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A study of tensile architecture

by

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To J.L.P, J.L.P, & J.M.P.

P.T.L.

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SCOPE OF STUDY

Modern fabric tensile architecture, for all intrinsic purposes, had its beginning in the genius of Frei Otto. Otto's studies, writings, and structures of the 1950's and 60's formed the foundation on which future designers and architects based their designs. The basis of this study is founded upon that genius and provides the starting point for further exploration. Following is the sequential procedure used to study tensile structures and architecture.

In order to reinforce the concepts of tensile architecture, the studies (i.e., basic anticlastic curve models and soap film models) of Frei Otto were duplicated to experience first-hand the building blocks on which tensile architecture is shaped. In conjunction with the models; the writings and projects of architects, designers and engineers active in the industry were reviewed to further develop the understanding of tensile architecture. Finally, the acquired knowledge was utilized in the design of several projects employing the concepts of tensile architecture.

This study was not intended to influence the tensile architectural field. It is premature for such an undertaking. The only purpose was to take the first step; to gather information on the subject then use the knowledge as a spring board in presenting significant contributions for the advancement of tensile architecture.

DEFINITION OF FABRIC TENSILE STRUCTURE AND ARCHITECTURE

Structures are means for transmitting forces and moments. Structures are classified according to the type of stresses, tension, compressive and bending, acting on them. Structure is also characterized by its supporting system, line, surface, and three-dimensionality. Every structure can also be evaluated according to whether or not it is prestressed. Fabric tensile structures use prestressed tension-loaded surface support systems to transmit forces and moments. The Recommended Code Provisions for Architectural Fabric defines fabric tensile structures as "a non-pressurized architectural fabric structure wherein the membrane is prestressed and the structural support system includes cables and/or rigid elements to help develop and maintain the structural form." Tensile structure is also known as tension structure, and tensioned membrane structure.

Tensile architecture is the manipulation of a structural form to produce aesthetically pleasing environments and shapes.

INTRODUCTION

Justification

In years past, fabric structures were perceived to be temporary, not a viable material for permanent structures even though fabric had been proven durable. Recently, economical issues have forced architects and owners to reconsider the use of fabric. Slowly, the value of fabric is becoming apparent, for the material has gained acceptance as a permanent building material. The future of fabric appears to have an unlimited potential.

Peter McCleary, Dean of Graduate Studies at the University of Pennsylvania, has published a study examining the development in building forms from compression to bending and beyond. For example, compression aided in the creation of the Roman structural walls and vaulted ceilings, beams became stronger eventually evolving into slabs, and columns became less intrusive. The next logical step, as deduced by McCleary, is that of building forms produced by tension. There are a growing number of architects, designers, and engineers who concur with McCleary. In the process of this discourse, the individual can draw his/her own conclusion from the current evidence available.

Advantages/Disadvantages

Aesthetics

Fabric tensile architecture, and for that matter all tensile structures, are unique from most conventional structures. With conventional structures the form is determined first then the structural system is shoehorned in place. But with tensile architecture, the form is derived from the structural system; the two can not be separated. Thus, with fabric structures not only are the form and structural system integrated, but all aspects of fabric structures are a whole, and they also cannot be separated. With the inherent qualities of fabric the designer needs to be aware of lighting, mechanical, and sound control requirements from the conception of the design.

The fabric membrane is both form and structure, both structure and enclosure, and both external expression and internal sense of space. As a result, the sculpturous form produced can not be matched by conventional construction systems. This Gestalt effect that intrigues architects and engineers and awes the public. As stated by FTL's Todd Dalland, "Walking beneath a tensile structure is an emotional, sensual experience" (Rebeck, 1990b, p.25).

Lighting

The fabric can be translucent. So, during the daylight hours the space below the structure is flooded with soft, diffused light. This is unlike the light allowed by glass skylights which is harsh, has severe shadowing, and glare. Due to the fabric's transparency, a person can decipher the weather beyond the enclosure. The sun can be seen filtering through the fabric, the rain can be heard hitting the fabric, and, in some cases, the clouds can be seen passing by. As one designer states, the atmosphere produced is "mediterranean" in quality (Cook, 1990b, p.27). The amount of translucency of the fabric can be adjusted from virtually 0% to 100% depending on the type and thickness of fabric and whether or not an insulating layer is used. On the practical side, during the daylight hours less artificial lighting is required to illuminate an area, thus rendering energy and cost savings. During evening hours the fabric can be used as a reflector for indirect light bathing the area with soft light and at the same time illuminating the fabric to become an advertising beacon in the night.

Mechanical

The normal light colored fabric reflects heat which makes it ideal for hot climate areas. At the Haj Terminal in Saudi Arabia the designer used fabric structures to produce an artificial forest in the middle of the desert. Outside the temperature could be 130°F but under the canopies the environment is pleasant. When the structure is enclosed this quality can also produce significant energy and cost savings during the cooling cycle. During the heating cycle, though, energy would be lost through the fabric unless an insulating layer was installed (Huge, 1983).

Sound Control

A more detailed analysis of the acoustical properties of fabric is discussed in another section of this report.

Economy

Fabric structures were originally developed as low cost shelters for sporting events and exhibitions. It is at those large scale projects that fabric structures have proven to be the most economical material. Actually, the only competition to fabric structures is other types of fabric structures. During the bidding process, several owners requested that quotes be given for both cable-supported and air-supported systems. The statistical results determined that these systems cost virtually the same. On the Haj Terminal the entire 4,725,000 sq.ft. area was constructed for $17.50/sq.ft. (1981 cost) including the fabric and support system (Tent, 1980). For large domed stradia, like the Georgia Dome or the Suncoast Dome, the use of fabric makes economical sense.

For smaller structures, however, fabric is more expensive than conventional steel-framed construction. This is due, in part, to the specialized technology and engineering required to construct a fabric tensile structure. In order to be competetive with conventional construction the span of the area being covered would have to be greater than 100 to 120 feet(Rebeck, 1991a, p.31). Another cost saving factor would be the repetitive use of components. It is less costly to produce ten of one item than it is to produce one of ten items. As the fabric industry becomes more acceptable in construction, the cost will probably become more competitve.

