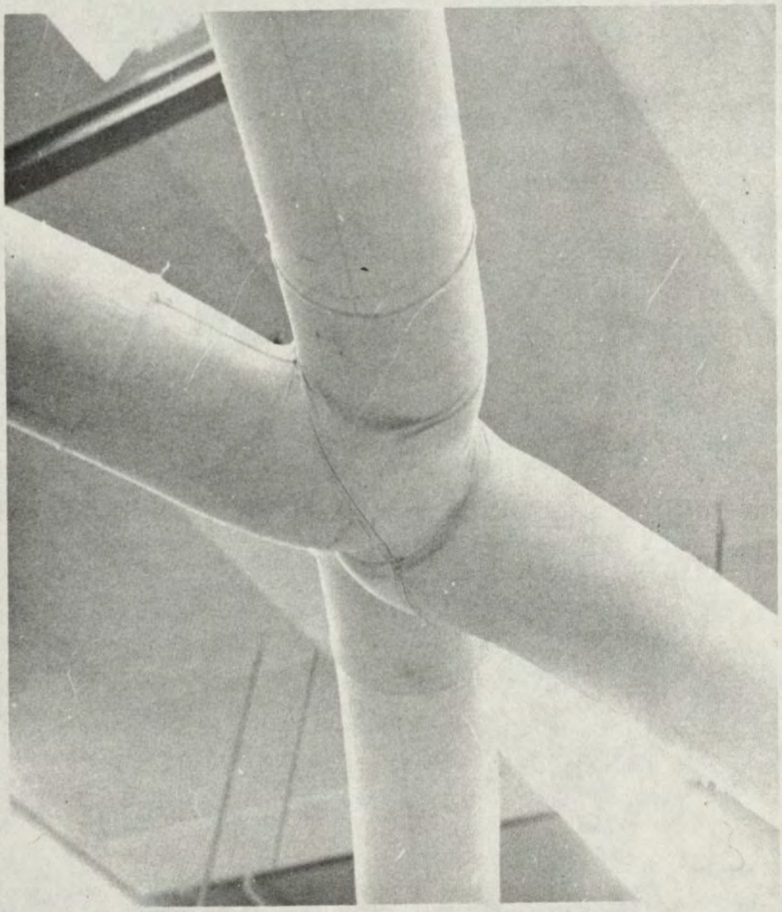


FIGURE 16. CONNECTION OF THE ARCHES IN THE CROSSED ARCH CONCEPT.

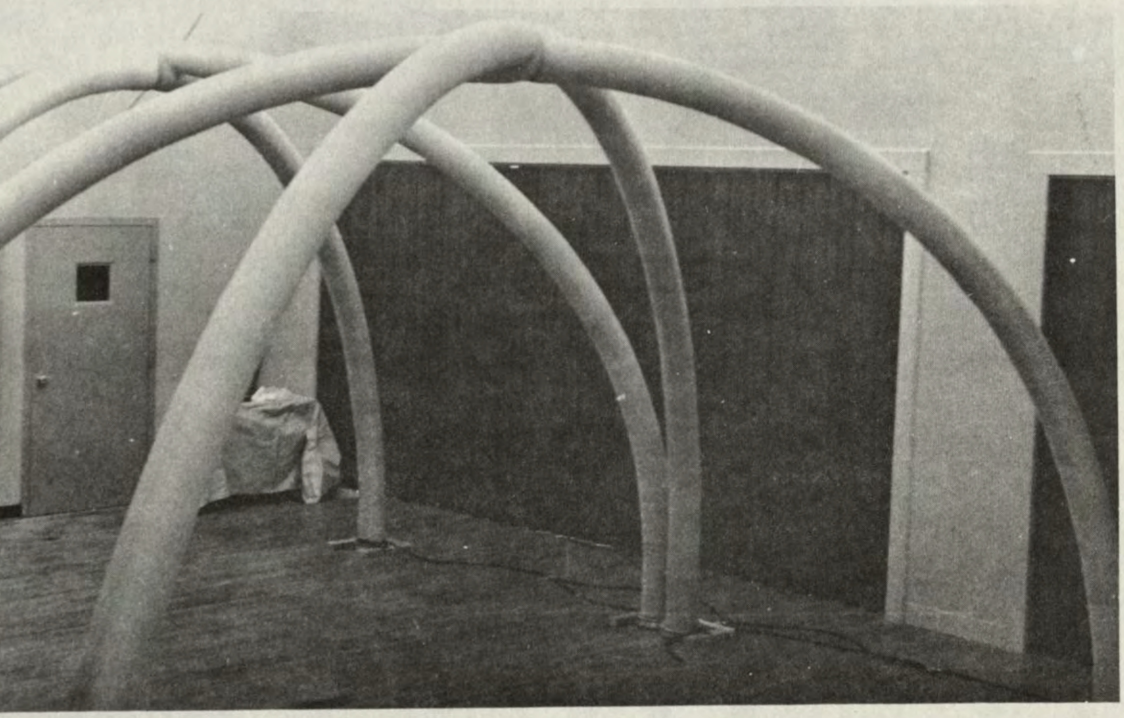
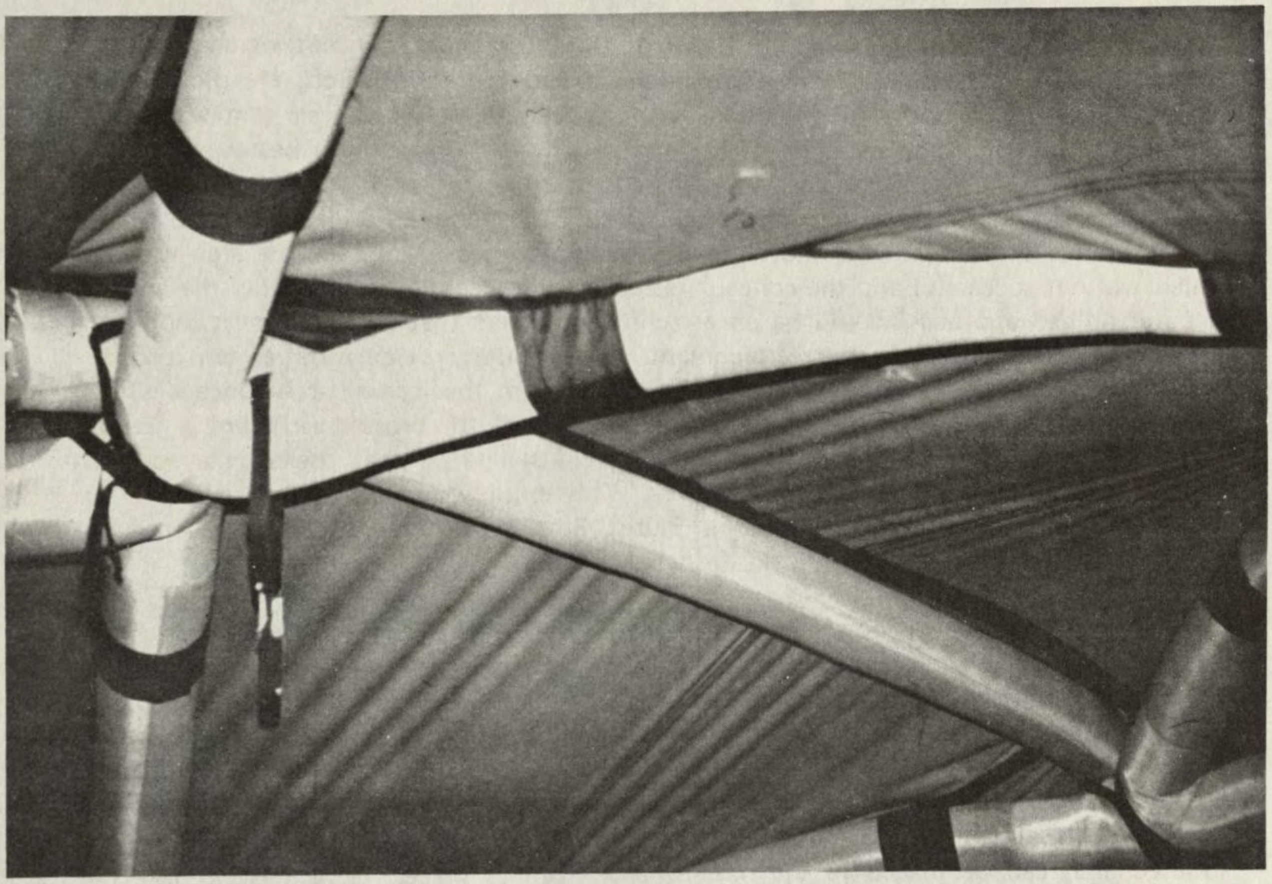


FIGURE 17. DOUBLE MODULE CROSSED ARCH FRAME ASSEMBLY.

As indicated above, two modifications of the crossed-arch concept were made and tested. These modifications, the midspan beam and the center arch, are pictured in Figure 18. Both of these modifications were conceived after the basic tent was made so they were not considered in its design and thus were installed in a best-way-possible basis. The midspan beam was made using a short section of straight Kevlar tube fitted with end caps. This beam was placed under the arch modules and strapped in place. The technique of doing this is shown in Figure 18a with a beam over the arch module which was not successful and the concept tested had the beam attached under the arches. A more refined approach would be an attachment harness that would connect the beam to the arch module with a butt attachment. This would provide a better tent profile. The center arch was made using one of the arches from the leaning arch concept which has a smaller radius of curvature. Because the height of the crossed-arch tent is greater than this radius of curvature, the end caps were installed so that the angular span of the center arch was greater than π radians. This extra span was used to account for this height difference. As can be seen in Figure 18b, the center arch was not set between the two arches at the center but in front of them.

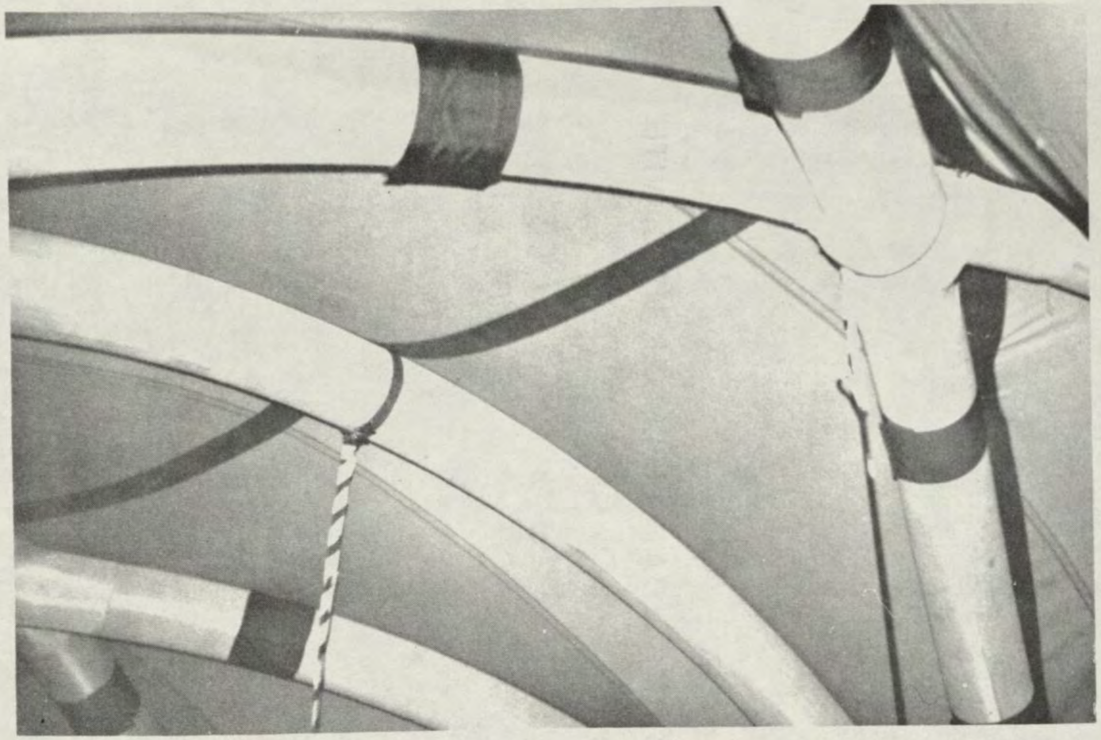
The leaning-arch concept is illustrated in Figure 5. This concept utilized the same end cap as the crossed-arch concept. However, because the leaning arch is tipped out of its plane, an end cap adapter was required, as shown in Figure 19. This block was made of wood and was attached to the end caps with metal fittings. The joining of the two arches that form a module is accomplished with a harness as shown in Figure 20. The harness consists of two fabric cylinders joined together by sewing along the length. Opposite this sewn juncture each cylinder has a laced opening along its length so the inflated arch can be placed in the harness and laced in place. It is best to lace the arch in place when only slightly pressurized and upon further pressurization the expansion of the arch will firmly seat the arch in the harness. This harness achieves the objective of preventing movement of one of the arches relative to the other. The center arch modification was also used with the concept and was carried out pretty much as was done for the crossed-arch concept, except that here an arch having a radius of curvature of 2.44 m was used, and its angular span was shortened to less than π radians to account for the decrease in height over the arch radius due to the leaning over of the arches in the basic module. A photograph of the double module leaning arch frame assembly is shown in Figure 21.

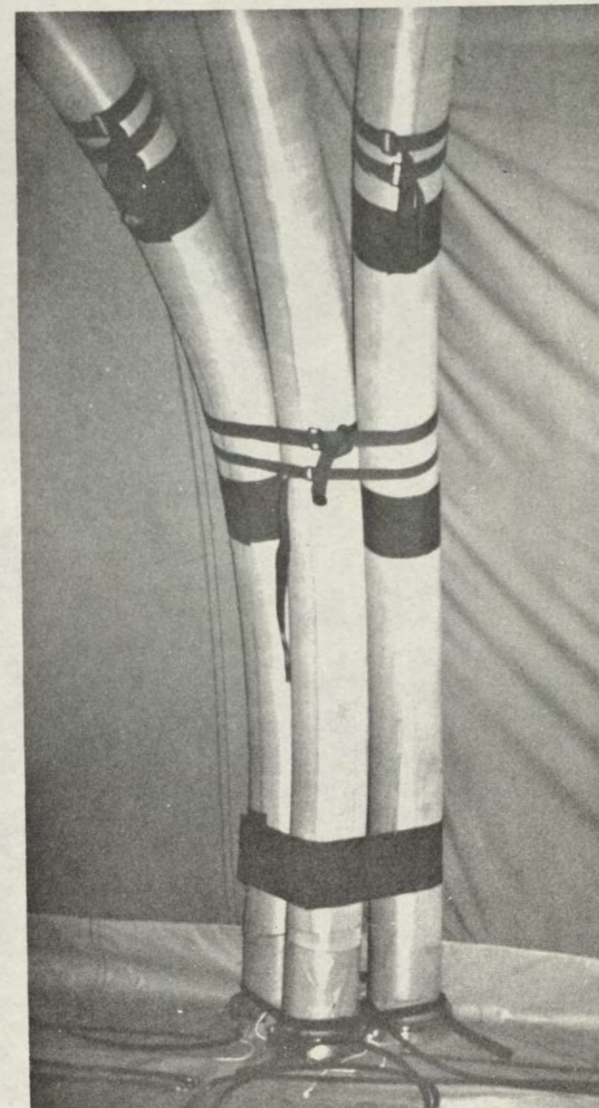
The arch and purlin concept, as was indicated above, was fabricated using a slightly different philosophy. This philosophy was to use straight tubes to fabricate a segmented arch, as shown in Figure 6. Here we will briefly indicate the fabrication techniques used for the arches and bladders, the means used to close the ends, and the type of connection used for the arches and purlins. Each of the arch segments was pattern cut from the straight Kevlar tube with the pattern designed so the adjacent segments would join at the proper angle. The segments were joined by sewing with a double-fell seam. The bladders for these segmented arches were made from 0.1-kg/m^2 neoprene-coated polyester fabric. The fabric was made into a tube with a 5-cm-wide cemented seam along the length of the tube. Tucks were made in this bladder at positions corresponding to the



(a) MIDSPAN BEAM

FIGURE 18. MODIFICATIONS OF THE CROSSED ARCH CONCEPT.





(b) CENTER ARCH

FIGURE 18. CONCLUDED.

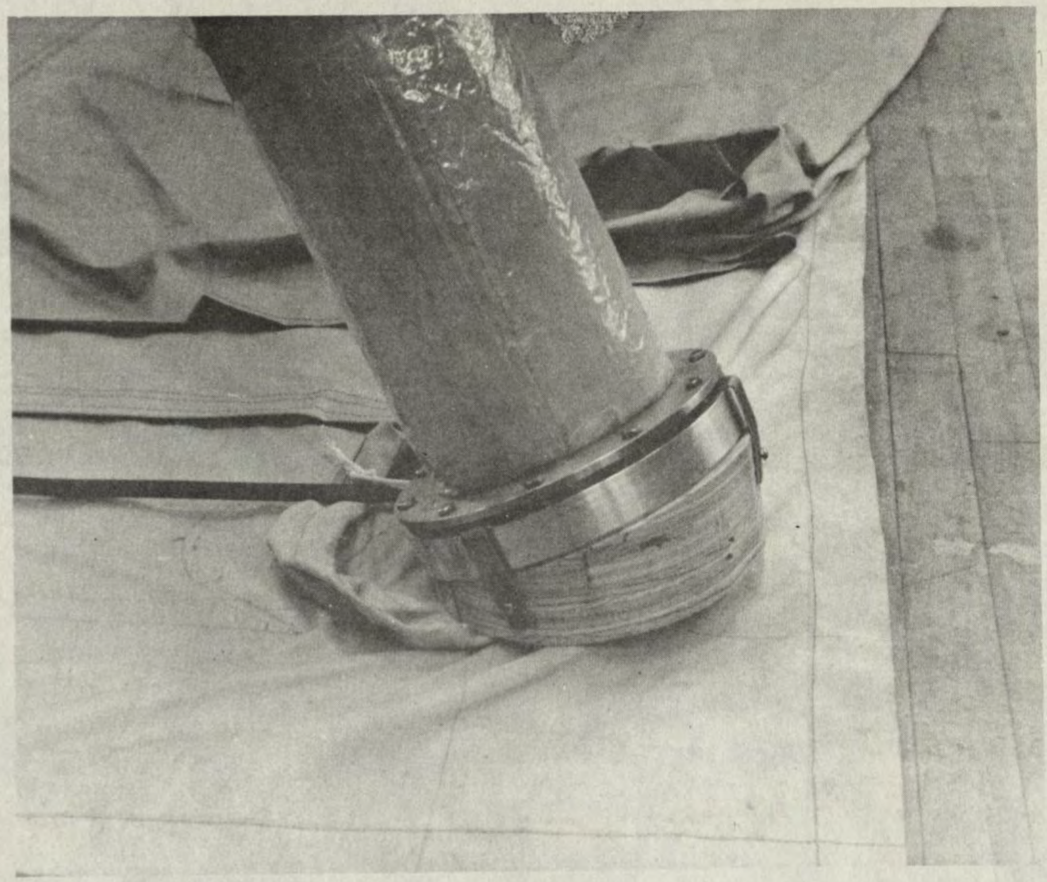


FIGURE 19. END CAP ADAPTER BLOCK USED WITH LEANING ARCH CONCEPT.

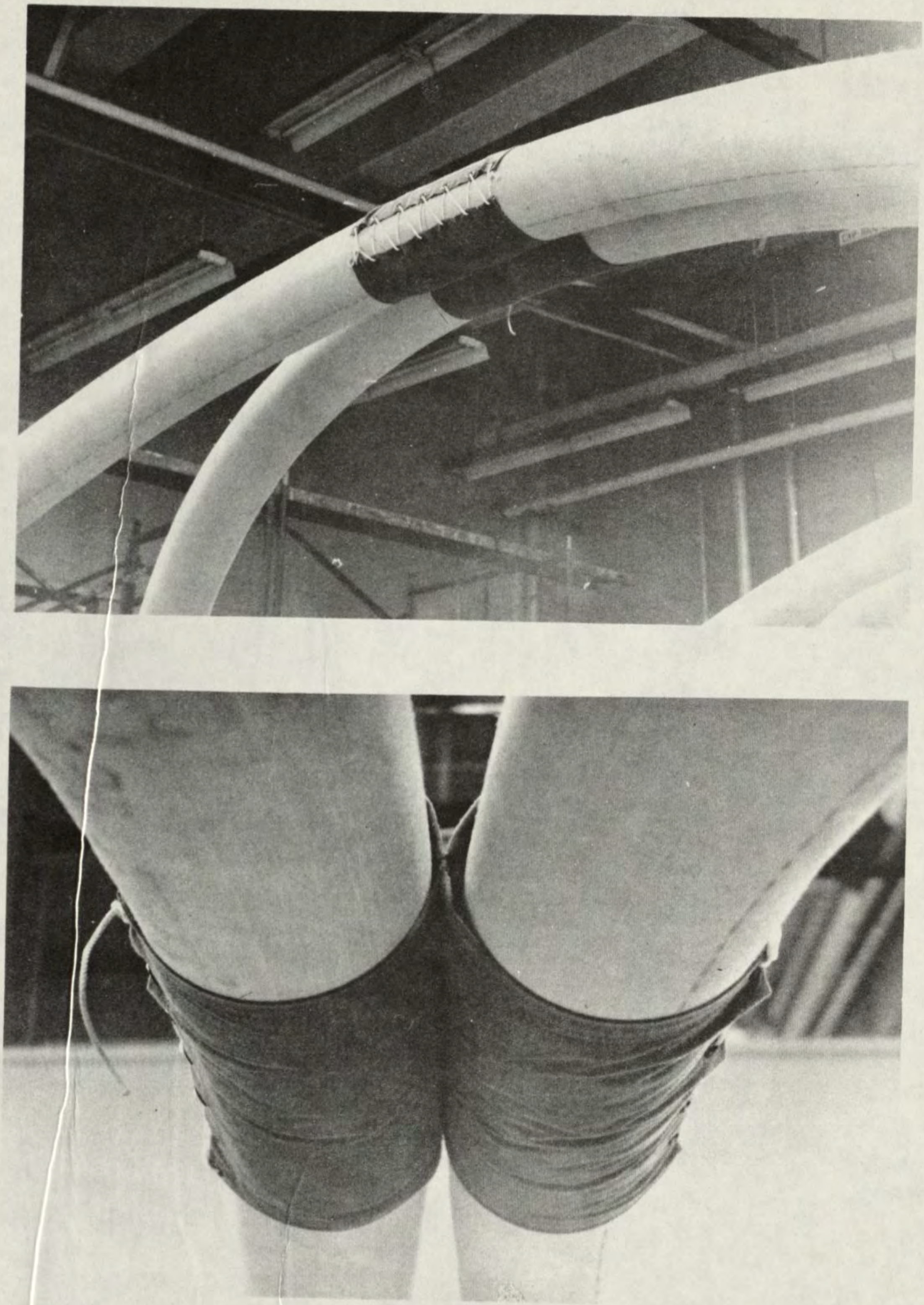


FIGURE 20. JOINING HARNESS USED FOR THE LEANING ARCH CONCEPT.

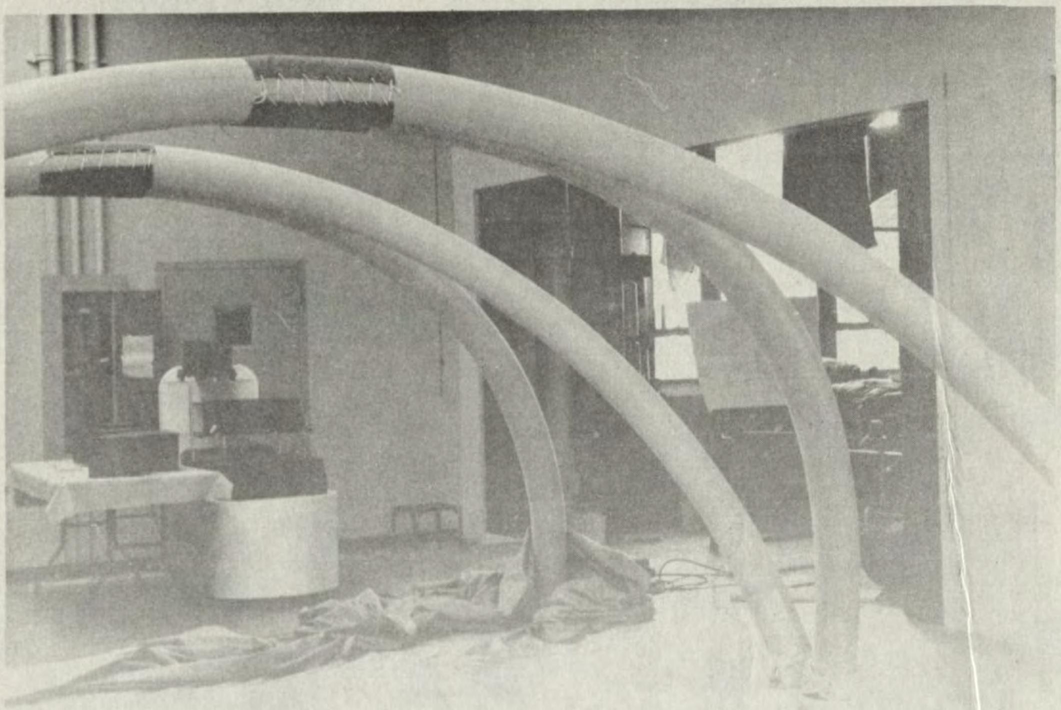


FIGURE 21. DOUBLE MODULE LEANING ARCH FRAME ASSEMBLY.

breaks in the segmented arch to form the bladder to the arch shape. The closure of the ends of the arches is illustrated in Figure 22. The ends of the bladder are cemented closed to retain the inflation gas which enters the bladder through an inflation valve. The bladder is placed inside the segmented Kevlar tube or arch and these are inserted in a close-out boot which has sand in its bottom. The sand provides a base for the irregular shaped bladder-end to distribute the load. There are no attachments such as sewing or adhesives between the bladder, Kevlar tube, or the close-out boot. The boot is sized so that when the arch is inflated these three materials pushed together by the expansion of the fabrics and the friction thus developed prevents the arch and bladder from pulling out of the close-out boot. The close-out boot is made of 0.33-kg/m^2 cotton duck. The purlins were also made from the straight Kevlar tubing and the coated polyester fabric was used for the bladder. The connection of the purlins and the arches was accomplished with a harness as shown schematically in Figure 23 and photographically in Figure 24. The harness is fitted over the arch, and the purlin with its bladder is laced into harness at a low pressure so that, when the pressure is increased, the purlin expands to fit tightly in the harness. This makes a friction joint which is reinforced with two restraint straps. Figure 23 depicts the connection of the end arch and the purlin. The connections to the center arch are done in the same way on both sides of the arch.

Fabrication of Prototype Tents

The fabrication of the prototype tents concerns the making of the environmental barrier and the floor and attaching these elements to the frames. These aspects are common for all three concepts. The barrier and floor were made using standard fabric construction techniques and require no comment here. The environmental barrier fabric is a 0.25-kg/m^2 50/50 polyester-cotton blend (MIL–C–43791 Type I) with a water repellent finish. The floor fabric is a 0.52-to 0.6-kg/m^2 vinyl-coated cotton cloth having a 0.33-kg/m^2 base fabric (MIL–C–10799 Type II, Class 1). The floor and barrier were sewn together to make an intergral unit. The barrier was attached to the frame with straps sewn to the barrier and secured around the frame elements, as shown in Figure 25. As can be seen, buckle straps were used along with wider straps closed with hook and pile tape. The securing of the arch ends to the tent floor is pictured in Figure 26 and consists of a pocket sewn to the tent floor. The arch end cap is captured in the pocket by a drawstring. Shown in Figure 26 is this arrangement for the leaning arch concept. A similar arrangement was used for the crossed-arch concept, as can be seen in Figure 25. In the arch-and-purlin concept the close-out boot was sewn directly to the floor. This is an important aspect of the construction because secure placement of the ends of the arches is necessary for maintaining the load-carrying stability of the arches. Photographs of the finished prototype tents are shown in Figures 27, 28, and 29.

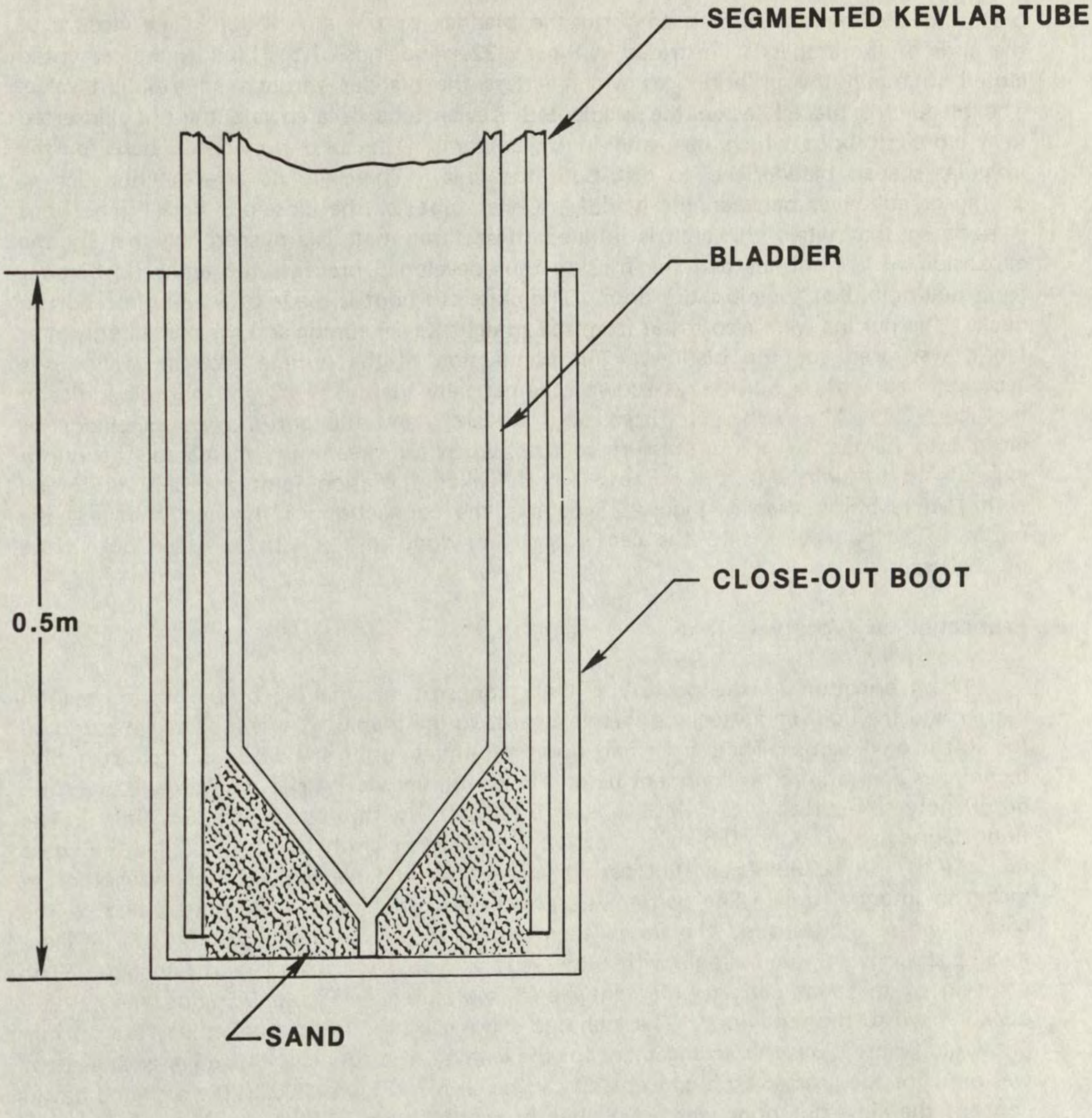


FIGURE 22. CLOSEOUT OF THE SEGMENTED ARCHES

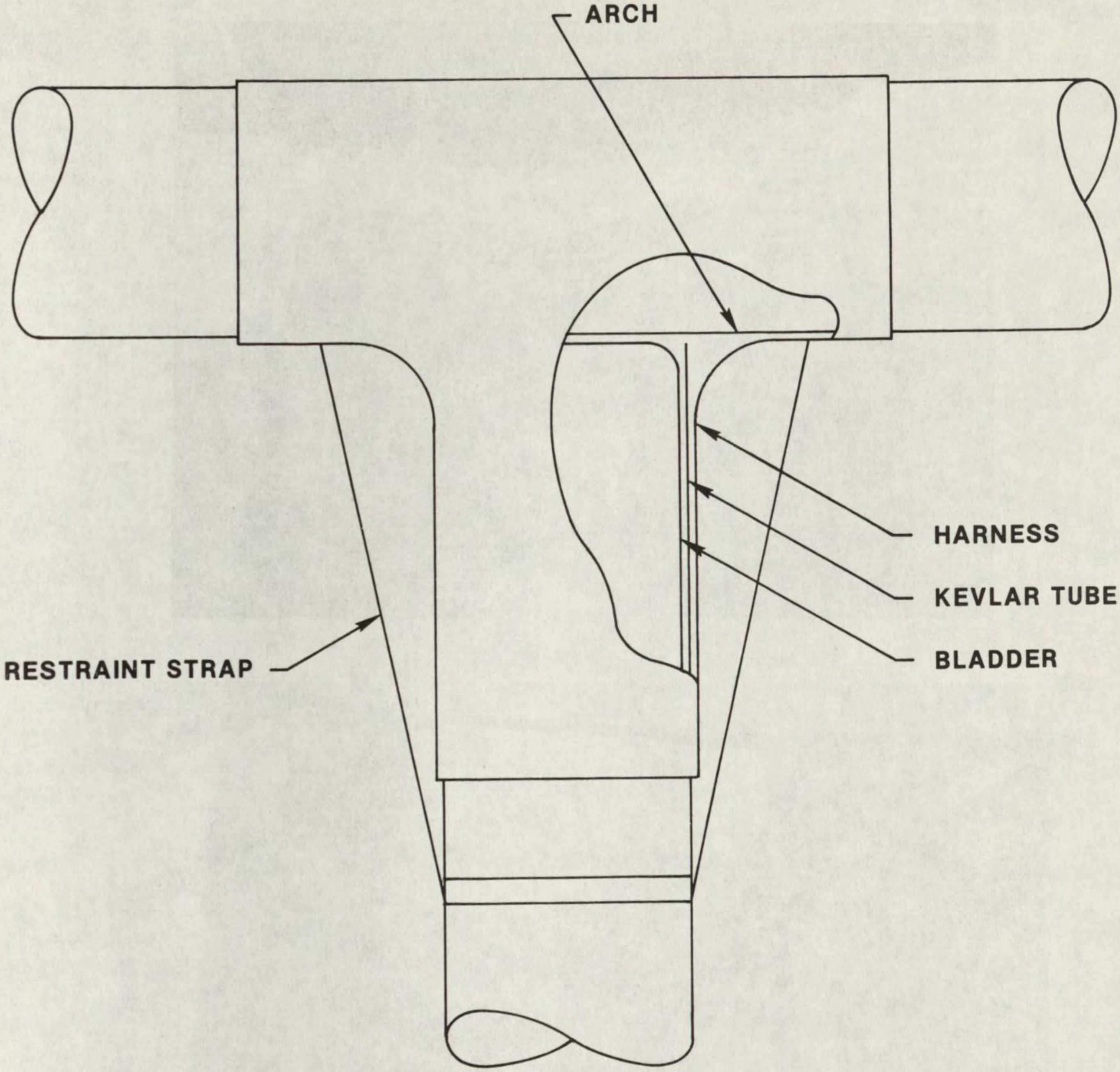
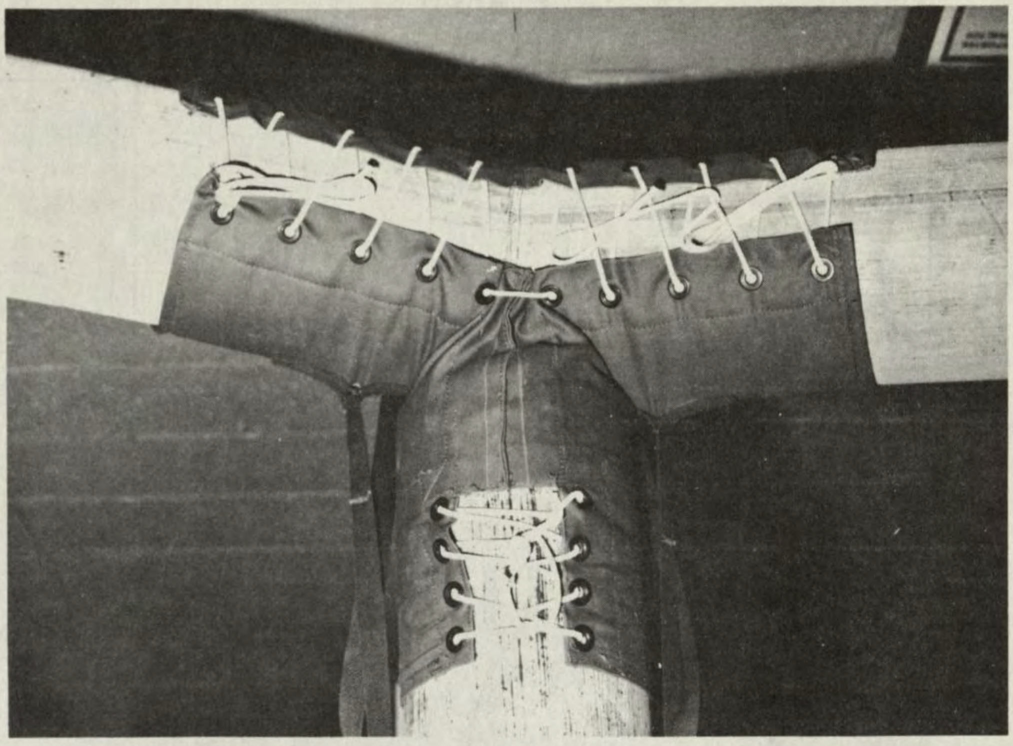


FIGURE 23. ARCH AND PURLIN CONNECTION HARNESS.



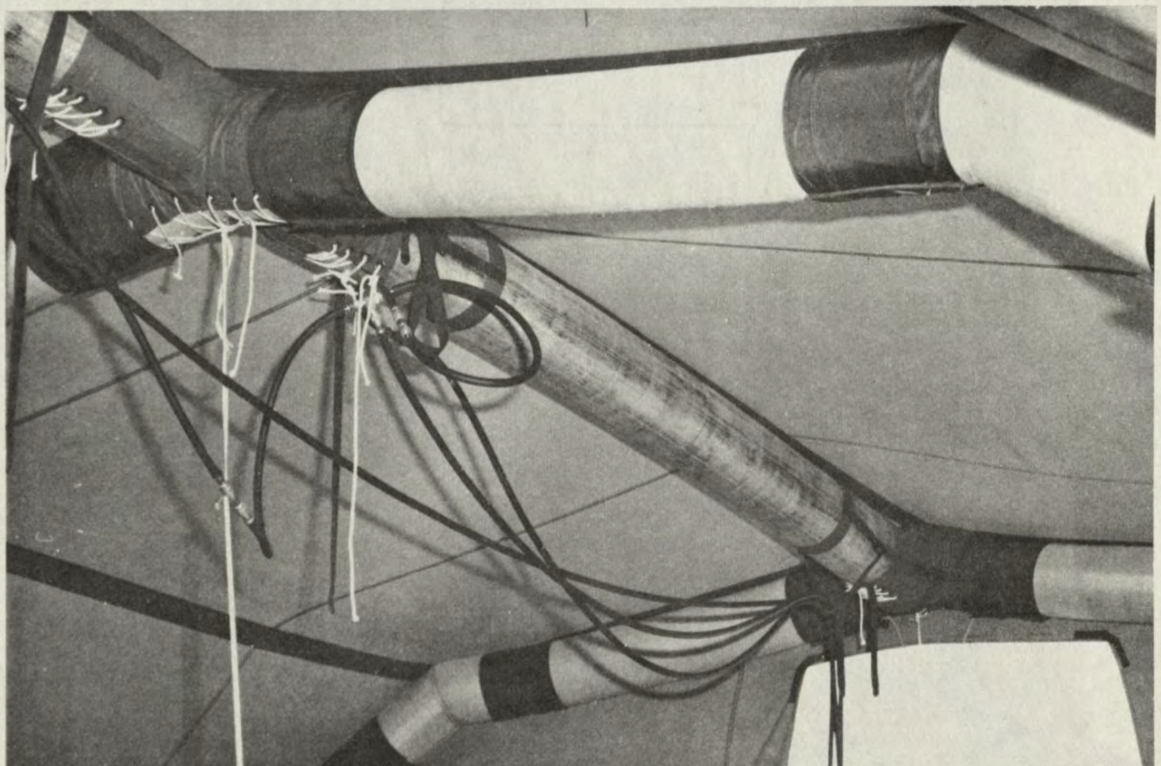


FIGURE 24. PHOTOGRAPH OF ARCH AND PURLIN CONNECTION.