Construction Time and Fabrication

Fabric structures require less time to install. Again at the Haj Terminal the entire 4,725,000 sq.ft. complex was constructed in 29 months. With each 21-unit module (150 ft x 150 ft) taking only 45 days to erect (Tent, 1980). This is considerably less than that which would be required to construct a conventional structure of the same size.

Also, fabric can be prefabricated in controlled factory conditions in lieu of unpredictable site conditions. Therefore, a higher quality of assemblage at a lower cost can be maintained.

HISTORY, KEY DESIGNERS AND KEY PROJECTS

Predecessors

Modern fabric tensile structures as demonstrated by the current works of the San Diego Convention Center or the Georgia Dome, had its beginning with Frei Otto and his work on the German Pavilion at Montreal in 1967. But before examining this work of Otto's or any other designers who may have followed him, a review of the background which leads up to the genesis might be beneficial. A thorough account of the developments, inventions, and projects which contributed to the growth of tensile architecture was compiled by Philip Drew in his book Tensile Architecture. It would be appropriate to briefly and selectively highlight the influences which directly affected the invention of the modern fabric tensile architecture.

Two distinct prototypes are forerunners to modern tensile architecture; the suspension bridge and the fabric tent. The suspension bridge, unfortunately, was the primary influence on early tensile structures. Influenced by the technology of suspension bridges only, designers were restricted to the limited vocabulary of the structural form which was implied by bridges, thereby hindering transition to the tensile architecture of today. Although nomadic tents represented a tensile surface system which could be easily translated into a system of modern fabric tensile structure, technology remained relatively undeveloped until recently.

The idea of suspension was proposed by C.J. Loscher in 1784. Povet, in 1821, designed a bridge based on the idea followed by Albert Bridge over the River Thames in 1873. From this technology, the earliest tensile building was developed in the early nineteenth century. The first tensile buildings incorporated only tensile roof systems as designed by Bederich Schnirch in Czechoslovikia (1824-26) and Naval Arsenal at

Lorient, France, in 1840. In 1858, Godrey Rhodes wrote a history of tents, Tents and Tent Life, From the Earliest Ages to the Present Time, (1858). Another early example of tensile building was V.G. Shookhov's All-Russian Exhibition in Nijny-Novgorod in 1896. Following this, few tensile structures were built until the early 1950's.

In 1952, Matthew Nowicki by designing the Raleigh Arena, in North Carolina, with an anticlastic curve roof firmly established the era of surface tension architecture. Although the roof structure was not fabric, the type of support system had a crucial influence on the later fabric structures of Frei Otto, Horst Berger, and Kent Hubbel to name a few.

Key Designers

Frei Otto

Frei Otto's approach was to develop a technique to provide building stability while reducing the material mass hence counteracting the superimposed loads. In most conventional systems, the material weight of the building usually exceeds the superimposed loads. Otto's vision was to produce structures of extreme lightness as well as extreme strength. He developed this concept by focusing the utilization of tensile stresses instead of the normal compression forces common to conventional buildings. Thin cables with synthetic fabric membranes were placed in tension and formed in specific shapes to distribute the superimposed load through the grounded anchors. After many years of experimental and analytical studies, Otto formed the theory of minimal surfaces. This contribution to the fabric tensile structure industry can not be overstated. Many, if not all, within the industry today have been influenced by Otto's genius.

Frei Otto started his formal study of architecture in 1947 at the Technical University in Berlin. During a student exchange in the United States in 1950, he was introduced to

Eero Saarinen and Fred Severud. At that time Severud was consulting with Matthew Norwicki in the design of the Raliegh Arena. Evidence of the American experience appeared when Otto returned to Berlin. As part of his studies Otto designed a suspended roof for a chapel project and wrote a doctoral thesis on suspended roofs.

In succeeding years, he researched and developed various types of tension structural system including prestressed fabric tensile structures. Starting in 1955, Otto produced a series of light canvas tent structures for the Federal Garden Exhibitions, the Interbau Building Exhibition, and the International Horticultural Exhibition. Of note are the Federal Garden Exhibitions in Cologne and Berlin; both in 1957. In these structures Otto introduced a variety of inventions such as arch-supported membranes and humped and undulating surfaces. Following these designs, Otto produced several diverse projects including pavilions and convertible roofs. One convertible roof of note, designed in collaboation with R. Taillibert in 1965, was placed over a terrace at the Palm Beach Casino, Cannes, France. Otto had been studying convertible roofs since 1960 but it wasn't until the Palm Beach Casino that Otto was able to utilize this knowledge.

It was at Montreal in 1967 that modern prestressed tensile surface structures reached maturity with the completion of Otto's German Pavilion. The project was characterized by an anticlastically curved prestressed cablenet suspended from masts of varying heights which were pulled down at restraining points and bounded by edge cables. In this project the full benefit of fabric tensile structure was realized and it subsequently became a major influence on the design of tensile structures which followed.

After the success of the German Pavilion, Frei Otto produced the main stadium and arena roofs for The XX Olympic Games at Munich in 1972. Not a significant advancement beyond the Montreal achievement, but the Munich project was considerably larger. Otto continued to create designs until 1981 with the design of the sports hall in Jeddah, Saudi Arabia. Below is a partial list of his projects.

Because of his tireless efforts, Frei Otto has been deemed the pioneer of fabric tensile architecture. His contributions influenced the designers, architects and engineers of his time and continues to inspire professionals in the field today. His accomplishments and genius can not be overstated (Cook, 1991e; Glaeser, 1972; Otto, 1967).