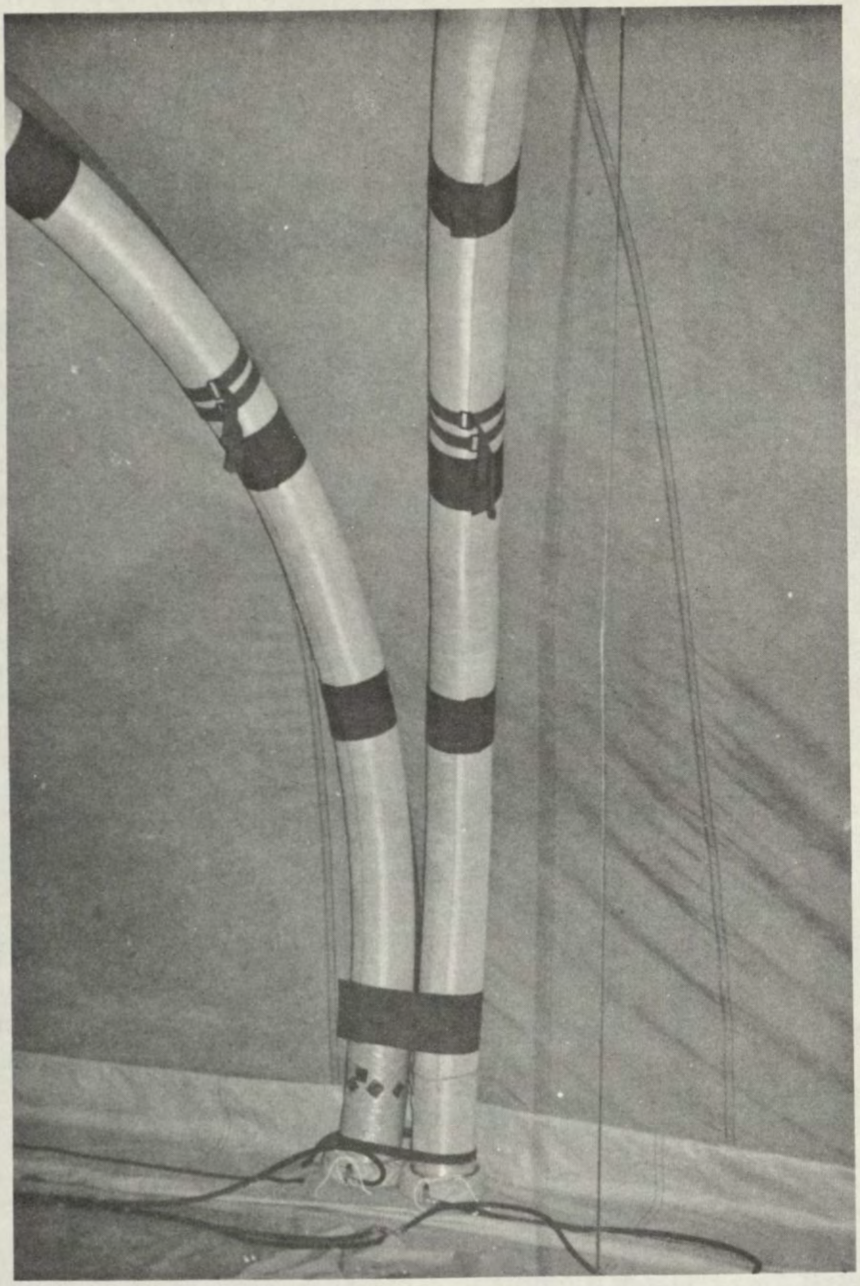


FIGURE 25. ATTACHMENT OF ENVIRONMENTAL BARRIER TO TENT FRAME.

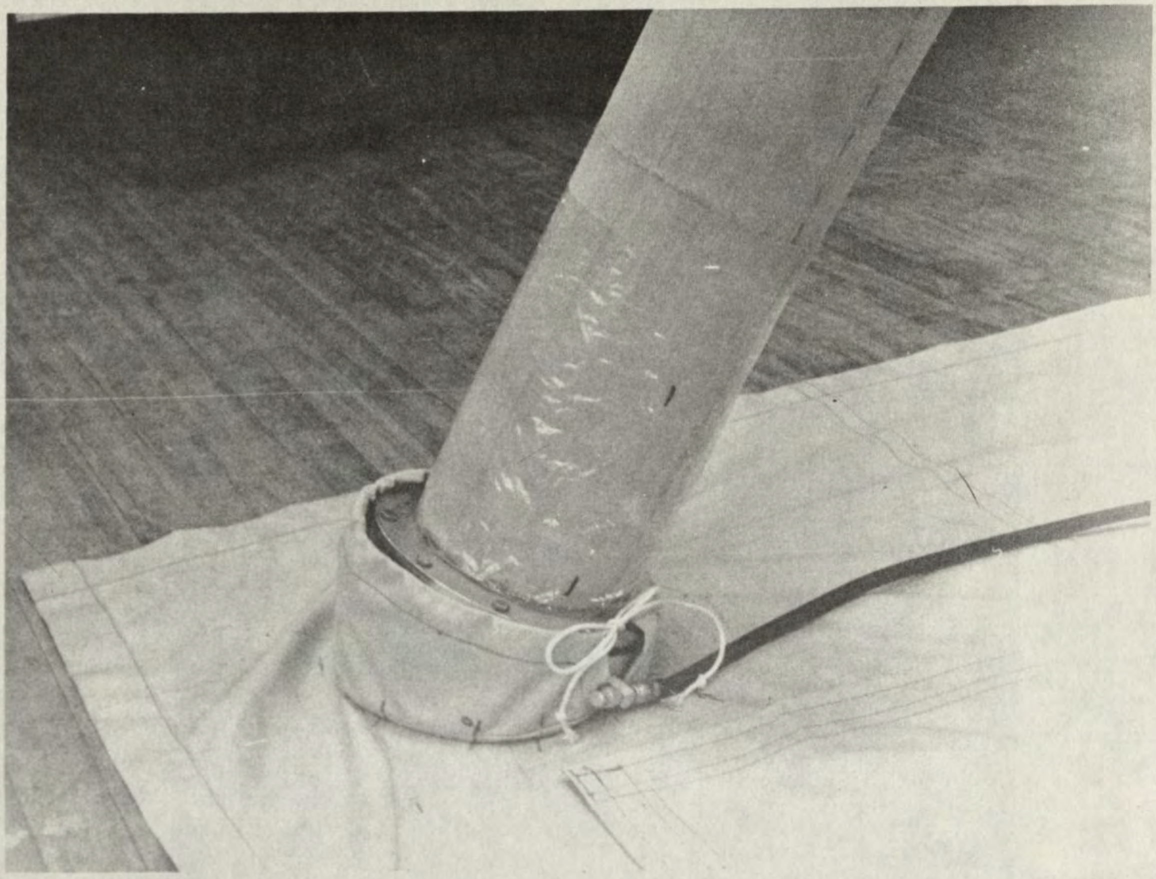


FIGURE 26. ATTACHMENT OF ARCH END CAP TO TENT FLOOR.

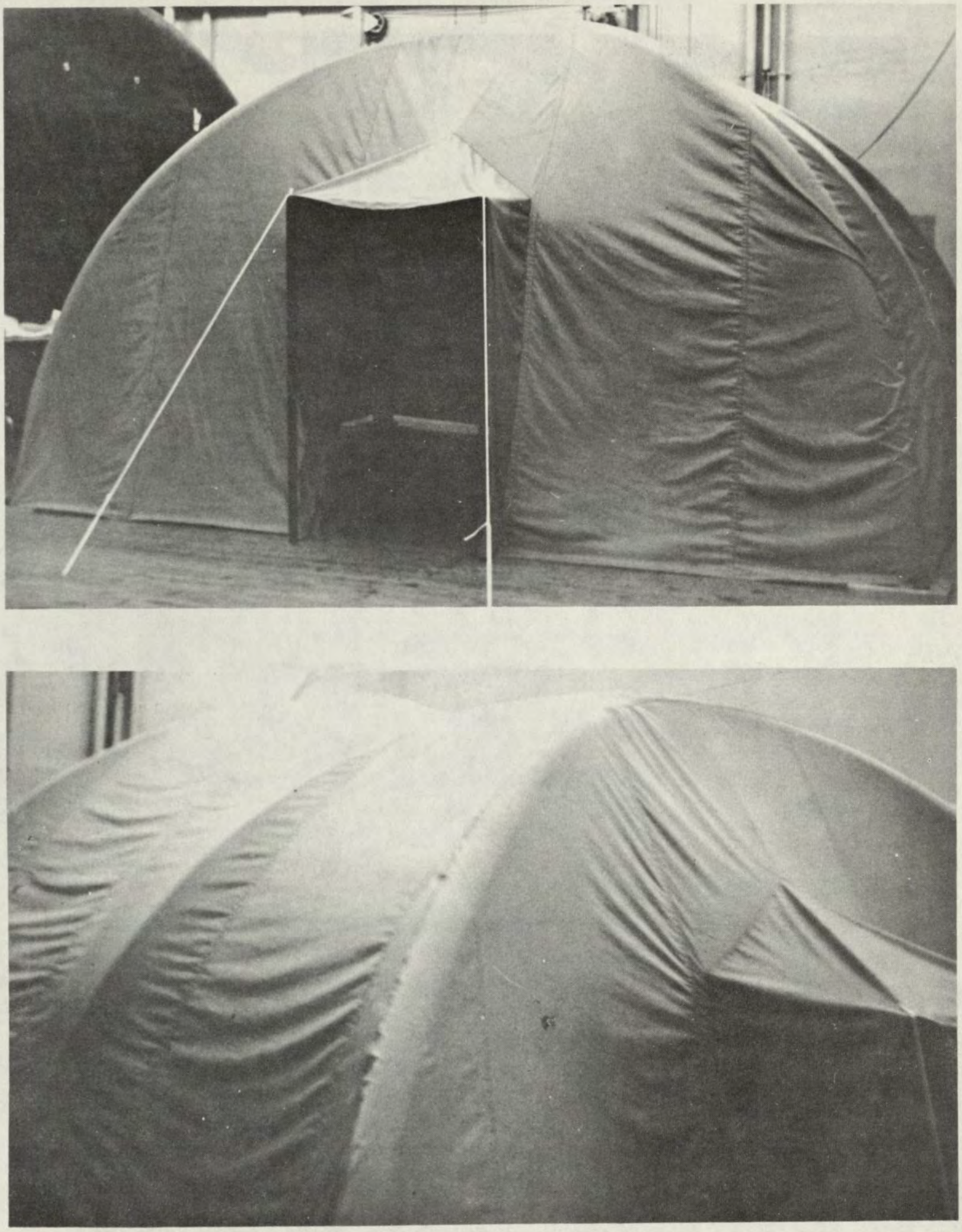


FIGURE 27. PROTOTYPE CROSSED ARCH TENT.

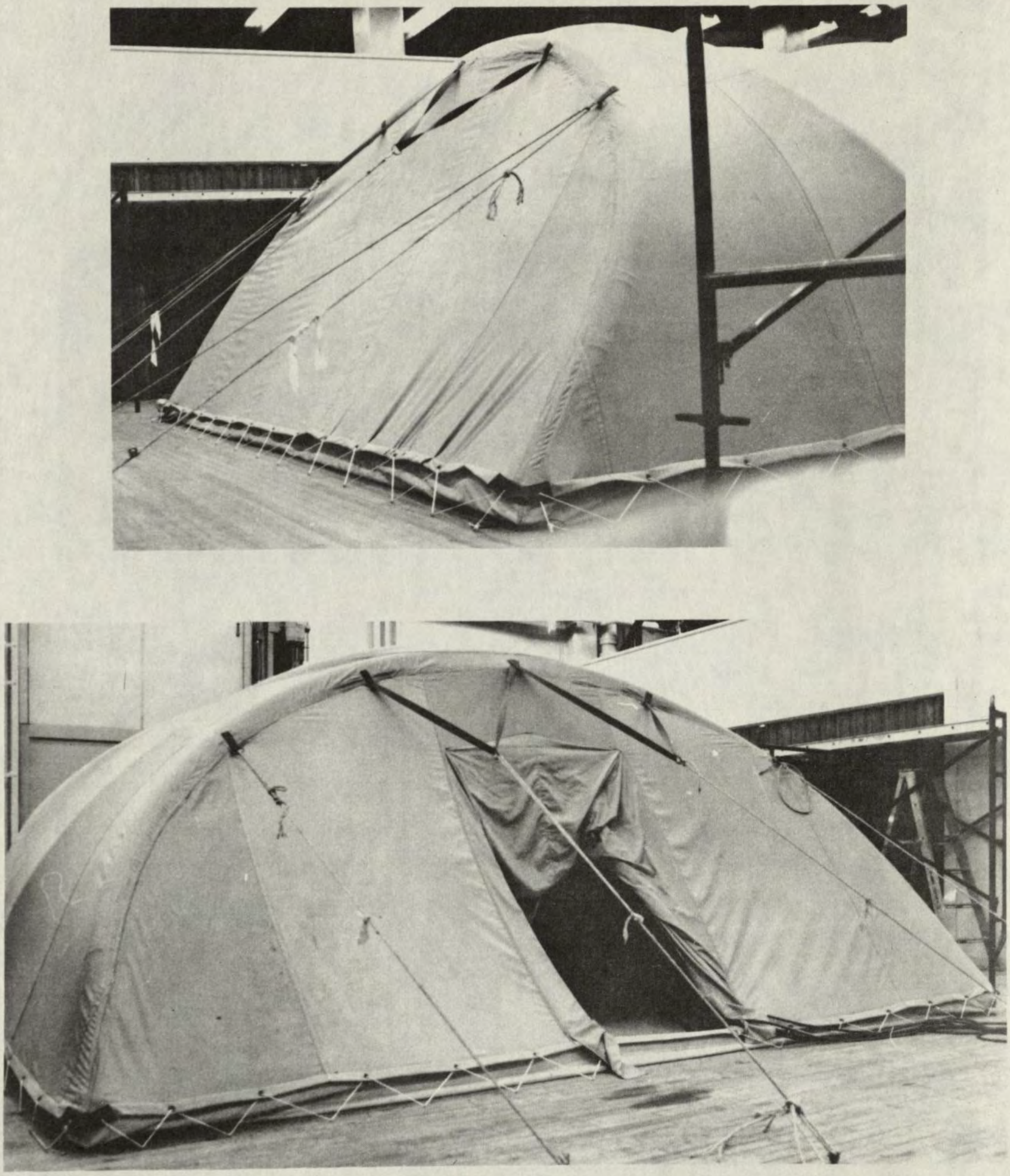
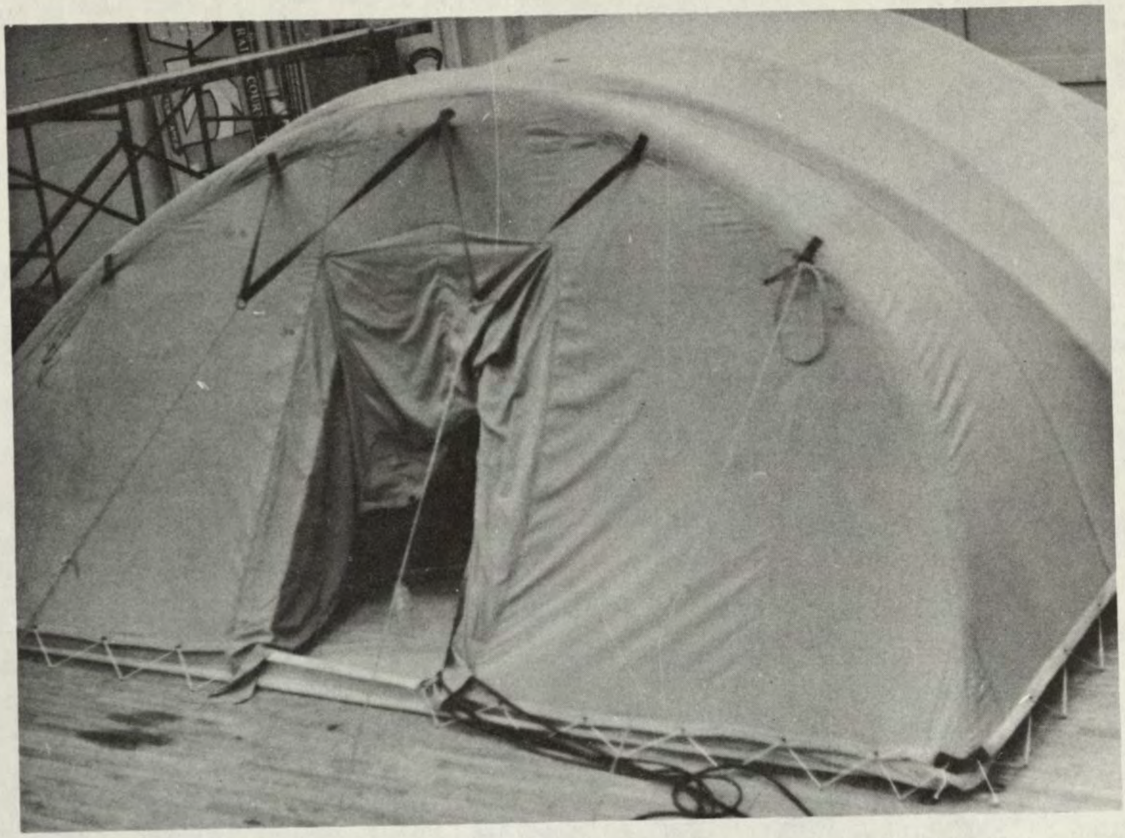


FIGURE 28. PROTOTYPE LEANING ARCH TENT.



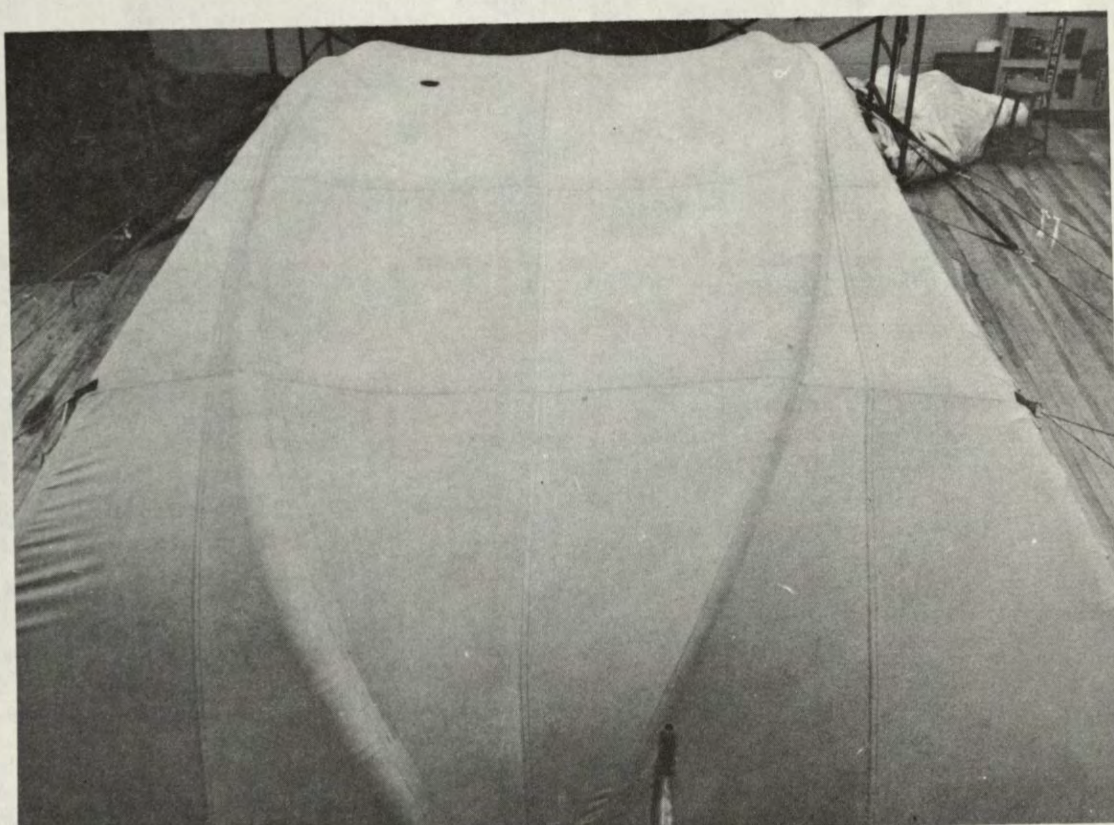


FIGURE 28. CONCLUDED.

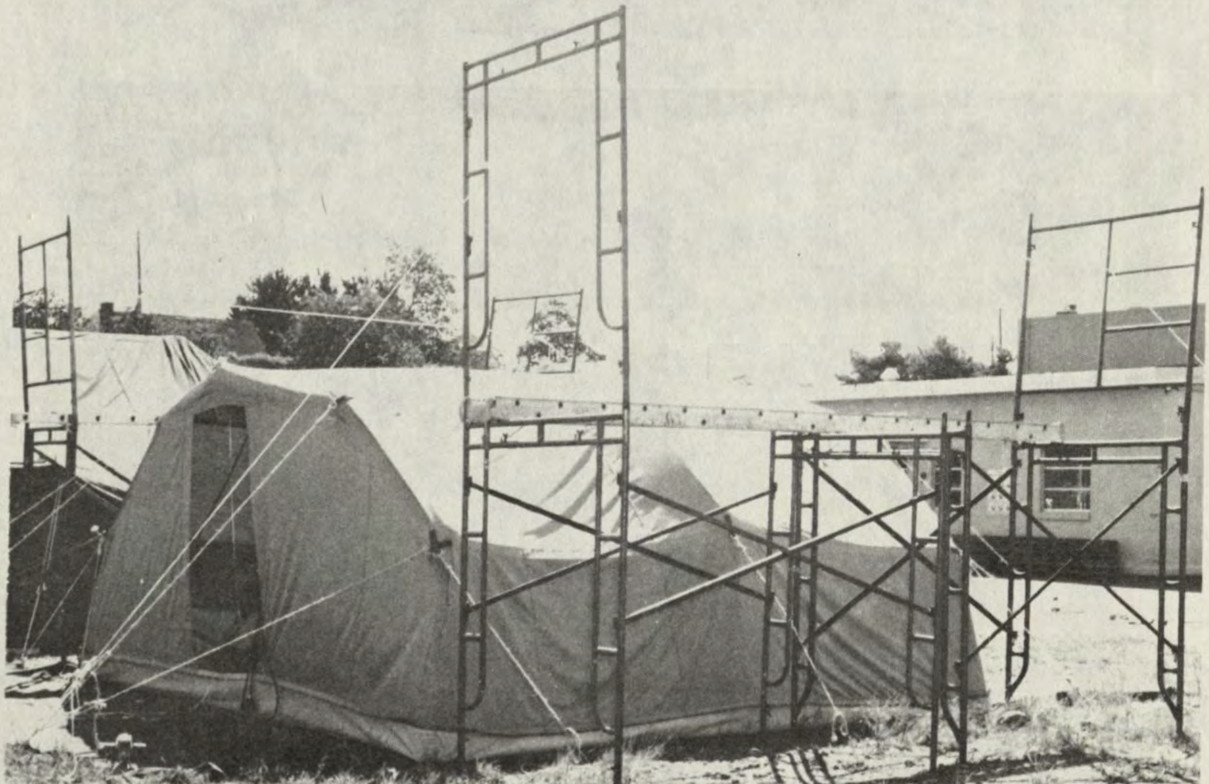


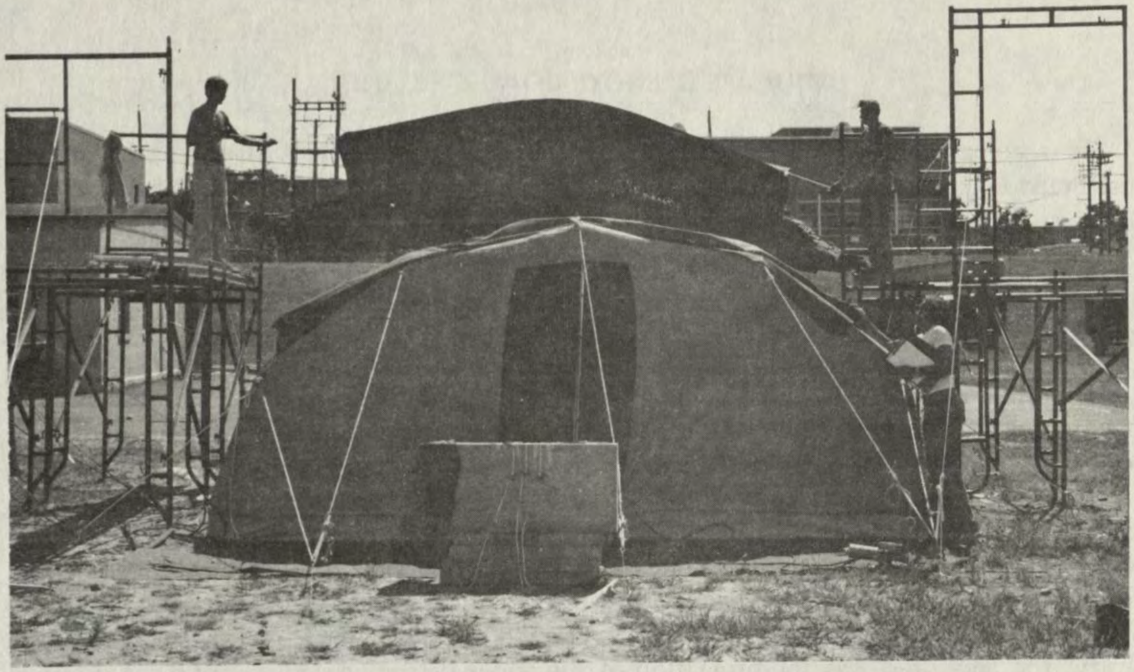
FIGURE 29. PROTOTYPE ARCH AND PURLIN TENT.

SIMULATED SNOW LOAD TESTING

To accomplish the objective of demonstrating that stable tent structures could be constructed with pressure-stabilized structural elements the prototype tents described above were tested under load. Of the two types of loads, wind and snow, that tents experience it was the previous experience with snow loading that raised questions about the stability of the pressurized rib concept and thus, we used only simulated snow loading in this investigation. The loading technique used was the laying on of fabric blankets as shown in Figure 30. The blankets were made from cotton duck fabrics having weights of 0.42 kg/m^2 to 0.84 kg/m^2. The blankets were 4.88 m x 3.96 m with the 4.88 m dimension placed along the length of the tent. Because of the nonvertical ends on the crossed-arch and leaning-arch tents, the blankets did hang over on the ends. The width of the blankets is less than the width of the tent because of the desire to include in the simulation the fact that snow will not remain on the steep slope areas of the tent. We assumed that snow would not stay on a surface having a slope greater than 45° and therefore the blanket width was chosen so that the blanket covered the roof area included in the angle of 45° either side of the vertical. In the conversion of the total applied load to a load density, the area used was the projection of the above described roof area on the ground plane. With some suitable approximations these areas are 12.9 m^2, 12.9 m^2, and 18.6 m^2 for the crossed-arch, leaning-arch, and arch-and-purlin concepts, respectively. The smaller areas of load application given for the crossed- and leaning-arch tents are the result of the nonvertical ends on these concepts. The loads are applied with these blankets incrementally by pulling each blanket over the tent and setting it in place. The weight of each blanket is known and recorded as the blanket is placed on the tent so a record of the total load, not the load density, is maintained. In addition, the deflection of the midpoint of the arches was measured for each blanket or increment of load. These deflections were measured with tape measures whose smallest division was 1/16 of an inch. In addition, the general character of the arch deformation was observed. The loading was continued until collapse occured.

RESULTS AND DISCUSSION

Since the further development of the pressurized rib tent concept depends in part on the ability to fabricate pressure-stabilized structural elements, some of the characteristics and behaviors of the elements used in this investigation deserve comment. In conducting the pressure tests on typical completed arches, one ruptured at 310 kPa and another at 330 kPa, or at about 60% of the design pressure level of 520 kPa. Because of this we imposed an operational pressure limit of 276 kPa on the use of these tubes. This limit caused serious curtailment of the snow load testing of the prototype pressurized rib tents, as will be discussed below. The problem with regard to tube fabrication is that these ruptures occurred at stress levels of one-fifth to one-sixth of the ideal or theoretical breaking strength. It was suggested by the weaver and by the results of reference 7 that these premature failures are the result of weaving inaccuracies. These inaccuracies are believed to be associated with the variation in shuttle tension causing the yarns in the crease areas to be of unequal lengths. Thus the shorter ones carry a greater portion of the load,



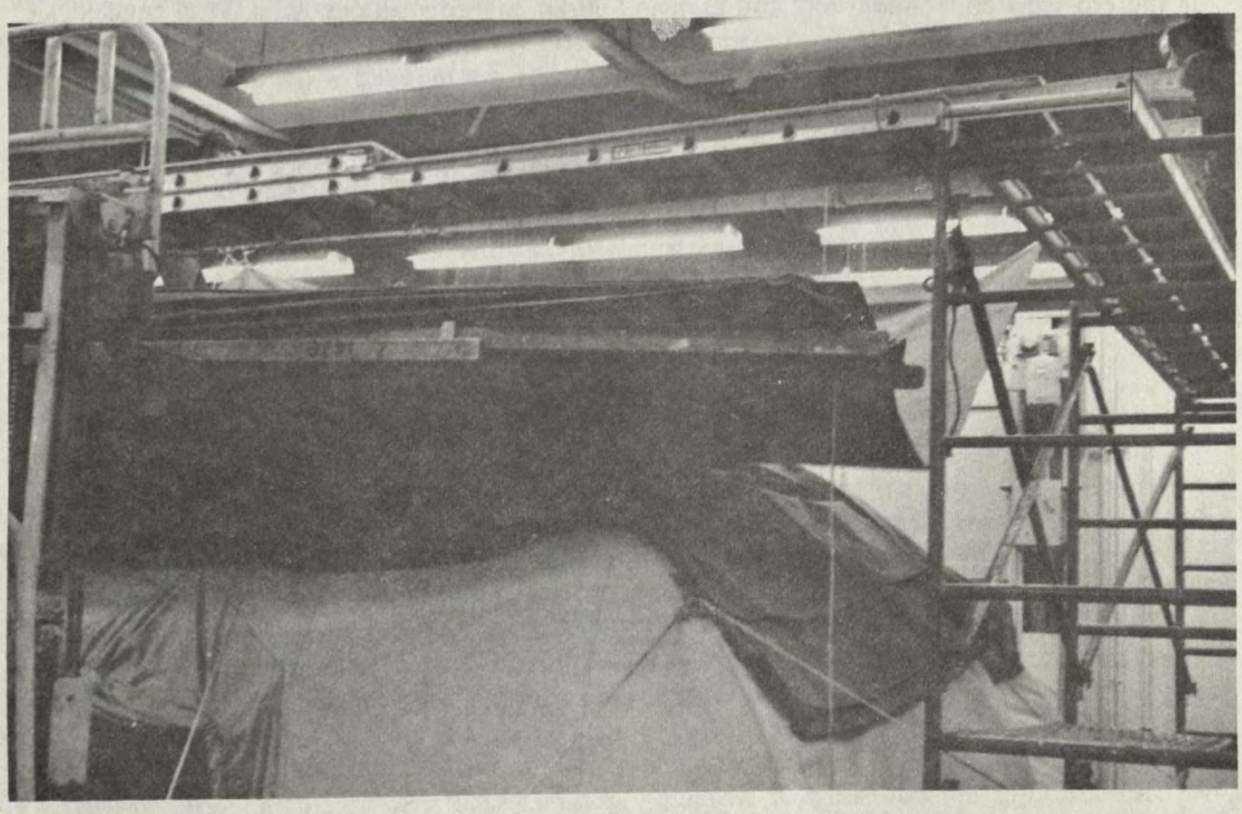


FIGURE 30. ILLUSTRATION OF THE SIMULATED SNOW LOAD TESTING TECHNIQUE.

resulting in early failure. If this basic problem cannot be overcome, additional yarns will be required in the weave, thus increasing the fabric mass. This is not desirable because of the preference to retain the low weight character of the pressurized rib concept. An alternative to this is choosing another material such as dacron which has a lower modulus, since the results in reference 7 indicate that the lower modulus materials are less susceptible to the effects of variations in yarn length in the crease region. It has been suggested that weaving these tubes on a circular loom would solve the basic problem because it does away with the repeated changes in direction and the resulting stopping and starting of the shuttle. While circular loom technology is available for weaving straight tubes, it would be necessary to develop it for the curved tubes or arches. It is interesting to note that on several occasions short pieces of Kevlar tube were inflated to the design pressure of 520 kPa without rupture. This indicates that short pieces probably containing no weaving imperfections were basically strong enough for the design pressure, thus the weave design was satisfactory.

The air retention of the structural elements is also a characteristic important to the pressurized-rib concept because of the desire to eliminate the dedicated compressor required by present air-supported tents. Our goal is to have the elements suffer no greater than a ten percent reduction in pressure over a period of seven days. Our experience in this investigation does not even come close to this goal. In using the bladders and aluminum end caps, a dedicated compressor was required to maintain pressure. Leaks could be attributed to two causes: sealing in the end cap and cracking of the bladder after several cycles of inflation. The difficulty with the sealing in the end cap is thought to be the result of the wrinkling of the bladder and the Kevlar tube when it is turned over the sealing ring. The cracking of the bladder can be attacked in two ways. First, a material with high fold endurance should be used, such as the nylon or composite films used here, and second by paying more attention to the sizing of the bladders and to their installation. The bladders used here were oversized 6% on the diameter which was perhaps excessive, leaving a lot of material in which wrinkles could form and be flattened upon pressurization. It may be better to closely fit the bladders to the tubes, perhaps even undersizing them and securing the bladder to the fabric. This could be accomplished by inflating the tube and bladder and putting spots of adhesive on the fabric to strike through and attach the bladder to the fabric. In doing this, the bladder would not have the freedom to move when not inflated, thus wrinkling and folds could not be formed. In using such a procedure, the bladder material would have to have sufficient flexibility to allow it to expand with the tube under pressure. An additional problem resulting from the use of straight tubular bladders with curved arches is the wrinkling on the inner radius required to make the straight bladder conform to the curved arch. This problem needs further work. The air retention characteristic of the neoprene latex-coated tubes with fabric end

[7] Steeves, Earl C.; Effect of Nonuniform Yarn Lengths on the Strength of Pressurized Fabric Tubes; US Army Natick Research and Development Command; Technical Report NATICK/TR–77/010; 1977 (AD A046960).

caps was extremely poor. When inflated and the inflation valve closed, they would remain rigid enough to stand erect for only 20 to 30 minutes. This is believed to be the result of pinholes in the coating. These tubes were coated with brushes and rollers, and it appears that this technique is unsatisfactory, and if coating is to be used, better application techniques must be developed.

The main concern with regard to the assembly of the coated arches and fabric end caps is the attachment of the end cap to the arch. As indicated above, an adhesive joint was used. With the complete arch assemblies no failures of this adhesive joint were experienced with inflation pressure up to 276-kPa. To further test our ability to make these joints, an uncoated Kevlar fabric end cap was joined to one of the uncoated Kevlar tubes that had been successfully inflated to 520-kPa without rupture. The joint was made with adhesive No. 1300L from the Minnesota Mining and Manufacturing Co., Inc., and the bond area was 10-cm wide, extending around the complete circumference. This tube-end cap assembly was pressure tested using a bladder to the design pressure of 520-kPa without failure. It thus appears that the end caps can be successfully bonded to the tubes with adhesives.

With regard to the fabrication of the segmented arch using straight tubes, two problems were revealed. The first of these, which can be seen in Figure 31, is the difficulty in joining the segments so that the resulting arch is free of distortion. This problem may be resolved by further investigation of the joining techniques. The second problem revealed is the reduction in strength as a result of the fabrication. Three attempts were made to inflate the segmented arch-and-purlin tent to 207-kPa and on each of the occasions the rear arch ruptured before this pressure was reached. On the third attempt the inflation was continued in the remaining elements and held at the pressure of 207-kPa. The beam at the rear of the tent ruptured after about one hour at pressure. It thus appears that more work is required on the development of fabrication techniques for segmented arches.

The results from the simulated snow load tests of these prototype tents are presented in Figures 32 through 43, Tables 1 and 2, and in the tables in the Appendix. From these data we infer information concerning the deformation and load-carrying capacity of the tents. Two measures of the load-carrying capacity are used, the wrinkling load and the collapse load.

The overall deformation of the fabric environmental barrier was not measured quantitatively but generally observed and one aspect of this deformation deserves comment. In both the crossed- and leaning-arch concepts the rather large area of unsupported fabric at the center of the tent underwent very large deformation on the order of a meter or more shortly before collapse. These deformations were so large that the space became unusable. This difficulty was essentially eliminated by both the midspan beam and the center arch modification.

The deformation of the structure was measured quantitatively and is characterized by load-deformation curves given as Figures 32 through 43. The load parameter used

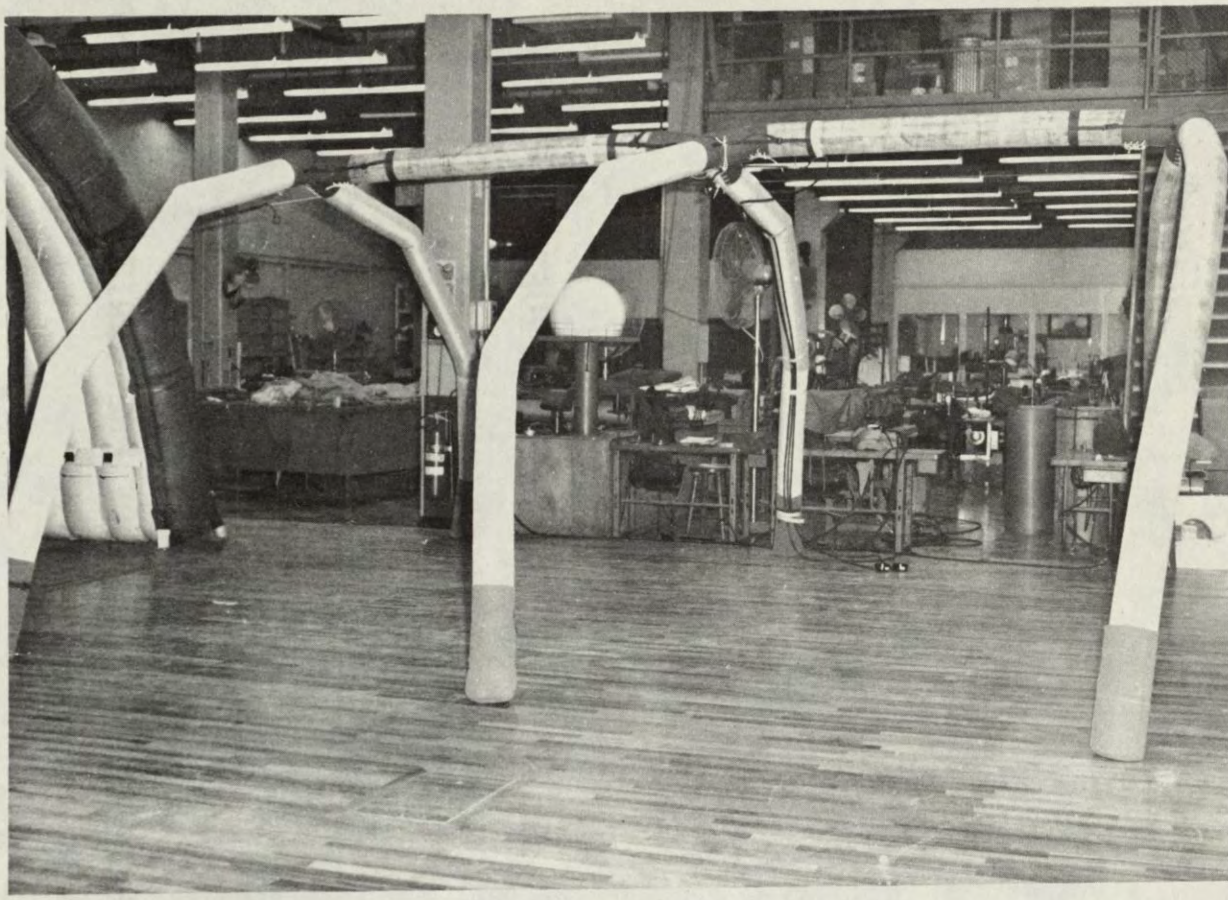


FIGURE 31. DOUBLE MODULE ARCH AND PURLIN FRAME ASSEMBLY WITH SEGMENTED ARCHES.