FREI OTTO (1925-)
(Partial List of Projects)

1957	Cologne Garden and Berlin Interbau Exhibitions
1958-70	Lectured at universities in the United States and several in Germany, including the Hochschule für Gestaltung in Ulm
1963	Swiss National Exhibition at Lausanne
1963	Pavilion for flower shows in Hamburg
1965	Variable shifting roofs in theaters in Cannes and in 1967 in Hersfeld
1967	German Pavilion at Expo '67 at Montreal, Canada
1967	Roofing for sports facilities and open-air theaters including one in Wunsiedel, West Germany
1968	Sports center in Kuwait with Kenzo Tange
1968-72	Hotel and conference center in Mecca, Saudi Arabia, with Rolf Gutbrod
1970	Year 'round swimming pool at Regensberg
1970-71	City in the Arctic
1971	Museum of Modern Art exhibit of his work, revived in 1975, 1977 to tour Europe, America, and Asia
1972	Shadow in the Desert
1972	Olympic stadiums in Munich, Germany
1975	Multiple Purpose Hall of the National Garden Show in Mannheim with Carlfried Muschler and Partners
1978	Council of Ministers hall in Riyahd, Saudi Arabia, with Sir Ove Arup and Rolf Gutbrod
1980	Munich Aviary, 1980
1981	Sports hall in Jeddah, Saudi Arabia

Horst Berger

Horst Berger is a structural engineer who has designed some of the world's most notable fabric structures. Berger's studies began at the University of Stuttgart where he majored in engineering rather than architecture thus providing an "objective approach." Berger's interest led him to concrete shell structures and other three-dimensional forms. His first job was in the bridge department of a West German engineering firm. In the following years, Berger moved to New York to work for Severud Associates. In 1968, Berger and David Geiger formed Geiger-Berger Associates. Geiger designed air-support roofs for projects like the Pontiac Silverdome and the Minneapolis Metrodome. Berger's interests were in cable-supported structures of which the Haj Terminal and the Riyadh Stadium were the most prominent. In 1983, Berger and Geiger separated to form their own engineering firms. But during his tenure at Geiger-Berger, Berger produced or consulted on fabric tensile structures for the Bullocks San Mateo Store, Harbor Place, University of Florida's Student Center, Tennessee State Amphitheatre, Queeney Park Pavilion, Crown Center Square Pavilion, and Sea World.

After Berger formed his own firm, Berger and his employees produced or consulted on numerous projects including a retractable roof for the City of Phoenix, the San Diego Convention Center, Knott Athletic Recreation/Convocation Complex, Cynthia Woods Mitchell Pavilion, and the Denver International Airport. Tensile structures were Horst Berger's obsession and passion.

Kent L. Hubbell

Kent Hubbell is relatively young compared to the other influential architects in the fabric tensile structure industry since he is only forty-six. He was a young man when fabric tensile structures were one of architecture's hottest new concepts. As a student at Cornell University, he became interested in the work of Frei Otto and did his thesis on this type of building. After graduating from Cornell in 1969, Hubbell went on to get an MFA from Yale in sculpture. Later he became an instructor at Cornell enlightening his students on the benefits of fabric structures.

Currently, Hubbell is the chairman of the architecture program at the University of Michigan, but still practices architecture through his firm. Some of the projects on which Hubbell is working or has completed, are the Grand Rapids Symphony Pavilion, Northgate Transit Center in Seattle, Chene Park Performance Center, and the Proctor & Gamble Performance Pavilion (Rebeck, 1990e).

FTL (Todd Dalland and Nick Goldsmith)

FTL is committed to the benefits inherent in fabric tensile structures. They believe that "fabric is well-suited to an age of rising energy costs and the scarcity and impracticality of heavier materials" (Rebeck, 1990b, p.22). Actually, FTL is predicting a greater relationship between structures andmaterials of which fabric tensile structures are a prime example. Goldsmith calls it "a pure building - an edifice where structure and material are as perfectly integrated as human technique will allow" (Rebeck, 1990b, p.22). "All the functions of a building - structure, lighting, engineering, and so on - are designed together rather than separately" (Rebeck, 1990b, p.22).

FTL has been producing "pure buildings" since 1978. They have worked with various well-known architects, most recently with Michael Graves, but have also worked on projects where they were the sole designers. Some of their projects include the interior fabric structures of the Dolphin Hotel at Disney World and the Pier 6 Music Pavilion at Baltimore which replaced a temporary fabric tensile structure originally designed by them. FTL has even produced tensile structures for lights and workstation lighting. Other projects which FTL lists among their accomplishments are Hoboken Ferry Terminal, a traveling performance space for joint use by the New York Philharmonic, the New York Metropolitan Opera and the City of New York.

FTL is collaborating with Peter McCleary in writing a study which traces the evolution of building forms mentioned earlier in this thesis. For McCleary, the next logical step could be forms in tension, which is where FTL is positioning themselves. As Dalland and Goldsmith suggest, "The beauty of fabric tensile structures is that they connect and unify inner and outer worlds, working with nature instead of trying to subdue it. Call it a relaxation through tension" (Rebeck, 1990b, p.25).

Other Notable Designers, Architects and Engineers

Harry Daugherty is an engineer who worked for Owens-Corning Fiberglas Corporation. He started with Owens-Corning in 1970. In 1976 he was selected to help start a fabric structures division. The fabric structures division's purpose was to manufacture patterns and install fabrics. Daugherty is intrigued with fabrics stating, "It's a kind of building system that stretches your mind, opens the door to all sorts of creative possibilities, it taxes your mental capacity; it requires so many skills, such as visualizing curved surfaces in space; it's a very interesting line of work to be in because you never see the same thing twice, and every time you do one, you are breaking into new technology" (Cook, 1991b, p.34).

Some of the key projects in which Daugherty has been involved include the Tennessee State Pavilion at the U.S. World's Fair in 1982; B.C. Place Amphitheatre, Vancouver, British Columbia; African Controlled Environment Structure at the Asheboro Zoo, Asheboro, North Carolina; Field House at Radford College, Radford, Virginia; Amphitheatre at Grand Traverse Resorts, Traverse City, Michigan; Skylight, East Towne Mall, Knoxville, Tennessee; and 163rd Street Mall and The Richards Building, both in Miami, Florida (Cook, 1991b).

Eberhand Zeidler, a partner in the architecture firm of Zeidler Roberts Partnership, is another proponent of the use of fabric in architectural designs. "Fabric can now adapt to anything you need it to in terms of heat, cleaning, sound - all issues can be resolved," Zeidler says. His first fabric tensile structure was the Ontario Place. Since then Zeidler has used fabric for Canada Place, Ontario Pavilion, Sherway Gardens, and yet to be constructed, Pearson International Airport, Toronto, Canada (Cook, 1990b).

"That we wouldn't have structures; we'd have force fields that would prevent entry of weather and really you could almost say that membrane structures are like that because they're so lightweight and they carry the forces through them in such a pure way - they're really a science fiction entity that's come true" (Cook, 1992d, p.35). Such exaggerated fantasy is that of David McCready. McCready along with Robert Barrow founded Space Tech PTY Ltd., an Australian firm involved in design, engineering, development, manufacture, and erection of space frame systems and lightweight membrane structures. Their projects include Keysborough Golf City, Phillip Island Penguin Reserve, and Shell Westgate South Side.

Additional credit, even though brief, should go to the efforts in the fabric industry by Bill Murrell and Gerald Larson. Bill Murrell (Cook, 1991f) is a designer of fabric structures though the majority of his designs are air-supported. Murrell is a strong supporter and promoter of fabric structures. Gerald Larson (Cook, 1992b) taught an independent study course about tents during his tenure at the University of Cincinnati. This humble beginning grew into a network of cooperative education programs between students and members of the fabrics industry.

Key Projects

Several outstanding projects were critical in the development and promotion of the technology. The most influential project was the previously discussed German

Pavilion by Frei Otto. Other projects were the Haj Terminal in Saudi Arabia, and the San Diego Convention Center.

The Haj Terminal (Armijos, 1991b) was commissioned to accommodate the 80,000 pilgrims traveling to Mecca for the Hajj season. In order to handle that number of passengers arriving at the same time the terminal had to be huge - an area of 4,725,000 square feet. The terminal was divided into two separate terminal units, each comprised of five modules of 21 tent units. Each tent unit consisted of 150 feet on a side, such that each terminal unit was 1,050 feet x 2,250 feet. Each tent unit consisted of four 148 foot high pylons at the corners with the fabric secured to the pylons at the 65 foot mark. The fabric extends to 115 feet high at which point it is gathered together by a steel ring. This ring is supported by cables from the top of the pylons. To adjust for thermal changes caused by the 130° F. temperature of the desert the openings in the fabric at the supporting steel rings were left open to allow the warm air under the roof to escape. Even on the most critical days, the temperature under the canopies was cool, breezy and pleasant.

Another key project was the San Diego Convention Center (Landmark, 1989). A number of observers described the Center as "a landmark", "a show piece", and "San Diego's equivalent to the Sidney Opera House." This assessment might be premature, but there is no doubt that the Center has been influential in the advancement of the design of fabric structures. The tensile fabric roof covers 90,000 square feet of exhibit area and spans 300 feet. The roof is held aloft by a series of cables spanning between concrete fins that line the area. Some of the cables carry two columns (or flying poles) which lend support to the roof's 12 peaks. At the end of the structure, the roof is cantilevered beyond the last set of fins by a horizontal floating strut which runs the full length of the roof. Along the center spine of the roof, a series of openings were placed to release warm air. This is similar to the technique employed at the Haj Terminal. To protect the openings from rain, a second fabric panel spaned across the two rows of peaks.

This fabric roof allowed the designer to create 90,000 square feet of additional exhibit space at minimal cost, and gave the building a distinct appearance. Whether the building advances to Opera House status remains to be seen, but if achieved, it will do so on the laurels of the fabric roof. The factor which made these projects a key to the design type is the reaction which they received from designers, architects, and engineers. The Haj Terminal drew a lot of attention because of its sheer size. The Convention Centerwas in a large population center. Both projects were impressive examples for the promotion of fabric tensile structures. Other renowned projects are: the Pier 6 Concert Pavilion, the Georgia Dome, the Suncoast Dome, the Denver International Airport, and the Canada Place.

COMPONENTS AND PERFORMANCE OF THE SYSTEM

General

Like any building, fabric tensile structures have loads acting on them which must be taken into acoount. The two major loads acting on a tensile structure are snow load and wind load. Snow loads act downward, while a wind load pulls and pushes the structure upward. Wind loads act on the structure laterally across the top or, if the structure is open-sided, up from below. Determining the value of the loads and design of the connections and foundation is the responsibility of the engineer who should be versed in tensile structure. The designer or architect should produce a design in close contact with the consulting engineer for appropriate detail of the connections.

Unlike typical post and beam structural systems, tensile structures depend on a curve rather than a plane. Not only does the curve give tensile structure its distinctive form but also its structural integrity. The basic building block for tensile structure is the anticlastic shape of the hyperbolic paraboloid and the hyperboloid. Anticlastic shapes are basically double-curved with the curvatures opposing each other from a single intersecting point (Otto, 1967).

Fabric tensile structures can be divided into four components: the support system, fabric membrane, fabric attachment, and anchoring.

Support Systems

The support system is the means of maintaining the structural form. The support could be a pole, or a beam or a frame or point hung from a mast or the like. The support system could even be a combination of several different supports--a hybrid.

Harry Daugherty, P.E., an engineer and a fabric tensile structures consultant, identifies four families of fabric structures morphology; the cross arch, the folded plate, the radial folded plate, and the cone (Daugherty, 1992).

The cross arch utilizes arched frames spanning the diagonal of a rectangular or square opening. Then the fabric membrane is stressed over the frame and secured at the perimeter. The result, from below, is a vaulted arch ceiling. Several shopping malls have used this system in lieu of glass skylights to allow light without the glare into the mall's court: The Fort Worth Town Center, and the John A. Sibley Horticultural Center in Pine Mountain, Georgia are considered good models of the cross arch.

Folded plate structure is distinguished by high peaks and low valleys with a clear definition of each fabric panel. The ridges and valleys are in parallel series. This morphology produces the appearance of sails as seen on the San Diego Convention Center or the Canada Harbour Place in Van Couver, British Columbia.

The radial folded plate is similar to the folded plate except the ridges and valleys are not parallel but radial about a common center point. The Riyahd Stadium in Saudia Arabia demonstrates this family of morphology as does St. Petersburgh, Florida's Suncoast Dome.

Cones feature some sort of center mast or pole with guy-wire anchoring cables. A good example of this form is the Haj Terminal in Saudia Arabia. Comparatively smaller projects, but still important are: Kings Wood Amphitheater in Ontario, Canada; Sherway Gardens in Etobicoke, Ontario, Canada; and Frie Otto's Federal Garden Exhibition at Cologne.

The designer is not restricted to using these morphologies in their purest sense. On the contrary, these forms are merely starting blocks in the designer's search for inventive and imaginative designs. Some of the most intriguing designs exploding from this inventiveness were the Expo '90 Mitsui-Toshiba Pavilion in Osaka and the Expo '85 Suntory Exhibit Pavilion in Tsukuba, Japan. At the Mitsui-

Toshiba Pavilion the fabric membrane was supported by a series of point hung connection cables to surrounding space frames. The result was a form resembling a sphere. The Suntory Pavilion produced a dome shaped by the same method as the Mitsui-Toshiba Pavilion but the space frame is on the interior.