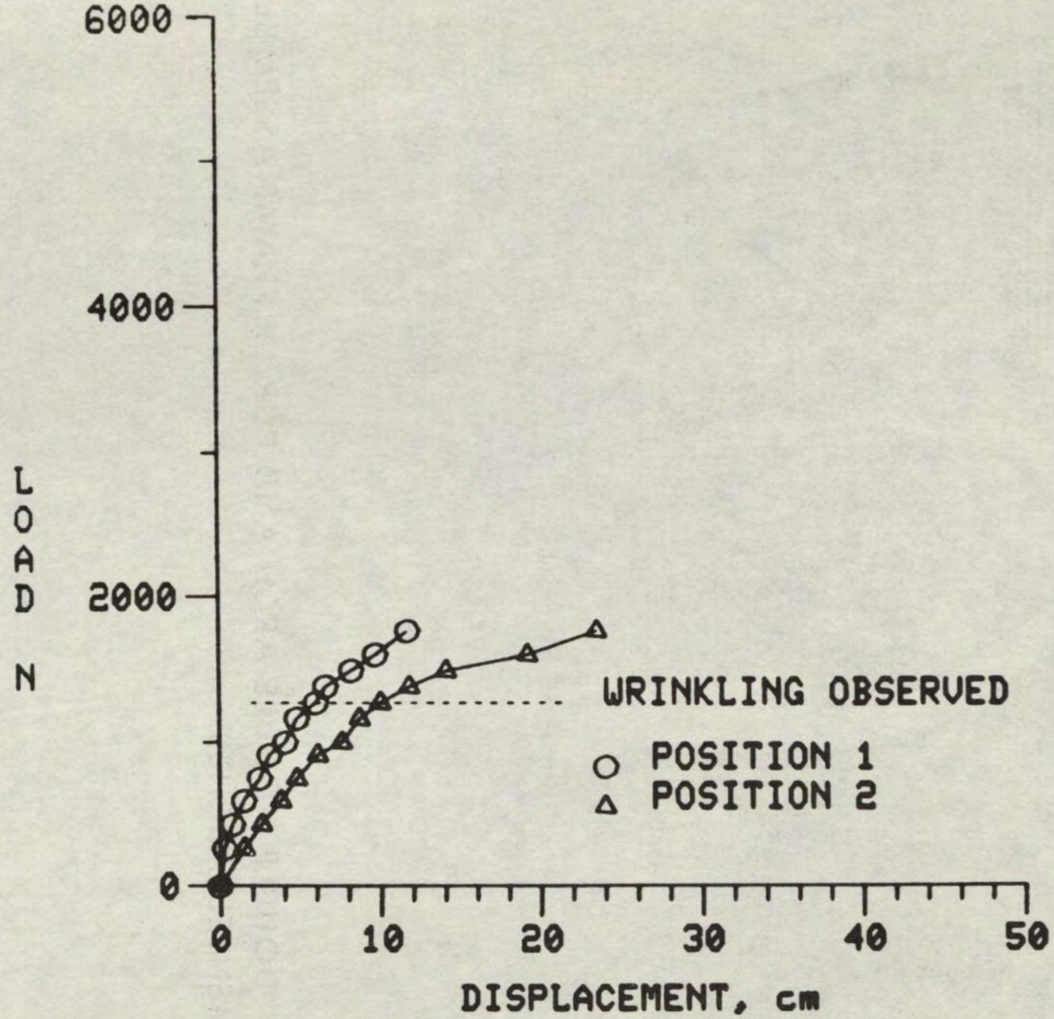


FIGURE 32. DEAD WEIGHT TESTS OF PRESSURIZED RIB TENTS
CROSSED ARCH, 138KPA

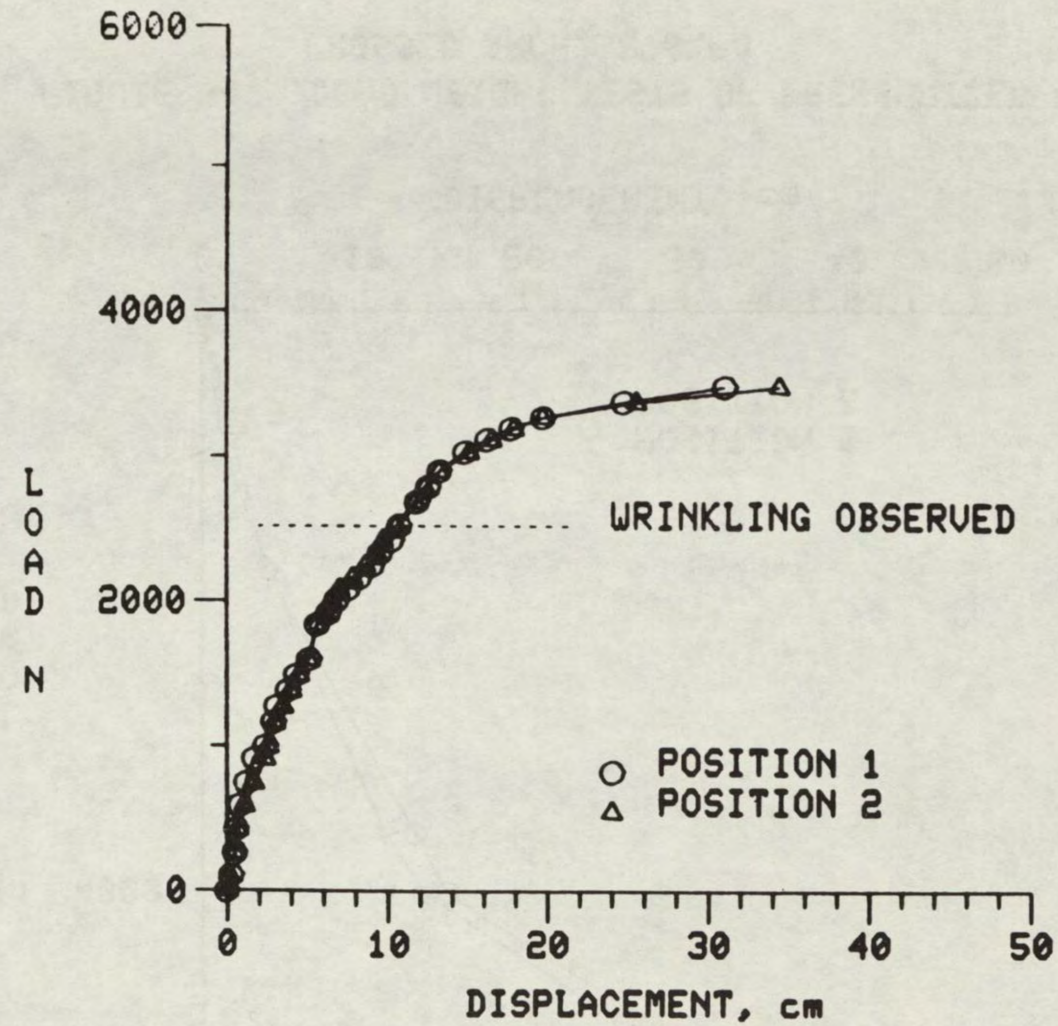


FIGURE 33. DEAD WEIGHT TESTS OF PRESSURIZED RIB TENTS
CROSSED ARCH, 207KPA

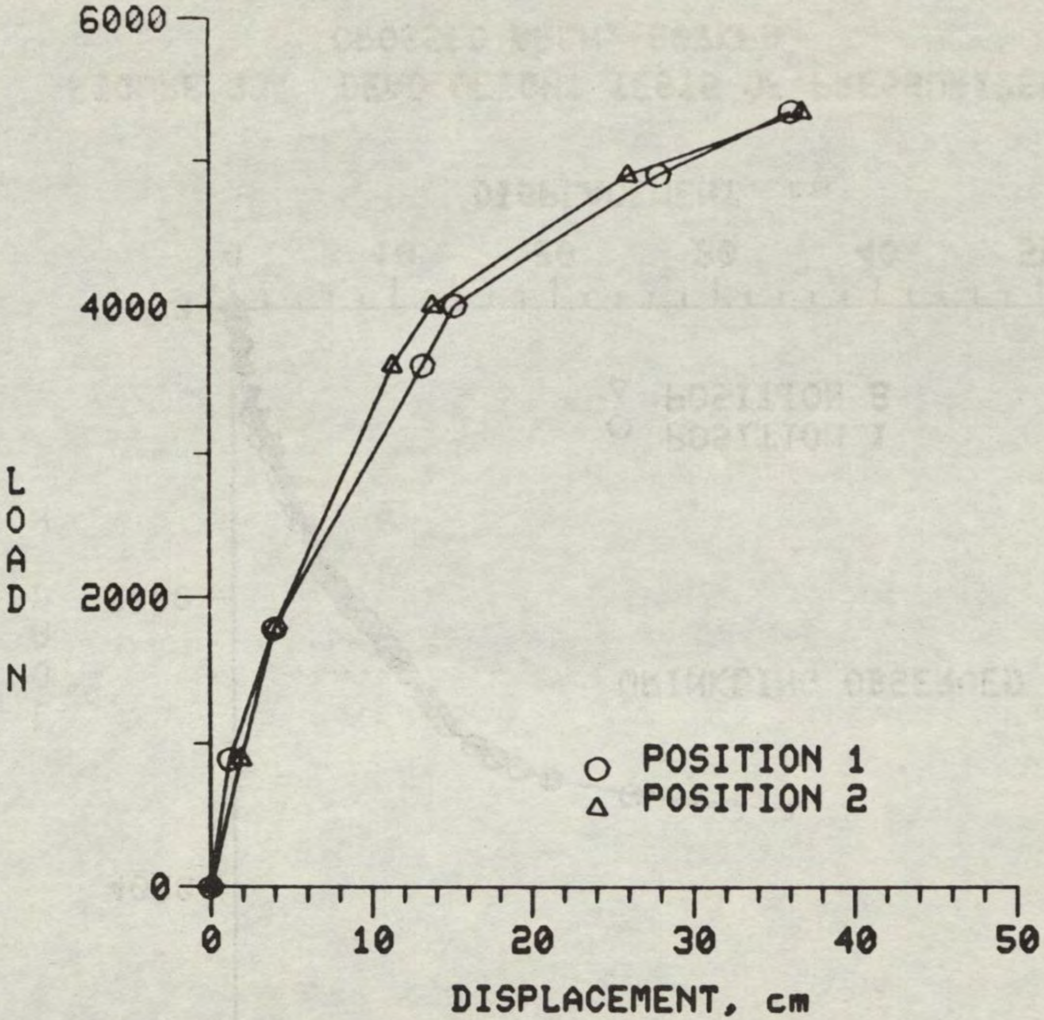


FIGURE 34. DEAD WEIGHT TESTS OF PRESSURIZED RIB TENTS
CROSSED ARCH, 276KPA

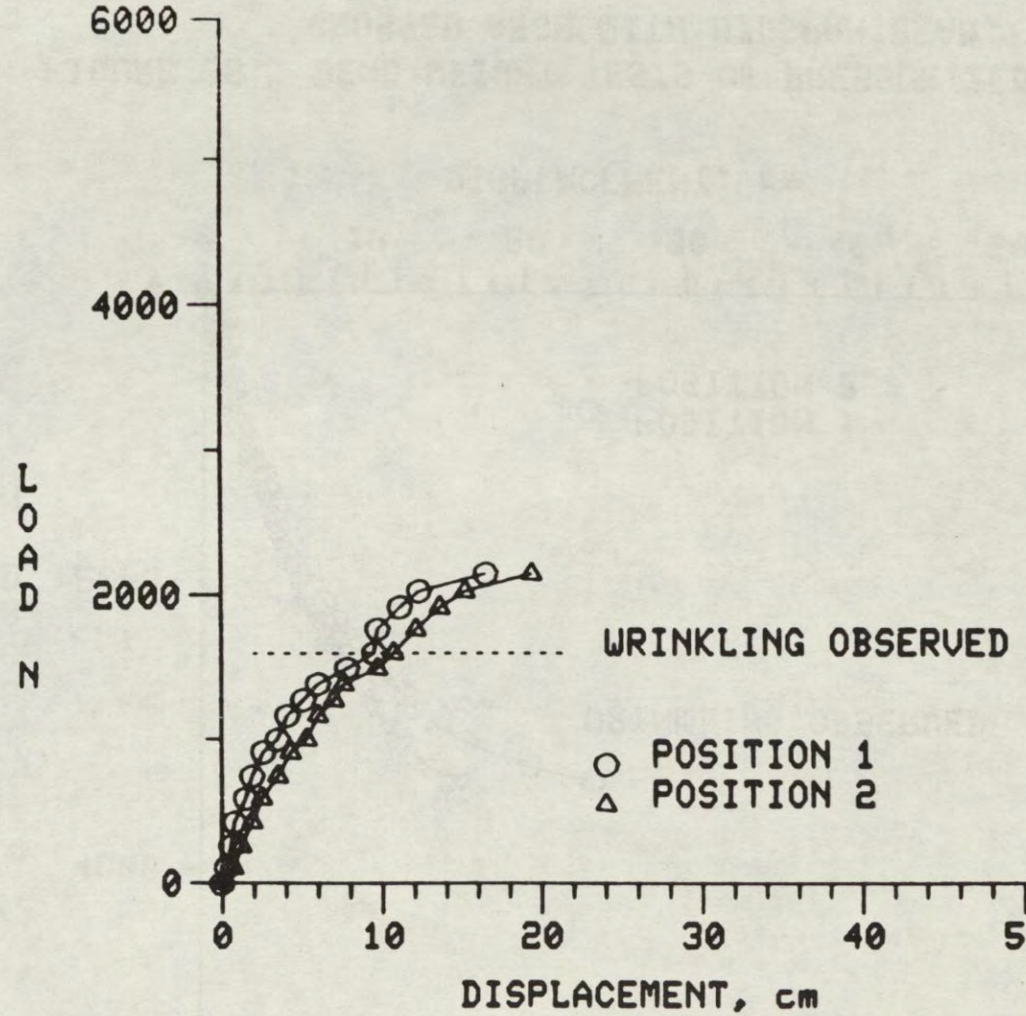


FIGURE 35. DEAD WEIGHT TESTS OF PRESSURIZED RIB TENTS CROSSED ARCH WITH MIDSPAN BEAM, 138KPA

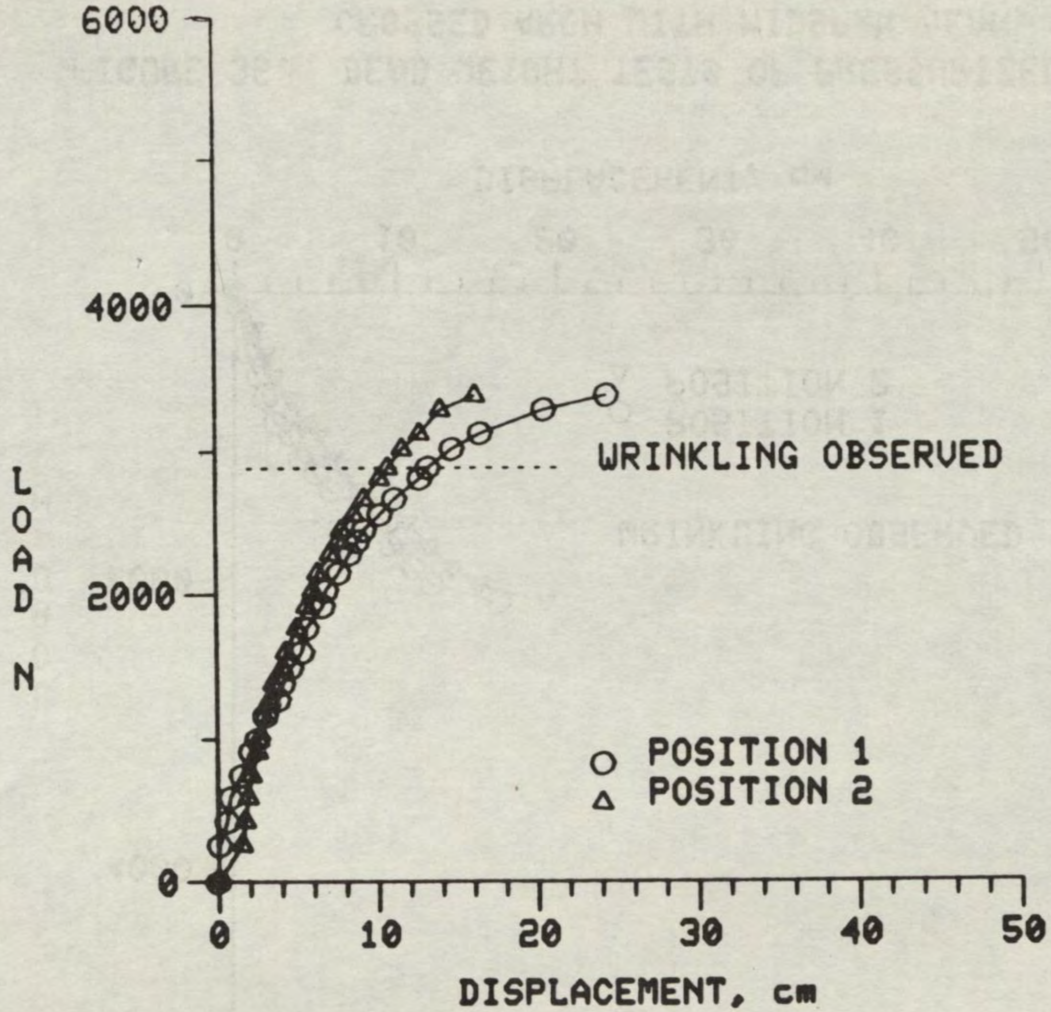


FIGURE 36. DEAD WEIGHT TESTS OF PRESSURIZED RIB TENTS
CROSSED ARCH WITH MIDSPAN BEAM, 207KPA

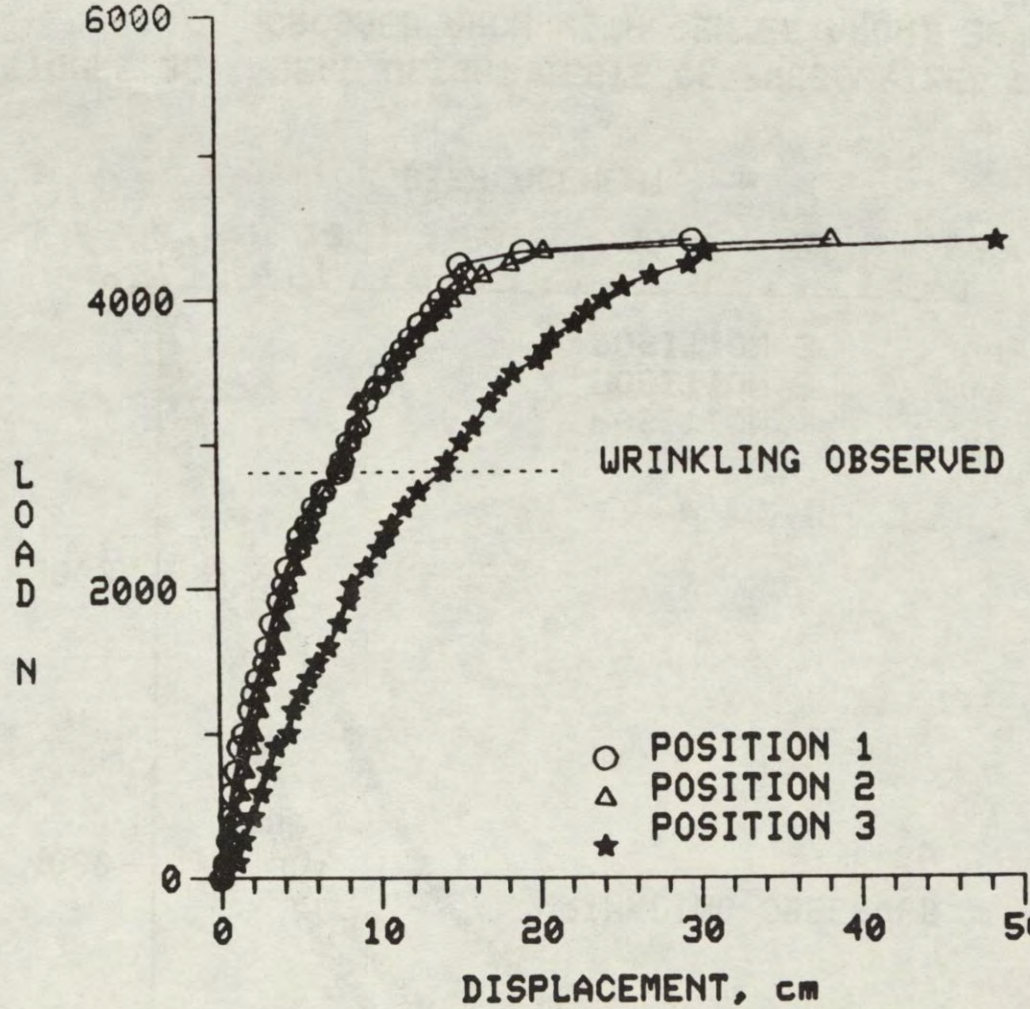


FIGURE 37. DEAD WEIGHT TESTS OF PRESSURIZED RIB TENTS CROSSED ARCH WITH CENTER ARCH, 138KPA

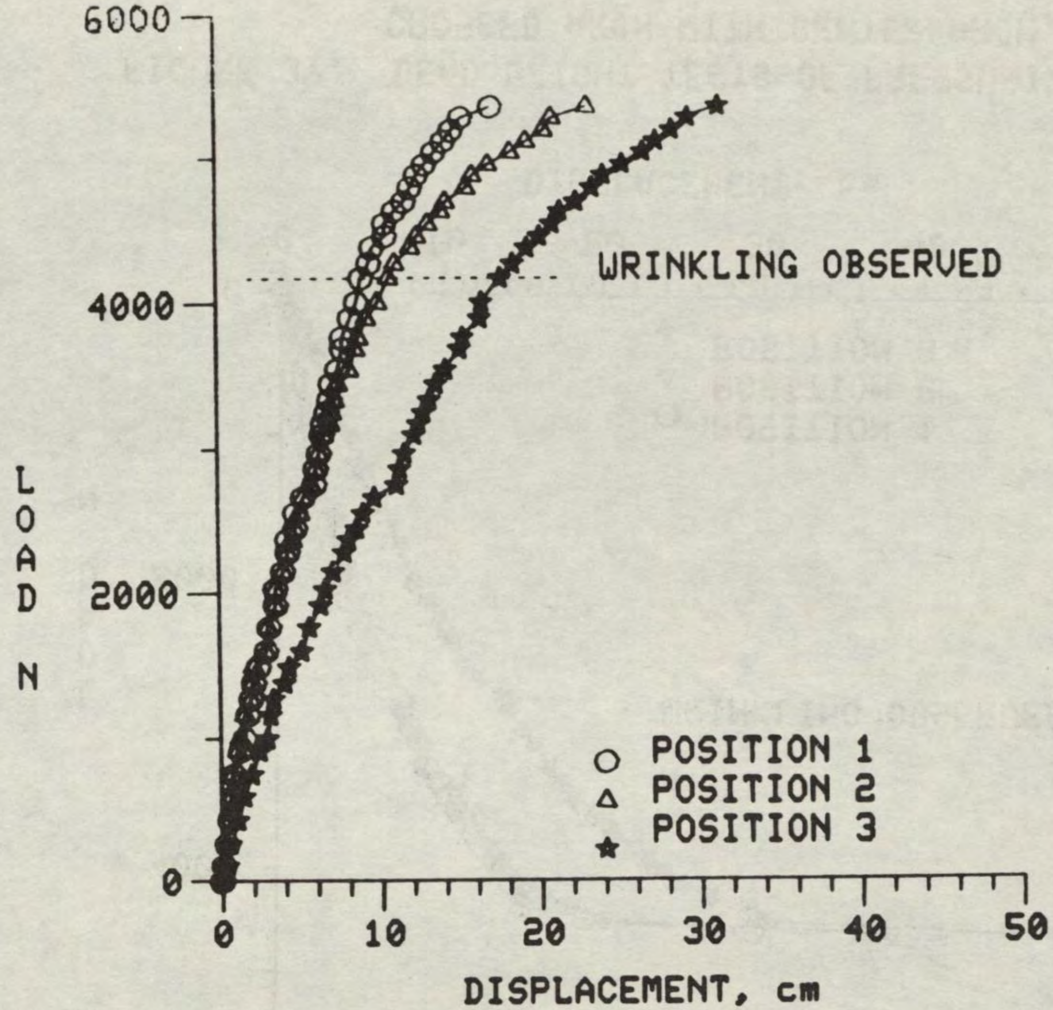


FIGURE 38. DEAD WEIGHT TESTS OF PRESSURIZED RIB TENTS
CROSSED ARCH WITH CENTER ARCH, 207KPA

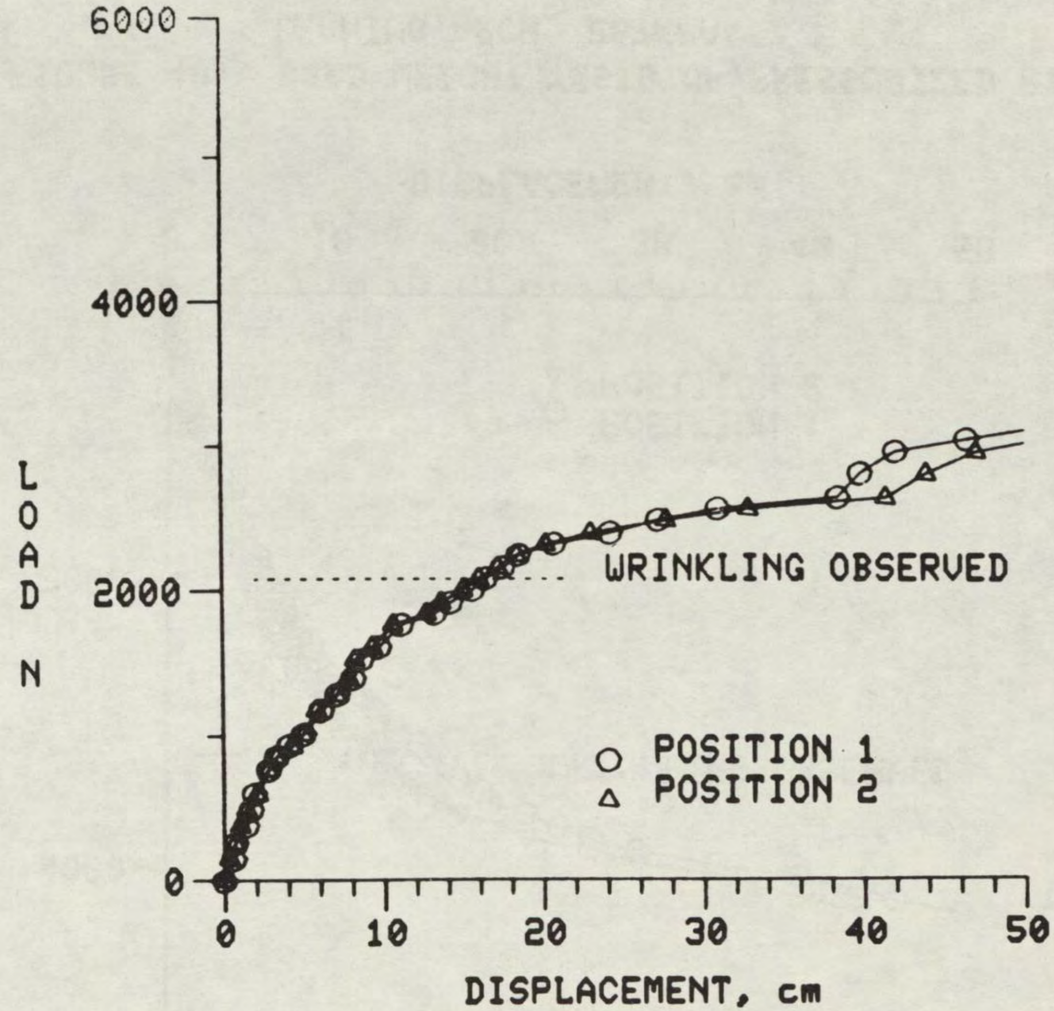


FIGURE 39. DEAD WEIGHT TESTS OF PRESSURIZED RIB TENTS