There are numerous examples of inventive form making and support systems. Two projects which broke new ground are the Georgia Dome in Atlanta (Rebeck, 1992a) and the Suncoast Dome in St. Petersburg (Rebeck and Campbell, 1990). With the apparent demise of air-supported structures, large domed stadia are using cable supports to keep the fabric aloft. Both domes use a concept developed by Buckminister Fuller. Fuller defined his concept, termed tensegrity, in this manner, "islands of compression reside in a sea of tension." The concept featured discontinuous compression elements and continuous tension members. On the Georgia Dome the fused triangular panels are tensioned using cables. These cables also hold aloft a series of three concrete "tension rings." Each ring, along with the cabling, support numerous steel support posts that provide upward compression. The posts support the roof but don't reach the ground. Instead the loads are taken up by the cable which transfer the load to the ground. This allows for an unobstructed view by every spectator.

On the Suncoast Dome (Rebeck and Campbell, 1990), David Gieger, project engineer, utilized a cable truss, which he invented, to support the roof membrane. The primary structure consists of perimeter compression ring beam, concentric tension hoops, diagonal and ridge cables, compression struts, and a center tension ring. The compression struts are arranged in concentric rings. The bottom of each ring of struts is connected by a tension hoop. The hoops and struts are "hung" from the tops of the adjacent struts by diagonal cables and so on until the loads are transferred to the perimeter compression ring beam.

Fabric

Architectural membranes may be divided into four groups: films, meshes, laminated fabrics, and coated fabrics. These groups represent the definitions adopted from V. William Murrell's article (Murrell, 1990).

Films are polymers supplied in sheet form, which are not laminated or coated. Examples include clear vinyl, PVF (polyvinylchloride), mylar TM, polyethylene and PTFE (polytetrafluoretheylene - e.g., teflon). Films are not as expensive as textiles but are limited in strength, stiffness, and durability.

Meshes are porous fabrics available as polyester weaves coated with vinyl or as knitted fabrics using high-density polyethylene, polypropylene or acrylic yarns. Meshes are relatively inexpensive but are not waterproof so their use is limited.

Laminated fabrics combine films with meshes to create the least expensive architectural fabric capable of long-term structural service. Laminates usually consist of vinyl films over woven or knitted nylon or polyester meshes. The lightest laminates, 6-8 ounces per square yard, are commonly used as acoustical and thermal liners suspended on the interior of an architectural fabric structure. Tents, awnings, and lower-cost tensile structures use laminates in the 12-18 ounce range. Air-supported structures and permanent tensile structures typically require 20-26 ounce fabrics with tedlar on PVDF finishes. The expected life-span of this laminated fabric is 15 to 20 years.

Coated fabrics typically use high-count, high-tensile base fabrics coated with a bondable substance for extra strength. There are four kinds of base fabrics; polyester, nylon, aramid, and fiberglass. Polyester is the most commonly used fabric because it has the best combination of strength, durability, cost and low elongation. Nylon is more durable and stronger but is more expensive and elongated. Aramid has extremely high yarn strength and low elongation but is susceptible to mechanical and UV damage. Fiberglass is less expensive than aramid but is more susceptible to mechanical damage (creasing or abrasions incurred during the manufacturing fabrication or installation process). Fiberglass, like polyester, can last 15 to 20 years in exterior application.

New membranes evolve at a constant rate in order to improve the system's performance. A new fabric that recently entered the market is Tenar, a 100 percent fluoropolymer material from W.L. Gore & Associates. The material is inert to UV radiation, acid rain, and combustion, and promotes an unsubstantiated claim of unlimited flex life.

To determine the best balance of strength, economy, and permanence of the tensile structural system for a specific project, several aspects of the project are considered. These aspects include: proposed dimension of the structure, service life, type of occupancy, budget, local code requirements, and desired sight lines. Also, property requirements also help determine the appropriate fabric for a certain application (Tables 1,2,3,4).

Useful properties of fabrics are (Daugherty, 1992):
- strip tensile strength
- grab tensile strength
- trapezoidal tear strength
- adhesion strength
- flame resistance
- finished weight
- base fabric weight
- coating material
- base fabric material
- special top coating available
- resistance to cold cracking

Additional notable properties (Daugherty, 1992):
- shading coefficients
- general solar, optical, thermal performance data

dimensional stability
general "handle-ability" (abrasion resistance, foldability, etc.)
color fastness
cleanability
seam strength and stability
acoustical data

Table 1 - Air & Tensile Structure Fabric Characteristics[a]

	Fire, UV resistant	**Self-cleaning**	**Colors**	**Average lifespan**	**Cost**
Vinyl-coated polyester	Yes	Moderate	Many colors	15 years	Lowest
Tedlar-clad vinyl-coated polyester	Yes	Yes	Many colors	20 years	Low
Vinyl-coated fiberglass	Yes	Moderate	Many colors	15 years	High
Tedlar-clad vinyl-coated fiberglass	Yes	Yes	Many colors	20 years	Higher
PTFE-coated fiberglass	Yes, best of the five	Yes	White	25 years	Highest

[a] "General Specifications." Fabrics & Architecture, December 1992: 66-74.

Table 2 - PVC (Vinyl)-Coated Polyester & PTFE-Coated Fiberglass Comparison[a]

	PVC (vinyl)-coated polyester	**PTFE-coated fiberglass**
Coated fabric weight oz./sq.yd.	28 (20-32)	37.5 (34-38)
Strip tensile lbs./in.	400, 350	520, 430
Trapezoidal tear, lbs./in.	65, 65	35, 38
Solar transmission	Translucent, depends on color	9-13%
Solar reflectance	Depends on color	67% min.
Flame out	2 sec. flame-out	1 sec. flame-out
Fire resistance	Method 5910 meets Calif. Fire Marshal req., UL 214, NFPA-701	Passes ASTM E-136; ASTM E-108 Class A

[a] "General Specifications." Fabrics & Architecture, December 1992: 66-74.