LEANING ARCH, 138KPA

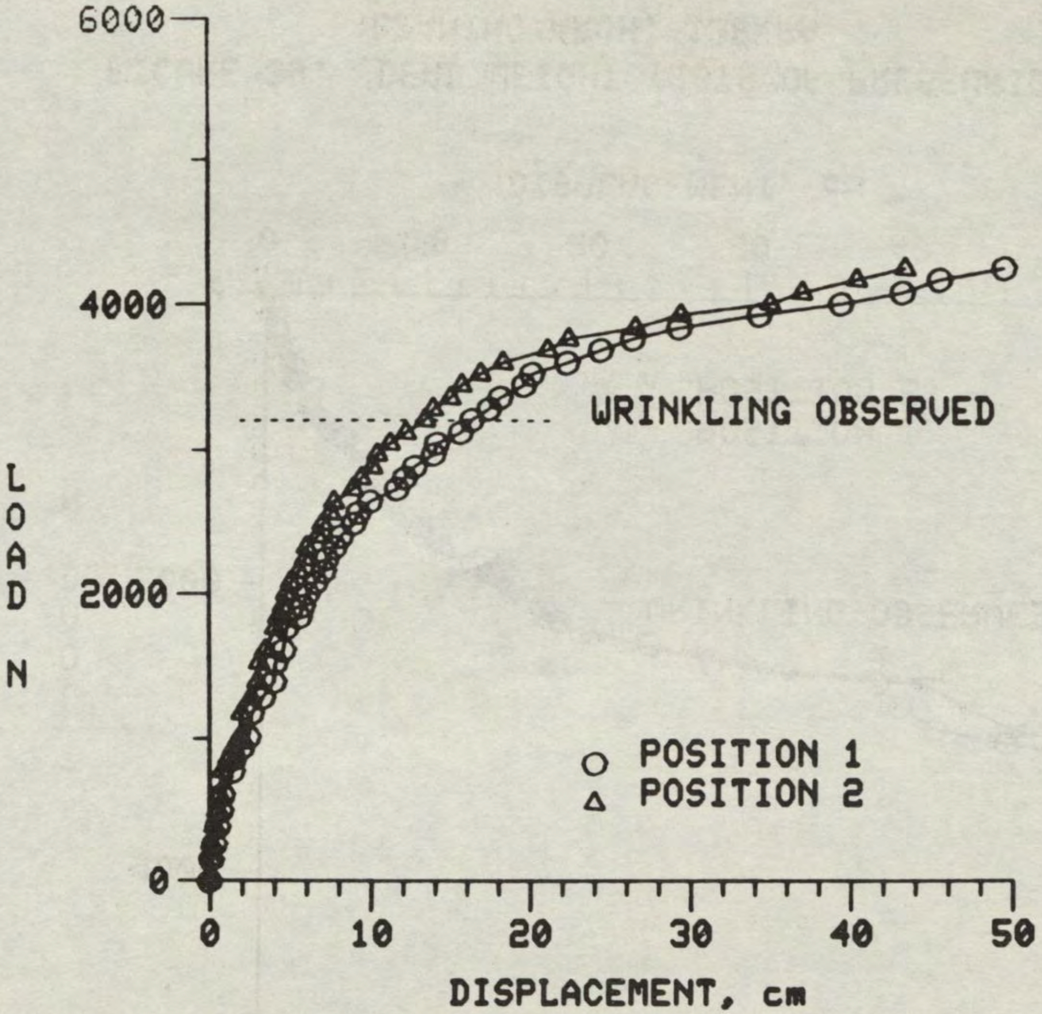


FIGURE 40. DEAD WEIGHT TESTS OF PRESSURIZED RIB TENTS
LEANING ARCH, 207KPA

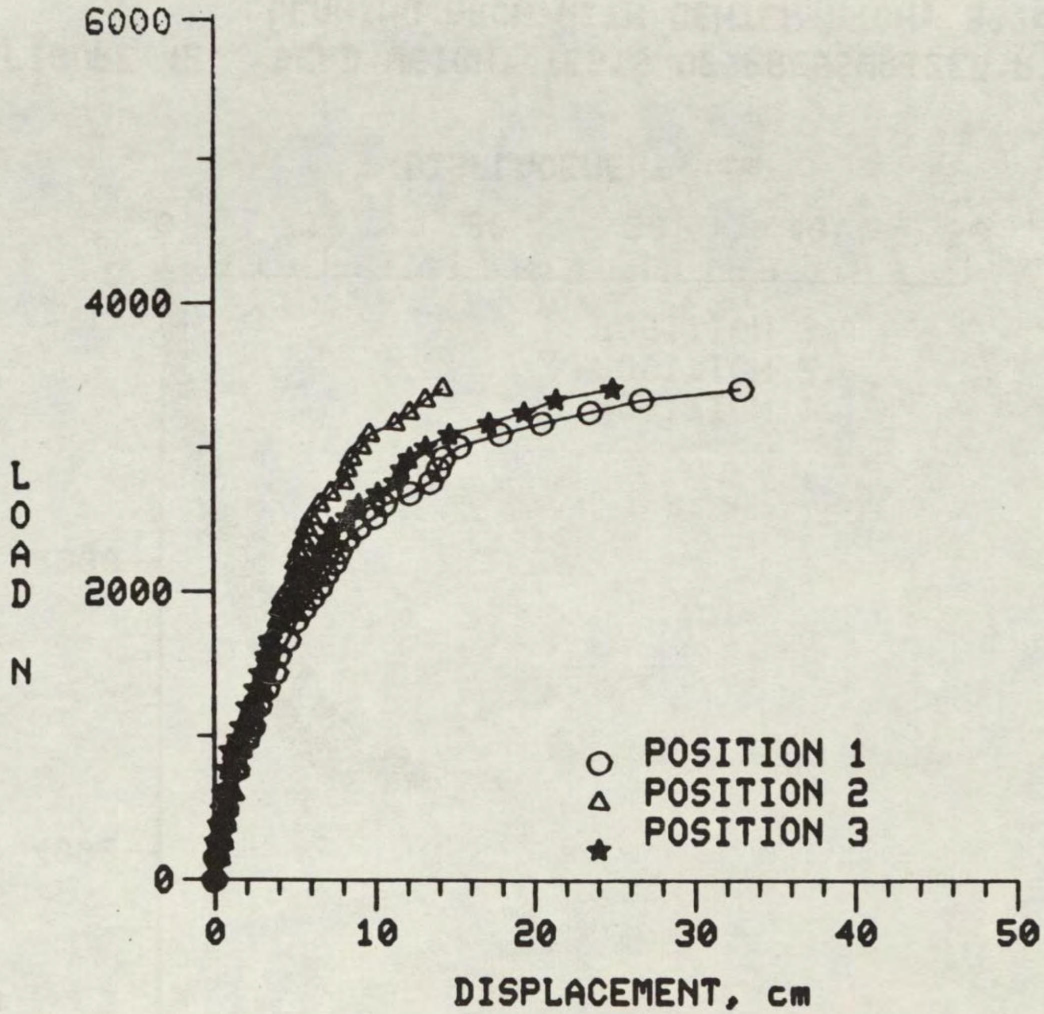


FIGURE 41. DEAD WEIGHT TESTS OF PRESSURIZED RIB TENTS
LEANING ARCH WITH CENTERARCH, 138KPA

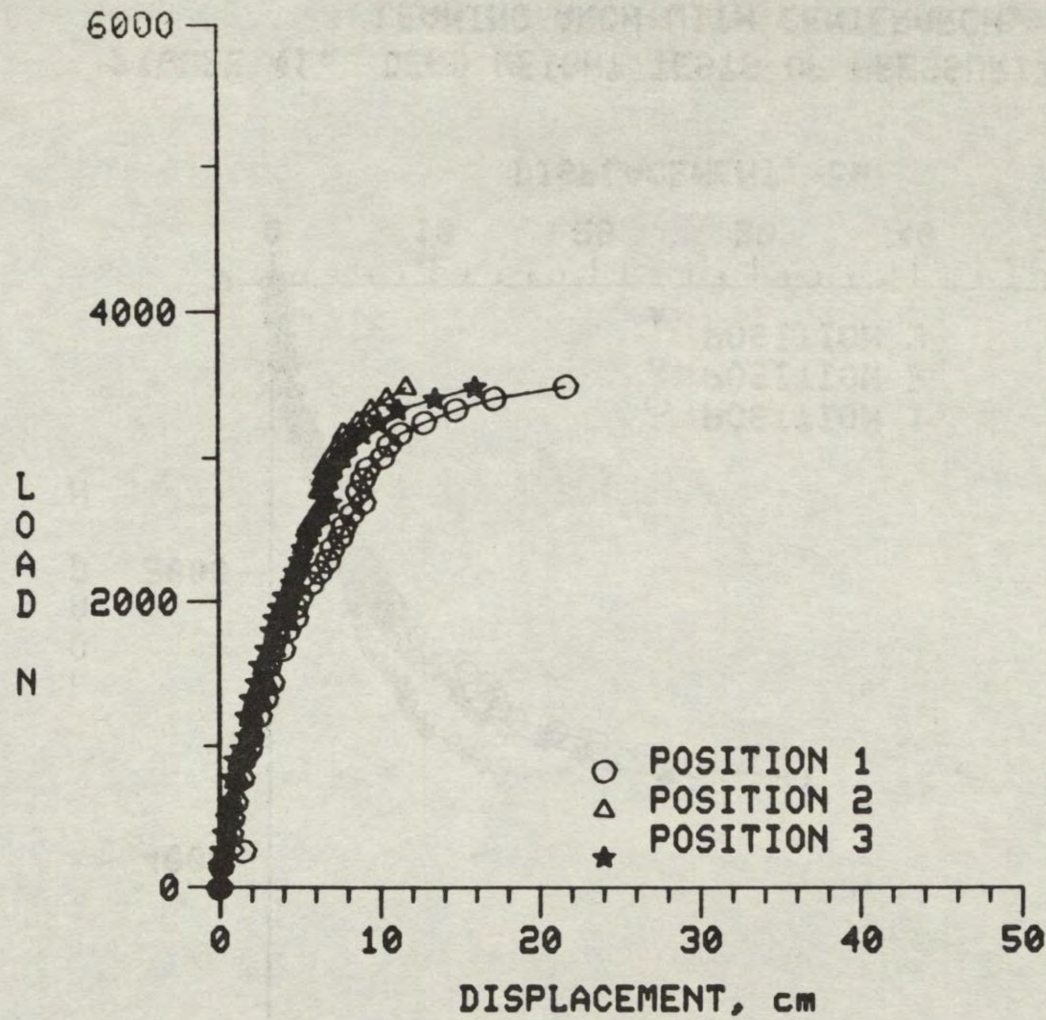


FIGURE 42. DEAD WEIGHT TESTS OF PRESSURIZED RIB TENTS
LEANING ARCH WITH CENTER ARCH, 207KPA

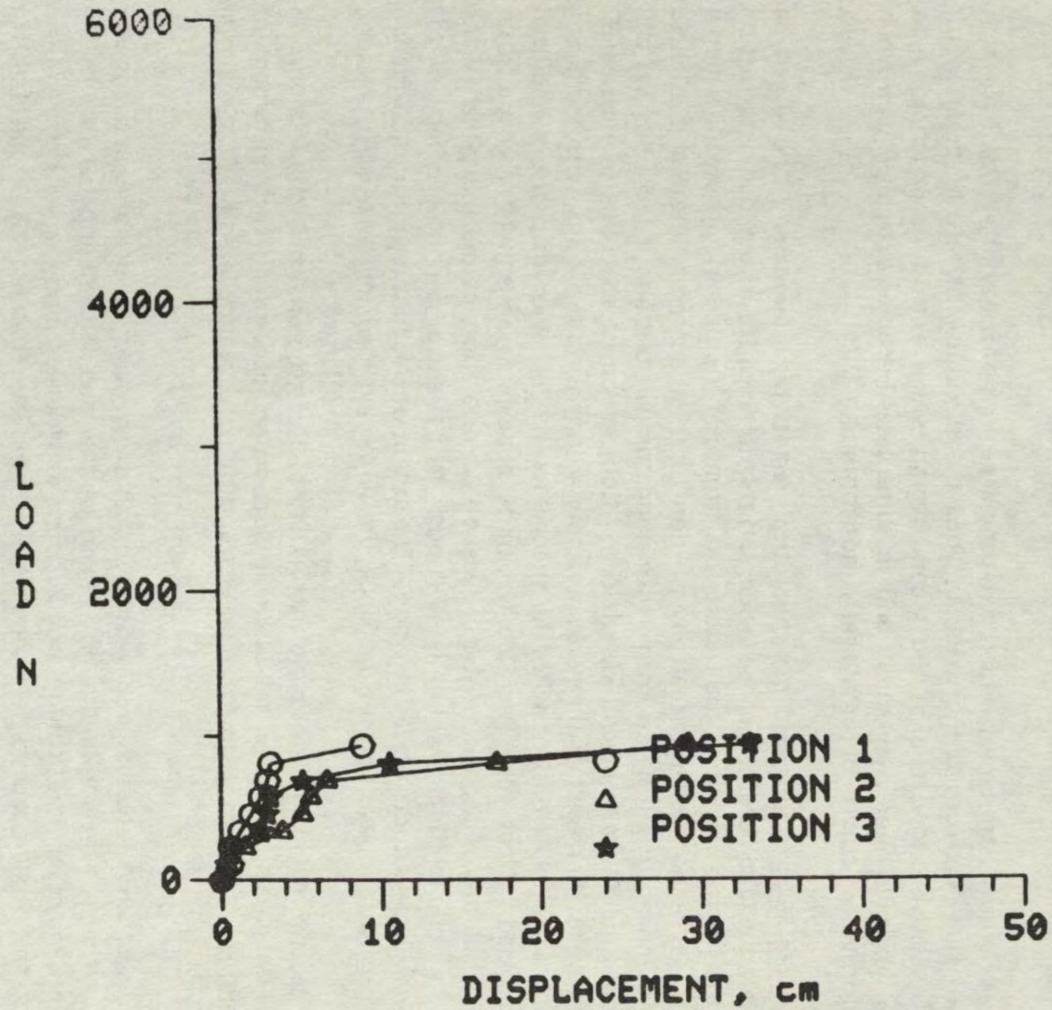


FIGURE 43. DEAD WEIGHT TESTS OF PRESSURIZED RIB TENTS ARCH AND PURLIN, 69KPA

in plotting these curves is the total load on the tent and the deformation is that of the midpoints of the arches or the arch modules. Positions 1 and 2 refer to the arch modules and position 3 designates the center arch, where applicable. These curves do not have constant slope so that when we use the term flexibility we do not mean the concept associated with linear structures, but refer to the local slope of the load-deformation curve.

The load-deformation curves exhibit two general regions of behavior; in the first which extends from zero load up to the wrinkling load the flexibility or rate of deformation with load is relatively low, and in the second region which extends from wrinkling to collapse the flexibility increases rapidly and in some cases becomes extremely high when the load-deformation curves become nearly horizontal.

It is in the first region that the theoretical results of references 2 and 4 can be used to explain the load-deformation behavior, and the nonlinearity of the load-deformation curves in this region are not the result of structural nonlinearity but of material non-linearity. It is not believed that any portion of these curves is linear and in these discussions no linearity will be assumed. In making comparisons about flexibility we will compare slopes at the same magnitude of load. Comparison of the plots in Figures 32 through 43 reveals that each of the concepts show a decreasing flexibility with increasing pressure and this is in agreement with the theory for the behavior of pressure stabilized arches under load. Near zero load the flexibility appears to be equal for all pressures and concepts but this is thought to be a question of resolution in the data, that is, the differences in the flexibility are not large enough to be seen within the accuracy of the data at the small magnitudes of deformation. The extent of this first region of deformation is made larger with increasing pressure since the wrinkling load increases with pressure.

In the second region of deformation wrinkling of the structure has begun so a portion of the wrinkled cross section is not active in supporting load. With each increment of load the wrinkled region increases so we have structural non-linearity in addition to material non-linearity in this region.

The crossed arch, crossed arch with midspan beam, and the leaning arch concept exhibit very similar behavior in the first region of the load-deformation curves. In the second region, however, the leaning arch concept experiences much larger deformations than any of the other concepts. It should be pointed out that not all of the data for the leaning arch at 138 kPa pressure is on Figure 39. As can be seen from the data in the Appendix, the deformations for this case are 82.0 and 84.5 cm at a load of 3380 N. Little can be said about the flexibility of the arch-and-purlin concept since so little data is available. As indicated, the addition of the midspan beam had little significance on the flexibility of the structure but the addition of the center arch changed the load deformation significantly. Figures 37 and 38 for the crossed arch with the center arch modification seem to show that the center arch, position 3, is more flexible in both regions than the crossed arch pairs. This may well be the case since we have for position 3 the response of a single arch to load, whereas for the other positions we have the response of a pair of arches acting together. However, it must also be remembered that we have used the total loads on the structures as the load parameter in these plots, and we have no information about how the load is distributed among the three support structure elements. Thus, it is difficult to determine with any certainty the relative flexibility of the structural elements. The center arch does undergo considerably more deformation than the crossed arches. The results for the leaning arch with the center arch modification are quite in contrast to these results. As is seen in Figures 41 and 42, the center arch, position 3, undergoes deformations comparable with the leaning arch modules. This is perhaps not unexpected since both the leaning arch and the center arch are found to experience larger deformations than the crossed arch module. With regard to minimizing deformation, the crossed arch concept with center arch modification gives the best performance.

The other performance characteristic of interest is the load-carrying capability of these tents as measured by the collapse load and, where available, the wrinkling load. The collapse load for the prototype tent concepts at various pressures are given in Table 1, and the wrinkling loads are given in Table 2. These tables give their respective load parameters in terms of the total load and the load intensity based on the areas cited earlier. The wrinkling loads were determined merely by observing the arch and noting when wrinkling was initiated. A wrinkling load is not given for the crossed arch at a pressure of 276-kPa because observations were made too infrequently to obtain a meaningful indication of the beginning of wrinkling. The absence of wrinkling load values for the leaning-arch concept with the center arch modification is related to a more fundamental problem. In these tests wrinkling was not observed. It is believed that this is the result of loading of the arch out of its plane due to the overhang of the blankets on the sloping rear wall and some anomalous behavior of the arches. This anomalous behavior is related to the restraint of the arch ends which were observed to undergo large rotations during the three to four load increments prior to failure. Examination of the collapse load for this concept, leaning arch with center arch, reveals that collapse occurred at very nearly the same load for both inflation pressures. This also is an unexpected result further confirming the anomalous behavior. This same phenomenon was observed when the unmodified leaning-arch tent was first tested, but on retesting the difficulty was not observed and failure occurred as expected with wrinkling observed and inflation pressure level having the expected effect on load-carrying capability. For all the cases in which the wrinkling load was determined, it increased as the inflation pressure increased. Some theoretical results in reference 2 indicate that for pressure-stabilized beams the wrinkling load is proportional to the square of the inflation pressure. None of the cases shown in Table 2 obey such a relationship, but in all cases the increase in wrinkling load is at least proportional to the increase in pressure. A fifty percent increase in pressure yields 98%, 80%, 48%, and 54% increases in the wrinkling load, respectively, for the crossed arch, crossed arch with midspan beam, crossed arch with center arch, and leaning arch. Thus, using wrinkling load as a measure of load-carrying capability, the crossed arch concept, which has the 98% increase, benefits most from increases in pressure. The increases in the collapse load with pressure are less than those observed for the wrinkling load, but again the crossed arch increased the most. Both the wrinkling load and the collapse load results indicate that the leaning arch is stronger

Table 1

Collapse Load of Pressuried Rib Tent Concepts
Total Load and Load Intensity

Pressure, kPa	**69**	**138**	**207**	**276**
				*
Crossed Arch		1840.N 143.N/m²	3480.N 270.N/m²	5340.N 414.N/m²
Crossed Arch with Midspan Beam		2280. 177.	3490. 270.	
Crossed Arch with Center Arch		4470. 346.	5430. 421.	
Leaning Arch		3400. 263.	4240. 329.	
Leaning Arch with Center Arch		3480. 270.	3560. 276.	
Arch and Purlin	928. 50.	1286. 69.		

*Did not collapse, test terminated.

Table 2

Wrinkling Load of Pressurized Rib Tent Concepts
Total Load and Load Intensity

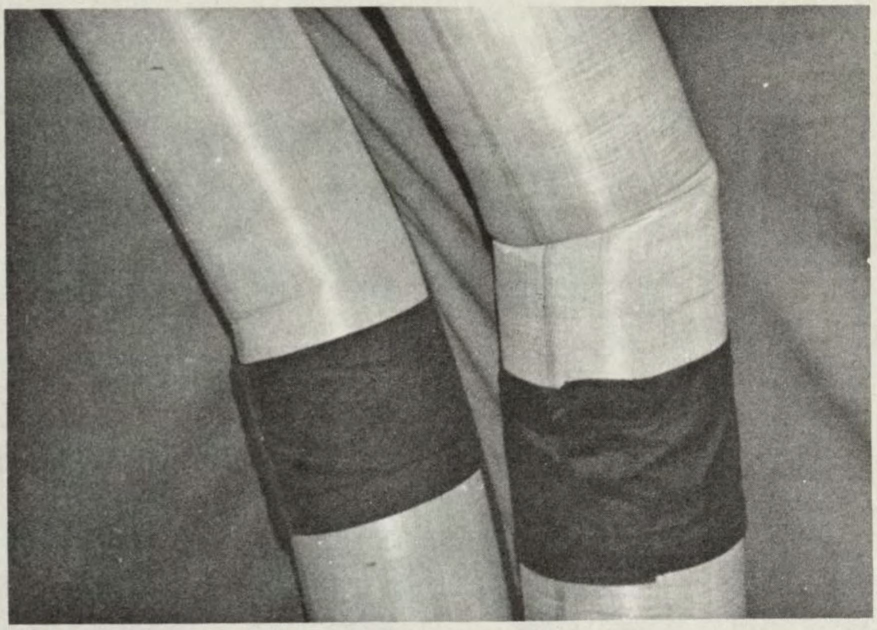
Pressure, kPa	69	138	207	276
Crossed Arch		1270.N 98.N/m^2	2510.N 194.N/m^2	
Crossed Arch with Midspan Beam		1600. 124.	2880. 223.	
Crossed Arch with Center Arch		2800. 217.	4160. 322.	
Leaning Arch		2080. 161.	3200. 248.	
Leaning Arch with Center Arch				
Arch and Purlin				

than the crossed arch, but it must be remembered that the leaning arch suffers some anomaly in behavior that is not understood. Both the midspan beam and the center arch give increases in the load-carrying capability of the crossed-arch concept. The midspan beam gives rather moderate increases. The 25% increase in structure required for the addition of the center arch results in more than double the load-carrying capability at an inflation pressure of 138-kPa and more than a 50% increase at 207-kPa. Thus, this is a very useful modification. The arch-and-purlin concept had very poor load-carrying capability with respect to the other concepts. This is at least partly due to the segmented design used which was based on the approximation of a circle by equal-length segments. This resulted in rather long and nearly horizontal segments joining at the center of the arch which had to withstand load predominantly by bending deformation as opposed to the stronger axial deformation. A more satisfactory design might be attained by a shape with a higher height-to-width ratio so that the segments which join at the center could be shorter and more vertical.

The anomalous behavior exhibited by the leaning-arch concept has been described, and this is in contrast to the crossed arch which exhibited behavior that was expected and is well understood; that is, failure by wrinkling, as shown in Figure 44, leading to eventual collapse of the structure. This wrinkling occurred at approximately one meter from the end of the arch and started as a small crease which became a more pronounced wrinkle involving a greater part of the tube circumference as the load increased. A theoretical study of the wrinkling behavior of pressure-stabilized beams is presented in reference 8 and the load deflection curves given there have the same character as those found in this work and presented as Figure 32 throught 43. These load deformation curves show a gradual failure proceeding over many load increments and a period of time of 5 to 10 minutes. The deformation of the arches during failure remained in the plane of the arch all the way to collapse. The crossed-arch prototype in the collapsed state is shown in Figure 45 and the large bends can be seen in the arches at the location of wrinkling. Noting that this figure shows the crossed-arch concept and the position and direction of the large bends on opposite ends of an arch reveals that even in the collapsed state there is no out-of-phone deformation. It thus seems clear that the mode of failure was wrinkling and the absence of a rapid out-of-plane failure of the arches does rule out any possibility of stability failures.

Having established the failure mode for pressurized rib tents, the question naturally arises as to whether one of these tents can be made strong enough to resist the 479-N/m^2 snow load requirement placed on operational tentage. Examination of the test results in Tables 1 and 2 reveals that at the pressures used none of the tents met this requirement, although the crossed arch with 276-kPa inflation pressure achieved 86% of this requirement without collapse. Unfortunately, the inability of the tubes to withstand design pressure of 520-kPa prevented a demonstration of meeting this load-carrying requirement. However,

[8] Stein, Manual and John M. Hedgepeth; Analysis of Partly Wrinkled Membranes, NASA TN D–813, 1961.



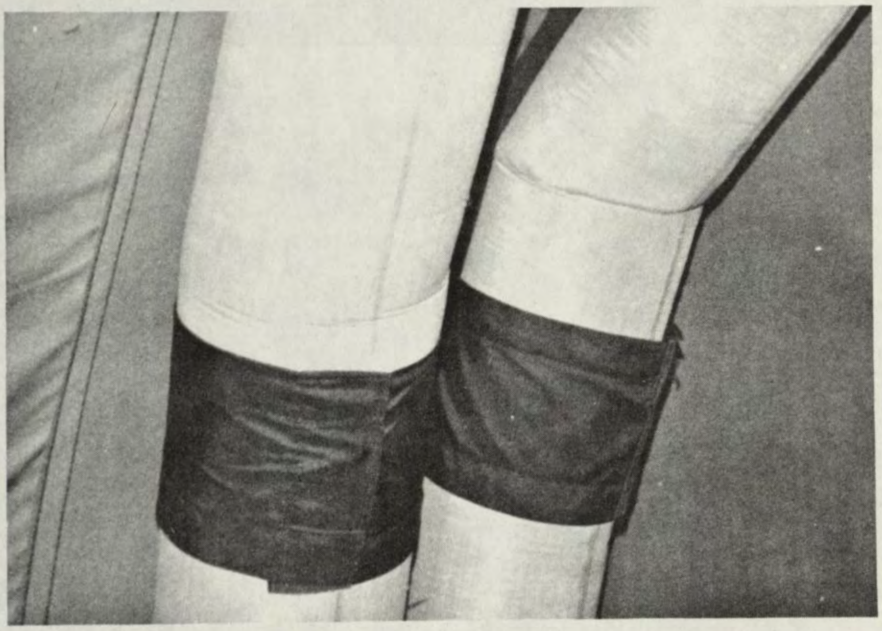


FIGURE 44. WRINKLING OF PRESSURE STABILIZED ARCHES UNDER LOAD.

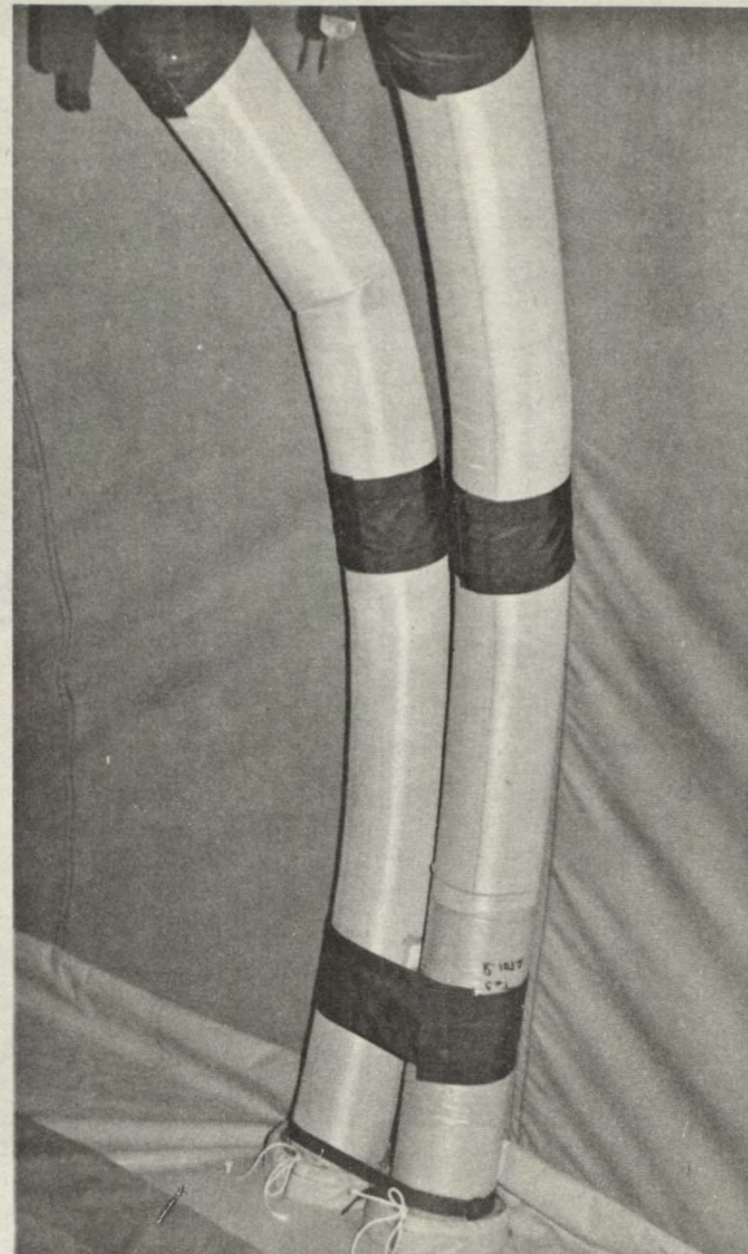


FIGURE 44. CONCLUDED.

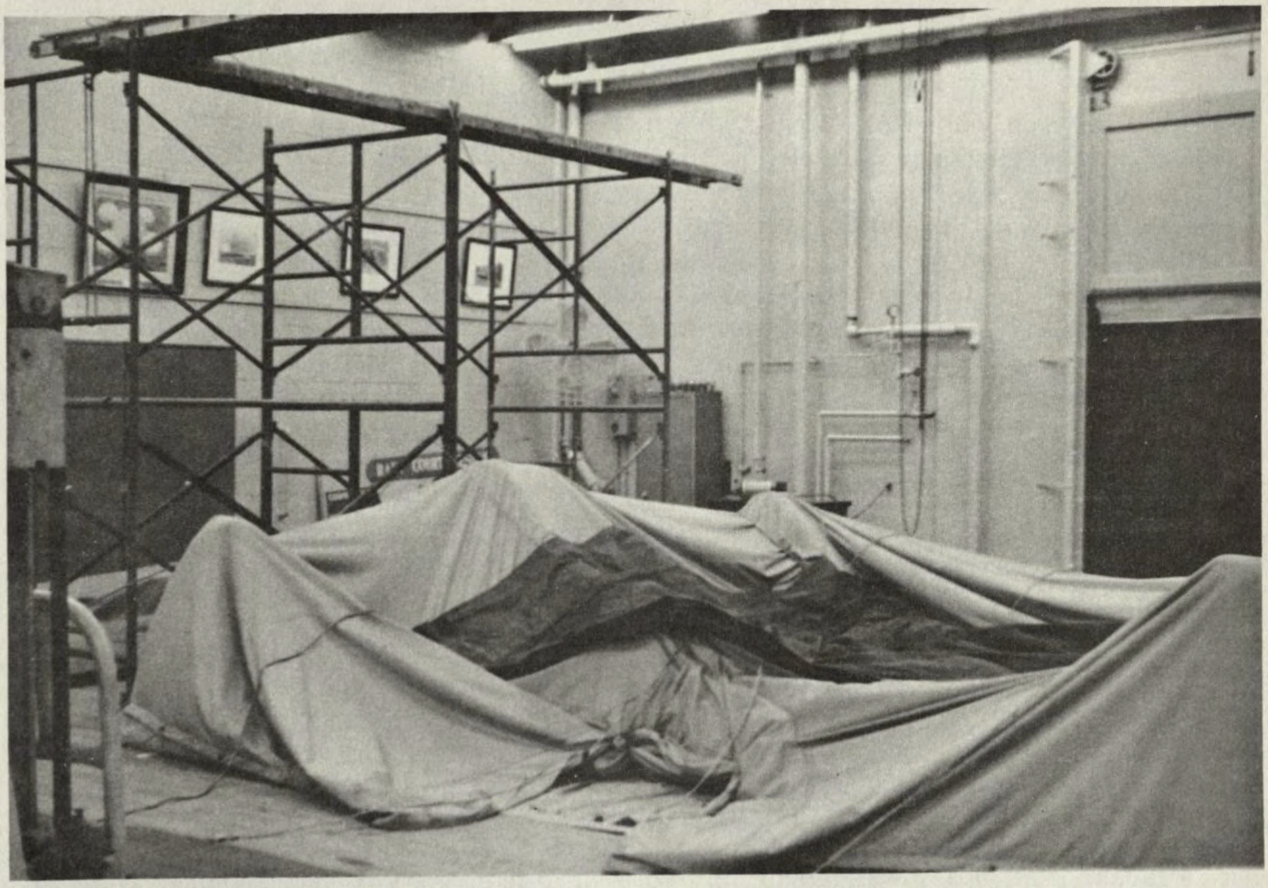


FIGURE 45. CROSSED ARCH PROTOTYPE TENT IN THE COLLAPSED STATE.

the data do confirm that strength increases with pressure, and if we assume that the strength increase is proportional to the increase in pressure, we find that the load requirement can be met with a pressure of 511-kPa for the crossed-arch concept and 307-kPa for the crossed arch with center arch modification. These extrapolations are based on the wrinkling loads cited in Table 2 for inflation pressures of 207-kPa. If we use the collapse loads at 207-kPa, then the inflation pressures needed to meet the snow load requirement are 376-kPa and 235-kPa for the crossed arch and crossed arch with center arch, respectively. Alternatively, we can use the strength data in Tables 1 and 2 for the two pressure levels of 138-kPa and 207-kPa to construct a linear extrapolation to estimate the pressure needed to meet the snow load requirement of 479-N/m^2. Doing this, we find that, based on the wrinkling loads, pressures of 420-kPa and 310-kPa are needed for the crossed arch and the crossed arch with center arch, respectively, while the extrapolation of the collapse loads gives estimates of the pressures of 320-kPa and 265-kPa. These pressure estimates are within reason and within the range that has been anticipated for this concept. It should also be pointed out that pressure increases are not the only means available to the designer to increase strength; also available are the options of increasing the tube radius or using more structure by using perhaps three modules instead of two over the 4.9-m length. These results show that it is possible to make a stable tent structure which will meet the Army operational snow load requirement. The work remaining is to develop techniques for fabrication of tubes capable of withstanding the pressures required and having sufficient air-retaining capability so that the tubes will remain inflated with only 10 to 15 percent pressure drop over a week's time.