Table 3 - Polyester Fabric Properties[a]

	24 oz. Polyester Fabric		28 oz. Polyester Fabric		32 oz. Polyester Fabric	
	English	Metric	English	Metric	English	Metric
Base Fabric Weight	5 oz./yd.^{2}	170 g/m^2	7.5 oz./yd.^{2}	255 g/m^2	10.0 oz./yd.^{2}	340 g/m^2
Finished Coated Weight	24 oz./yd.^{2}	785 g/m^2	28 oz./yd.^{2}	950 g/m^2	32 oz./yd.^{2}	1090 g/m^2
Coating Distribution	65% outside and 35% inside.					
Tear Strength (Tongue Tear)	190 lbs.	86 kg.	275 lbs.	125 kg.	300 lbs.	136 kg.
Trapezoidal Tear Strength	60/50 lbs.	27/23 kg.	88/85 lbs.	38/38 kg.	140/140 lbs.	63/63 kg.
Breaking strength (Grab Tensile)	375/350 lbs.	170/159 kg.	700 lbs.	325 kg.	840/840 lbs.	380/380 kg.
Breaking strength (Strip Tensile)	300/275 lbs.	136/125 kg.	515 lbs.	234 kg.	650/650 lbs./in.	116/116 kg./cm.
Dead Load (room temp.) (160°F or 71°C) 2" seams	106 lbs. 53 lbs.	48 kg. 24 kg.	266 lbs. 133 lbs.	120 kg. 60 kg.	266 lbs. 133 lbs.	120 kg. 60 kg.
Adhesion (Minimum)	10 lbs./in.	1.8 kg./cm.	10 lbs./in.	1.8 kg./cm.	10 lbs./in.	1.8 kg./cm.
Cold Crack (Pass)	- 40°F	- 40°C	- 40°F	- 40°C	- 40°F	- 40°C
Accelerated Weathering	No cracking, blooming or bleeding					
Flame Resistance: (Meets NFPA No. 701)	2 seconds flameout, self extinguishing					
Flame Spread	Less than 25					
Operating Temperature	-40°F to +150°F	-40°C to +65°C	-40°F to +150°F	-40°C to +65°C	-40°F to +160°F	-40°C to +71°C
Color	Translucent, white (other colors available)					

[a] Information from Thermo-Flex, Inc.

Table 4 - Principal Combinations of Substrate Fabrics, Coatings and Top Coatings[a]

Substrate	**Coating**	**Top Coating**
Polyamid*	PVC Polyvinylchloride	Acrylic
Polyester**	Chloroprene (e.g. Neoprene)	Tedlar Laminate
Polypropylene	Chlorosulphonated Polyethylene E.G. Hypalon	Polyurethane
Polyvinylalcohol	Polyvinylfluoride	FEP Perfluoro-ethylene-propylene
Glass	Polyurethane	Chlorosulphonated Polyethylene e.g. Hypalon
	Silicone Rubber	
	PTFE Polytetrafluoretheylene e.g. Teflon	

[a] Advisory Board on the Built Environment. Architectural Fabric Structures: The Use of Tensioned Fabric Structures by Federal Agencies. Washington D.C.: National Academy Press, 1985.

Architectural Fabric Manufacturers

Following is a partial list of fabric manufacturers:

- Vestar

- Stafford Textiles Limited
  2200 Lakeshore Boulevard W.
  Toronto, Ontario, Canada
  M8V 1A4
  (416) 252-3133

- Dupont Tedlar & Teflon

- Hoeschst Celanese Trevira Pep
  (Precision Engineered Polyester)
  (800) 633-4583

- Plastatech Engineering, Ltd.
  725 Morley Drive
  Saginaw, MI 48601
  (517) 754-6500

- Vintex, Inc.
  691 Gana Court
  Mississauga, Ontario, Canada
  L55 1P2

- Owens-Corning Fiberglas Corporation
  Fiberglas Tower
  Toledo, OH 43659
  (419) 248-7841

Fabric Attachment

At some point in fabric tensile structures the fabric must be secured to anchorage. This is accomplished with either clamps or sleeves.

Sleeves are fabric tubes or pockets through which a perimeter cable is passed. The pockets are then fastened to the fabric. This is the least expensive of the two types of fabric attachment and results in a more free-form or curvilinear edge. This method of attachment is primarily used in open-air functions such as theaters or shading structures where air-tightness is not an issue.

Clamps are used when a tighter connection between the fabric and the "hard structure" is needed. Mall skylights or air supported structures offer examples of this application. The connection consists of two steel bars clamped together with the fabric sandwiched in between. This assembly is anchored to the "hard structure" (General, 1992).

Anchoring

The loads that are acting on the membrane and supporting system eventually have to be transferred into a stable anchor which is usually the earth or a hard structure. In some cases cables link the membrane or the perimeter beams to the anchor. The connection between each element is aesthetically critical on the designers part and challenging on the part of the engineer. The designer desires the connection to continue the light, free-flowing character produced by the curved membrane. The composition of the element becomes even more crucial when the membrane's and supporting system's line forces direct a viewer's eye to the connection. Inappropriate visual character, poor composition, or incorrect scale can destroy any visual impression which the project is intended to display.

On the engineer's side, not only does he or she have to satisfy the designers aesthetic issue, but must also accommodate unusual loading conditions. Unlike most structural systems, tensile structure's connections are designed to move under loading. In addition, some of the primary structure materials are flexible.

The team work between the designer and engineer is invaluable in this type of structure. In most construction the structural members are hidden from view by walls, ceilings, etc. allowing their connection to be as "ugly" as necessary. The opposite is true with tensile structures. The member connections either enhance the design thereby producing a successful project, or destroy it.

Pier 6 Concert Pavilion in Baltimore illustrates that "tensile structure engineering can be expressed in a choreography of grace and elegance" (Bilenker, 1992, p.28). Todd Dalland, designer, designed concrete footing caps to be flush with the grade, hexagonal anchor plates, and columns and mast as lean as possible. Dalland didn't desire his touchdown points to have "all the grace of an elephant in combat boots" (Bilenker, 1992, p.28); but to infuse with a "cogent and sensual expression of material in pure tension" (Bilenker, 1992, p.28). The tapered columns connected to the footing without protruding anchor bolts and the tensioning cables were detailed to give the appearance of being fastened directly into the ground. This level of refinement should be the goal of every design team.

Fabricators and Installers

Following is a partial list of fabricators and installers:

- Helios Industries, Inc.
  Hayward, CA

- ODC, Inc. (Dow Corning Corp.)
  Nokcross, GA

- Anchor Industries, Inc.
  Evansville, IN

- Spandome Corporation
  Mountain Lakes, NJ

- Clycan Alpha Ltd.
  Lexington, KY

- Armbruster Manufacturing Company
  Springfield, IL

- Air Structures, Inc.
  Sacramento, CA

- Asati
  Tappan, NY

- Tensar Structures, Inc.
  Akron, NY

- Birdair
  Amherst, NY

- Warner Shelter Systems, Ltd.
  Calgary, Alberta

- Thermo-Flex
  Salinas, KS

- Canobbio
  Milano, Italy

Acoustical Performance

Fabric tensile structures are erected as a low-cost alternative to the hard-structure amphitheaters and band shells. In these applications the acoustical performance of the fabric becomes crucial to the design phase to ensure the appropriate quality of sound. And, it is surprising to discover that the fabric and the shape of tensile structures is an excellent reflector of sound waves. This is particularly true of fabrics that are tightly woven and then coated. Vinyl-coated polyester and teflon-coated fabrics are strong acoustically. Tensile structures reflect middle and high frequencies while lower frequencies go through the membrane. Also tensile structures do not absorb sound, therefore, they don't work as sound attenuation surface. Tensile structures will not restrict the sound from penetrating into the surrounding areas nor will they isolate the site from undesirable outside sounds (Rebeck, 1990f).

Code Provisions

The unconventional fabric tensile structure does not lend itself to be evaluated by conventional building codes. Current building codes apply to conventional construction such as those of wood, steel, or concrete and do not translate to fabric structures. As a matter of fact, the vinyl-coated fabrics used in tensile structures do not meet fire code test requirements designed for permanent conventional building materials. Additional provisions will be required to evaluate tensile structures.

During a fire, the polyester and fiberglass fabrics melt. As a result the roof "opens-up" to allow harmful smoke to escape. Also the fabrics do not add fuel to the fire like wood and other materials do. When a fire develops in a fabric structure, the fabric does not adversely contribute to the fatalities.

The Architectural Fabric Structures Institute (AFSI) has put together the recommended code provisions for architectural fabric structures. Some of the major code organizations have adopted the AFSI proposal, but other codes have requirements that are more restrictive. The Uniform Building Code requires a permanent architectural fabric structure roof to pass the ASTM E-108 roofing test with a Class B burning brand. Currently, only glass-based fabrics have passed this test (Rebeck, 1990d).

Insulation Properties

Energy consumption with tensile structure has been a "trade-off." The translucency of the roof saves on lighting cost but the lack of insulation increases heating and cooling cost. A tensile structure can meet energy codes in states with mild climates like Georgia and Southern California. Conventional roofing will have to be used in colder climates.

In the 1980's, Owens-Corning Fiberglass Corporation conducted an experiment which demonstrated that insulated fabric roofs could perform as well as conventional construction. The insulation is sandwiched between the exterior fabric membrane and a lighter interior fabric liner. The system performed well thermally but condensation became a problem. Water would form between the fabric layers resulting in interior water leakage that destroyed the insulation. To solve the problem, a vapor barrier would be required and the space ventilated. Also, a means to discharge the water promptly, if and when condensation occurs, would be needed. This can be accomplished with the vapor barrier and a gutter system fastened to the perimeter cable or anchor.

Another possible solution is to increase the insulating properties of the fabric itself. As of yet, this has not been accomplished. However, Laurence Howard, of Laurence Partners, is working on an innovative solution of doing just that. If Howard succeeds, the condensation problem could be eliminated (Gorman, 1992).

DESIGN PROCESS AND DESIGNS

General

Fabric tension structures are simultaneously architectural form and structural function. Therefore, during the design process an understanding of the structure is essential.

> The need for an integrated design process, however, goes beyond form and structure. Fabric tension structures are at the same time structure and envelope, building sculpture and architectural space, lighting system and acoustical environment. Structure, construction, and material behavior enter into the design process as much as the functional requirements of the space, the choice of proportions, and the relationship to the exterior environment. The structure, however, remains the major design tool and is the basis for the accompanying study of completed and planned fabric tension structures (Berger, 1985).

Since this technology requires a familiarity with these new design tools, not many architects are willing to venture into tensile structures even though most of them admire the forms that they express. According to Horst Berger, all that is required for understanding the form expressing structural system of fabric structures is the observation of previous built structures. To further understand the multiple personality of tensile structures, Berger emphasizes working on models by hand in lieu of computers. "Using hands is part of the mental process, and it brings in ideas you couldn't draw with a pencil" (Berger, 1985). Working with models helped Berger think in three dimensions. This technique is essential if architects are to produce these types of structures.

Space Tech PTY Ltd. takes a little different approach to the design process. They use computer graphic imaging for assistance during the design process. The program produced by Buro Happold enables the designer to generate surfaces for study although the firm still gains valuable hands-on experience by undertaking the actual construction themselves.

The characteristics of Frei Otto's design approach does not resemble the normal approach an architect would take nor does it resemble the normal approach an engineer would take. The approach that Otto used was that of an inventor. By exploring all practical applications for a given problem, Otto started with numerous sketches until all theoretical aspects for space and structure were covered. In the process, a progression of study models were built and rebuilt. Simple soap film models were produced to verify minimal surfaces and solid wood models were tested in wind tunnels. With instruments invented by or methods innovated by Otto himself, each model was measured for use in forming additional models and the permanent structures.

When designing tensile structures, one theme resounds through all the previous innovators, designers, and producers - that theme is to know the material. Fabric is unique, unlike any other, and has it's own personality. Following is a series of studies designed to disclose in an elementary way the nature of the system and attempts to utilize the system to a given problem.

Soap Film Models

Frei Otto used soap film models to determine minimum surface area within a closed curve or frame. Although, the minimum surface is not always the optimum structural shape when additional external loads are applied, Otto considered it important in the design of membrane and cable net structures. For this reason Otto's soap film models were duplicated in this study to see first-hand the surface shapes produced within a certain frame. This knowledge was an advantage in developing the forms of membrane surfaces during the design process.