CONCLUDING REMARKS

A program for testing alternative pressurized rib tent concepts under simulated snow loads to determine if a stable structure could be built has been completed and fully described. Included in this report is a description of the concepts, details of their fabrication and testing, and a description of the test results. These results demonstrate that the fabrication of a stable tent support structure using pressure-stabilized structural elements is possible and that with the aid of higher inflation pressure or other design alternatives a pressurized rib tent meeting the operational snow load requirements can be made. With an inflation pressure of 276 kPa the crossed arch concept achieved 86% of this snow load requirement. A comparison of the concepts at the same inflation pressure shows that the crossed arch concept with the center arch modification gave the best performance with regard to both minimizing deformation and load-carrying capability. The crossed arch concept with the center arch modification showed an anomalous behavior which should be understood and resolved prior to its use.

Much was learned regarding the fabrication of pressurized structural elements and this largely involved problems to be solved. With regard to the weaving of the curved arches the use of the three-dimensional weaving technique was successful and is thought to have been crucial in the successful completion of this investigation. There is, however, the unique strength problem associated with this procedure that needs resolution before higher pressures can be used. It also appears that the use of the three-dimensionally woven hemispherical end caps as end closures is a viable concept with the end caps adhesively bonded to the woven tubes. The remaining fabrication problem of greatest magnitude is the means of providing air retention. The use of the polymer film bladder worked satisfactorily in this testing context but the problem of film cracking needs resolution prior to its use in any end item tentage structure. The use of manually applied coatings was unsatisfactory and the use of such coatings will require the development of application techniques that will provide leak-free coating on the woven contoured tubes. What is really needed is the development of new techniques or the application of some existing technology to the air retention problem.

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8. Stein, Manuel and John M. Hedgepeth; Analysis of Partly Wrinkled Membranes, NASA TN D–813, 1961.

APPENDIX

EXPERIMENTAL LOAD–DEFLECTION DATA FROM SIMULATED SNOW LOAD TESTS ON PRESSURIZED RIB TENT CONCEPTS

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS LOAD—DEFLECTION DATA

Structural concept: Crossed Arch
pressure: 138kPa

Load N	Deflection, cm 1	2	3	
111.		0.3		
271.	0.3	1.6		
431.	0.9	2.7		
592.	1.6	3.8		
752.	2.5	4.8		
907.	3.2	6.2		
996.	4.1	7.6		
1160.	4.8	8.7		
1270.	6.0	10.0		wrinkling begun
1380.	6.7	11.9		
1490.	8.3	14.1		
1600.	9.8	19.2		
1760.	11.8	23.6		
1840.				collapse, rear section stayed up on collapse of front section

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS LOAD–DEFLECTION DATA

Structural concept: Crossed Arch
pressure: 207 kPa

Load N	Deflection, cm 1	2	3
111.	0.3	0.2	
271.	0.5	0.5	
431.	0.6	0.8	
592.	0.9	1.11	
752.	1.3	1.8	
907.	1.8	2.4	
996.	2.4	2.7	
1160.	2.9	3.0	
1270.	3.2	3.6	
1380.	3.8	4.0	
1490.	4.3	4.5	
1600.	5.1	5.1	
1760.			
1840.	5.6	5.6	
1920.	6.4	6.2	
2000.	6.8	6.5	
2080.	7.5	7.0	
2160.	8.3	7.9	
2240.	9.0	8.6	
2330.	9.5	9.4	
2420.	10.2	9.7	

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS LOAD–DEFLECTION DATA

Structural concept: Crossed Arch
pressure: 207 kPA

Load N	Deflection, cm 1	2	3	
2510.	10.8	10.5		wrinkling begun
2600.				
2680.	11.9	11.8		
2780.	12.5	12.4		
2890.	13.3	13.2		
3020.	14.9	15.1		
3100.	16.2	16.5		
3180.	17.8	17.9		
3260.	19.8	19.8		
3370.	24.8	25.6		
3480.	31.1	34.4		collapse

SIMULATED SNOW LOAD TESTS OF PRESSURIZED
RIB TENT CONCEPTS
LOAD–DEFLECTION DATA

Structural concept: Crossed Arch
pressure: 276 kPa

Load N	Deflection, cm 1	2	3	
890.	1.3	1.9		
1780.	4.4	4.4		
3590.	13.3	11.4		
4000.	15.2	13.9		
4890.	27.9	26.		
	29.2	29.2		after 60 min. delay
	29.8	29.8		after 120 min. delay
5340.	36.2	36.8		terminated without collapse

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS LOAD–DEFLECTION DATA

Structural concept: Crossed arch with Midspan Beam
pressure: 138 kPa

Load N	Deflection, cm 1	2	3	
111.	0.3	0.8		
271.	0.6	1.3		
431.	0.9	1.9		
591.	1.6	2.5		
752.	1.9	3.6		
907.	2.7	4.4		
996.	3.5	5.4		
1160.	4.1	6.0		
1270.	5.1	7.0		
1380.	6.0	7.6		
1490.	7.9	9.8		
1600.	9.5	10.8		wrinkling begun
1760.	9.8	12.1		
1920.	11.1	13.6		
2020.	12.4	15.2		
2140.	16.5	19.4		
2280.				collapse

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS LOAD–DEFLECTION DATA

Structural concept: Crossed Arch with Midspan Beam
pressure: 207 kPa

Load N	Deflection, cm 1	2	3
111.		1.6	
271.	0.2	1.6	
431.	0.6	1.8	
591.	0.9	1.9	
752.	1.6	2.2	
907.	2.2	2.5	
996.	2.5	2.7	
1160.	3.0	2.9	
1270.	3.8	3.3	
1380.	4.1	3.6	
1490.	4.6	4.1	
1600.	5.4	4.4	
1760.	5.7	5.0	
1920.	6.7	5.6	
2020.	6.8	6.0	
2140.	7.6	6.4	
2280.	8.4	7.1	
2360.	8.9	7.6	
2440.	9.2	7.9	
2550.	10.3	8.6	
2660.	11.1	9.2	

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS LOAD–DEFLECTION DATA

Structural concept: Crossed Arch with Midspan Beam
pressure: 207 kPa

Load N	Deflection, cm 1	2	3	
2800.	12.8	10.2		
2880.	13.3	10.8		wrinkling begun
3010.	14.8	11.6		
3120.	16.5	12.7		
3280.	20.6	14.0		
3380.	24.4	16.2		
3490.				collapse

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS
LOAD–DEFLECTION DATA

Structural concept: Crossed Arch with Center Arch
pressure: 138 kPa

Load N	Deflection, cm 1	2	3	
111.	0.3	0.2	1.1	
271.	0.5	0.6	1.4	
431.	0.6	0.9	2.1	
592.	0.8	1.3	2.5	
752.	1.0	1.6	3.0	
907.	1.3	1.9	3.6	
996.	1.6	2.2	4.3	
1160.	1.9	2.4	4.6	
1270.	2.2	2.5	5.1	
1380.	2.4	2.9	5.6	
1490.	2.9	3.2	6.2	
1600.	3.0	3.6	6.8	
1760.	3.3	3.8	7.5	
1920.	3.8	4.1	8.1	
2020.	4.1	4.4	8.4	
2140.	4.4	4.8	9.2	
2280.	5.0	5.2	10.0	
2360.	5.2	5.6	10.5	
2440.	5.7	5.7	10.9	
2560.	6.0	6.2	11.6	
2670.	6.7	6.7	12.5	60 min. break in loading

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS LOAD–DEFLECTION DATA

Structural concept: Crossed Arch with Center Arch
pressure: 138 kPa

Load N	Deflection, cm 1	2	3	
2800.	7.6	7.6	14.1	slight wrinkle in center arch
2880.	7.9	7.8	14.4	
3010.	8.3	8.4	15.2	
3120.	3.9	8.7	16.0	
3280.	9.4	8.9	17.0	
3390.	10.0	9.8	17.8	
3490.	10.6	11.0	18.6	
3570.	11.1	11.3	20.0	
3650.	11.6	11.9	20.5	
3730.	12.1	12.4	21.1	
3820.	12.7	13.3	22.4	
3910.	13.5	14.1	23.2	
3990.	14.0	14.8	24.3	
4070.	14.6	15.6	25.4	
4150.	15.6	16.8	27.3	
4230.	15.2	18.4	29.5	
4310.	19.2	20.6	30.6	
4390.	29.8	38.4	48.7	
4470.				collapse

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS LOAD–DEFLECTION DATA

Structural concept: Crossed Arch with Center Arch
pressure: 207 kPa

Load N	Deflection, cm 1	2	3	
111.	0.2	0.2	0.3	
271.	0.3	0.3	0.5	
431.	0.5	0.5	1.0	
592.	0.8	0.6	1.4	
752.	0.9	0.8	1.9	
907.	1.3	1.1	2.4	
996.	1.6	1.3	2.9	
1160.	1.8	1.6	3.2	
1270.	1.9	1.9	3.3	
1380.	2.2	2.1	4.0	
1490.	2.4	2.2	4.4	
1600.	2.9	2.9	5.2	
1760.	3.2	3.0	5.7	
1920.	3.5	3.5	6.4	
2020.	3.6	3.6	6.7	
2140.	4.0	4.0	7.2	
2280.	4.3	4.3	7.8	
2360.	4.4	4.6	8.1	
2440.	4.8	4.9	8.6	
2550.	4.9	5.2	9.0	
2660.	5.4	5.4	9.7	15 min. break in loading

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS LOAD–DEFLECTION DATA

Structural concept: Crossed Arch with Center Arch
pressure: 207 kPa

Load N	Deflection, cm 1	2	3	
2740.	6.0	5.9	11.1	
2850.	6.2	6.2	11.4	
2960.	6.3	6.4	11.6	
3090.	6.5	6.7	12.2	
3170.	6.7	7.0	12.5	
3250.	6.8	7.1	12.9	
3330.	7.0	7.3	13.2	
3440.	7.2	7.5	13.6	
3540.	7.5	8.3	14.3	
3680.	7.8	8.6	15.1	
3760.	7.9	8.9	15.4	
3890.	8.4	9.4	16.4	
4000.	8.7	10.0	16.5	
4160.	9.0	10.8	17.8	hint of wrinkle in center arch
4260.	9.5	11.1	18.6	
4370.	9.8	12.1	19.4	
4450.	10.5	12.5	20.2	
4530.	10.5	13.2	21.0	wrinkle in center arch
4620.	11.1	14.0	21.6	
4690.	11.8	14.4	22.5	
4780.	12.1	15.6	23.5	

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS LOAD–DEFLECTION DATA

Structural concept: Crossed Arch with Center Arch
pressure: 207 kPa

Load N	Deflection, cm 1	2	3	
4870.	12.5	16.0	24.3	
4950.	13.0	17.1	25.4	wrinkle in crossed arch at center
5030.	13.6	18.4	26.7	
5110.	14.3	19.4	27.6	
5190.	14.8	20.5	28.6	
5270.	15.4	21.1	29.5	
5350.	17.2	23.2	31.4	collapse
5430.				

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS
LOAD–DEFLECTION DATA

Structural concept: Leaning Arch
pressure: 138 kPa

Load N	Deflection, cm 1	2	3	
100.	0.6	0.3		
271.	0.8	0.8		
382.	1.4	1.1		
494.	1.7	1.4		
605.	1.9	2.2		
765.	2.8	2.8		
854.	3.3	3.3		
934.	4.2	4.4		
1010.	5.0	5.0		
1170.	6.1	5.8		
1280.	7.2	7.2		
1390.	8.1	7.8		
1520.	8.6	8.3		
1610.	9.7	9.4		
1760.	11.1	10.6		
1840.	13.3	12.8		10 min. break in loading
1920.	14.2	13.6		
2000.	15.6	15.0		
2080.	16.4	16.1		wrinkling of center rib
2160.	17.5	17.2		
2240.	18.6	18.4		

SIMULATED SNOW LOAD TESTS OF PRESSURIZED
RIB TENT CONCEPTS
LOAD–DEFLECTION DATA

Structural concept: Leaning Arch
pressure: 138 kPa

Load N	Deflection, cm 1	2	3
2320.	20.8	20.3	
2400.	24.2	23.1	
2480.	27.2	27.8	
2560.	30.9	32.8	
2640.	38.4	41.4	
2800.	39.8	43.9	
2950.	42.0	47.0	
3040.	46.4	51.4	
3150.	53.1	60.6	
3240.	68.1	72.0	
3330.	82.0	84.5	
3400.			collapse

SIMULATED SNOW LOAD TESTS OF PRESSURIZED
RIB TENT CONCEPTS
LOAD–DEFLECTION DATA

Structural concept: Leaning Arch
pressure: 207 kPa

Load N	Deflection, cm 1	2	3
160.	0.2	0.2	
271.	0.3	0.2	
382.	0.5	0.3	
494.	0.8	0.5	
605.	0.9	0.6	
765.	1.4	0.9	
854.	1.6	1.3	
934.	2.1	1.6	
1010.	2.4	1.9	
1170.	2.7	2.1	
1280.	3.3	2.7	
1390.	4.0	3.0	
1520.	4.1	3.2	
1610.	4.6	3.5	
1760.	4.9	4.1	
1840.	5.6	4.4	
1920.	5.9	4.6	
2000.	6.2	4.9	
2080.	6.7	5.2	
2160.	7.1	5.6	
2240.	7.3	6.0	

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS LOAD–DEFLECTION DATA

Structural concept: Leaning Arch
pressure: 207 kPa

Load N	Deflection, cm 1	2	3	
2320.	7.8	6.2		
2400.	8.3	6.8		
2480.	9.0	7.2		
2560.	9.4	7.6		
2640.	10.0	7.9		
2720.	11.75	9.0		10 min. break in loading
2800	12.2	9.5		
2880.	12.9	10.2		
2960.	14.0	10.5		
3040.	14.3	11.4		
3120.	15.7	12.4		
3200.	16.4	13.5		wrinkling begun
3280.	17.6	14.0		
3360.	18.2	15.1		
3440.	19.8	15.9		
3520.	20.2	17.0		
3600.	22.4	18.4		
3680.	24.6	21.3		
3760.	26.5	22.5		
3840.	29.4	26.8		
3920.	34.4	29.5		

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS LOAD–DEFLECTION DATA

Structural concept: Leaning Arch
pressure: 207 kPa

Load N	Deflection, cm 1	2	3
4000.	39.5	35.2	
4080.	43.3	37.2	
4160.	45.7	40.6	
4240.	49.7	43.5	

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS LOAD–DEFLECTION DATA

Structural concept: Leaning Arch with Center Arch
pressure: 138 kPa

Load N	Deflection, cm 1	2	3
160.	0.2	0.3	0.2
271.	0.3	0.5	0.2
382.	0.5	0.8	0.3
493.	0.8	0.9	0.5
605.	0.9	1.3	0.6
765.	1.4	1.6	0.9
898.	1.6	1.8	1.1
979.	2.0	2.2	1.6
1060.	2.4	2.4	1.8
1210.	2.8	2.7	2.2
1330.	3.3	3.0	2.7
1440.	3.8	3.2	2.9
1560.	4.0	3.3	3.3
1660.	4.6	3.5	3.6
1800.	5.1	4.0	4.3
1880.	5.7	4.1	4.6
1960.	6.2	4.4	5.1
2040.	6.7	4.8	5.6
2120.	7.0	5.1	5.9
2200.	7.5	5.2	6.4
2280.	7.8	5.4	6.7

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS LOAD–DEFLECTION DATA

Structural concept: Leaning Arch with Center Arch
pressure: 138 kPa

Load N	Deflection, cm 1	2	3	
2360.	8.4	5.7	7.1	
2440.	9.0	5.9	7.3	
2520.	10.0	6.2	8.4	
2600.	10.6	6.7	9.0	
2680.	12.2	7.3	10.3	
2760.	13.5	8.1	11.4	5 min. break in loading
2840.	14.0	8.4	11.8	
2920.	14.4	8.6	12.2	
3000.	15.4	9.2	13.2	
3080.	17.9	9.8	14.8	
3160.	20.5	11.4	17.3	
3240.	23.6	12.2	19.4	
3320.	26.7	13.2	21.4	
3400.	32.9	14.4	24.9	
3480.				collapse caused by rotation of end of arch in rear corner

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS LOAD–DEFLECTION DATA

Structural concept: Leaning Arch with Center Arch
pressure: 207 kPa

Load N	Deflection, cm 1	2	3
160.	0.2	0.2	0.0
271.	1.6	0.3	0.2
382.	0.8	0.5	0.3
493.	0.9	0.6	0.5
605.	1.1	0.9	0.6
765.	1.4	1.3	0.9
898.	1.6	1.4	1.1
979.	1.9	1.7	1.4
1060.	2.1	2.1	1.7
1210.	2.5	2.2	1.7
1330.	2.9	2.7	2.1
1440.	3.3	3.0	2.4
1560.	3.2	3.2	2.7
1660.	4.0	3.5	3.0
1800.	4.4	3.8	3.3
1880.	4.8	4.0	3.5
1960.	4.9	4.1	3.8
2040.	5.2	4.4	4.1
2120.	5.9	4.6	4.6
2200.	6.4	4.9	4.9
2280.	6.8	5.1	5.2

SIMULATED SNOW LOAD TESTS OF PRESSURIZED RIB TENT CONCEPTS LOAD–DEFLECTION DATA

Structural concept: Leaning Arch with Center Arch
pressure: 207 kPa

Load N	Deflection, cm 1	2	3	
2360.	7.1	5.4	5.4	
2440.	7.6	5.6	5.7	
2520.	7.9	5.7	6.0	
2600.	8.4	6.2	6.5	
2680.	9.0	6.7	7.0	
2760.	8.7	6.4	6.7	5 min. break in loading
2840.	9.0	6.5	7.0	
2920.	9.4	6.7	7.3	
3000.	10.3	7.0	7.8	
3080.	10.6	7.5	8.3	
3160.	11.4	7.9	9.0	
3240.	12.9	8.7	10.0	
3320.	14.9	9.5	11.3	
3400.	17.3	10.5	13.5	
3480.	21.8	11.8	16.0	
3560.	30.6			

SIMULATED SNOW LOAD TESTS OF PRESSURIZED
RIB TENT CONCEPTS
LOAD–DEFLECTION DATA

Structural concept: Arch and Purlin Concept
pressure: 69 kPa

Load N	Deflection, cm 1	2	3	
116.	0.6	0.3	0.3	
232.	0.6	1.6	0.6	
348.	1.3	3.8	2.5	
464.	1.9	5.1	2.9	
580.	2.5	5.7	3.2	
696.	2.9	6.7	5.1	
812.	3.2	17.2	10.5	
928.	8.9	29.2	33.0	collapse