As part of this thesis, approximately 15 models were produced and studied. Ten of the models were produced to study different shapes. Five were produced to study refinements for one design. The different shaped models ranged from simple frames demonstrating the anticipated anticlastic shape to complex frames for more advanced and, in some cases, unexpected shapes. Figures 1-4 show a sampling of the kind of simple models that were produced during this phase of the design process.

The five design models were produced after an initial design concept was formulated. The purpose for the models was first, to produce a 3-dimensional representation of the design concept and then, to refine the design until a desired shape was achieved. In other cases the refinements were subtle and in some cases the model indicated that the current refinement was undesirable and hence, was rejected. After the desired design was settled upon, a larger permanent model could be constructed to further study the design and construction.

Study Models

Following Otto's design process, several study models were produced and studied (Figures 5-7). The purpose of the models was to further study and refine the forms observed in the soap film models. Although the intent of models was to develop the design, the most beneficial aspect of producing the study models was the understanding gained by actually constructing small scale fabric structures. Through these constructions, a basic understanding of the forces acting within the fabric were acquired.

If Otto's process were to be followed, more advanced models would be produced to determine, among other things, loading and fabric cutting patterns. A designer should consult a fabric engineer to determine the loading and design connections.

Vacation House

The program for the vacation house was to design a structure that contained a bedroom, living area, toilet, and kitchen area. The site would be located by a lake somewhere. But the inventive fulfillment of the program is not the purpose of this study. The purpose was to stimulate the "mental process" pertaining to fabric tensile structures.

The concept was a simple box covered with a tensioned fabric roof (Figure 8). The fabric membrane was held aloft at one corner by a mast. The mast directed the forces diagonally down through the cube's steel frame to the earth. The opposite corner is fastened to a column which then is guyed to earth. The other corners are secured to a beam which is anchored to the earth by cables. The model was constructed of balsa wood and lycra fabric for the roof membrane. On the following pages are photographs of the final model.

Bird House

The bird house was a fund-raiser for a Des Moines charity (Figures 9 and 10). The bird houses were auctioned off, with the proceeds buying playground equipment. Since the opportunity presented itself, the bird house became an additional means to develop the "design tool" as Horst Berger would refer to it.

The design was strongly influenced by the design solution for the vacation house; the support system and Daugherty's fabric structure morphology are the same. The form of the fabric roof intentionally resembled a mother bird protecting her precious young from the harsh elements of nature. The bird house was constructed of wood, plexiglas, steel rod and weatherproof nylon fabric.

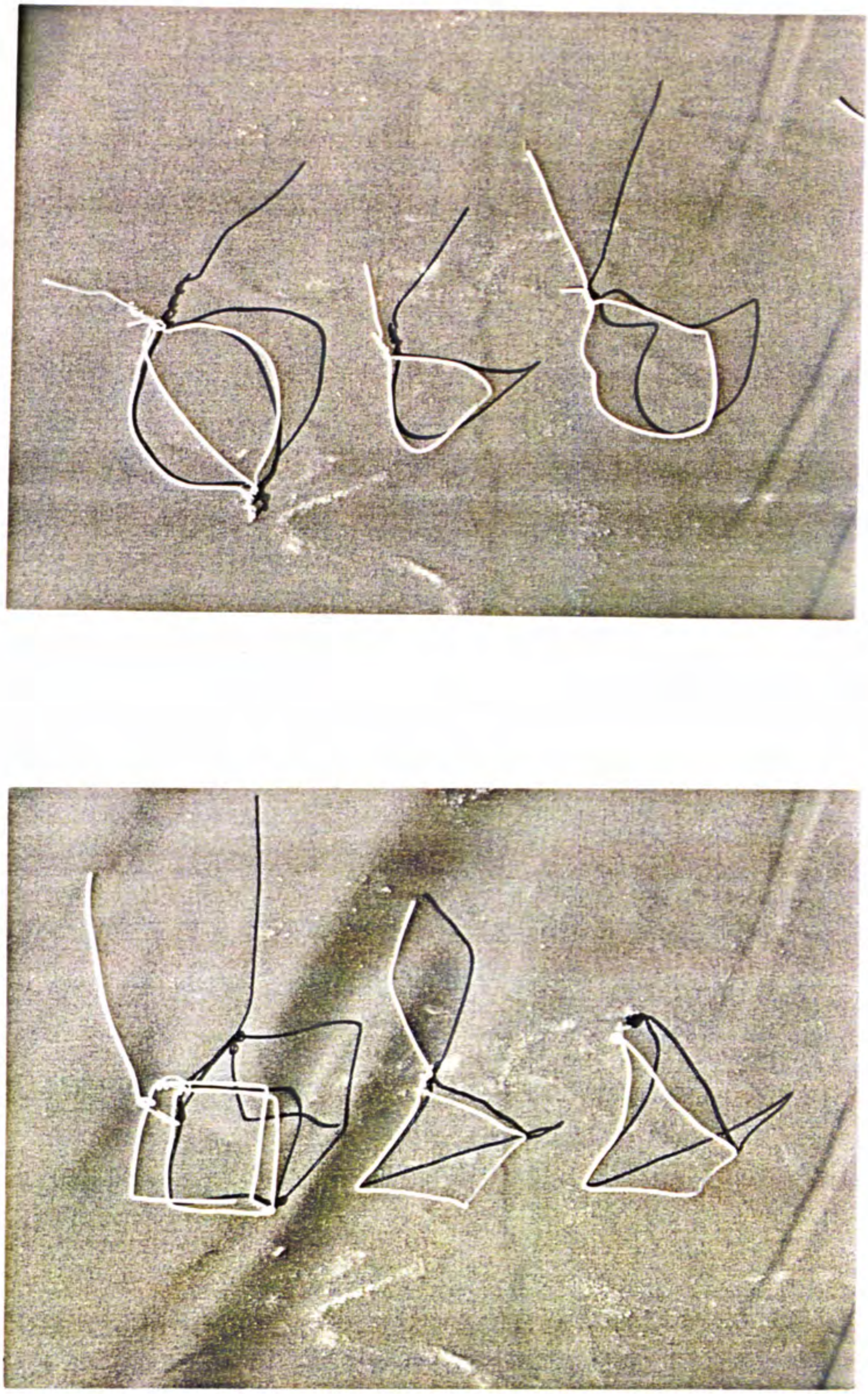


Figure 1 - Soap film models

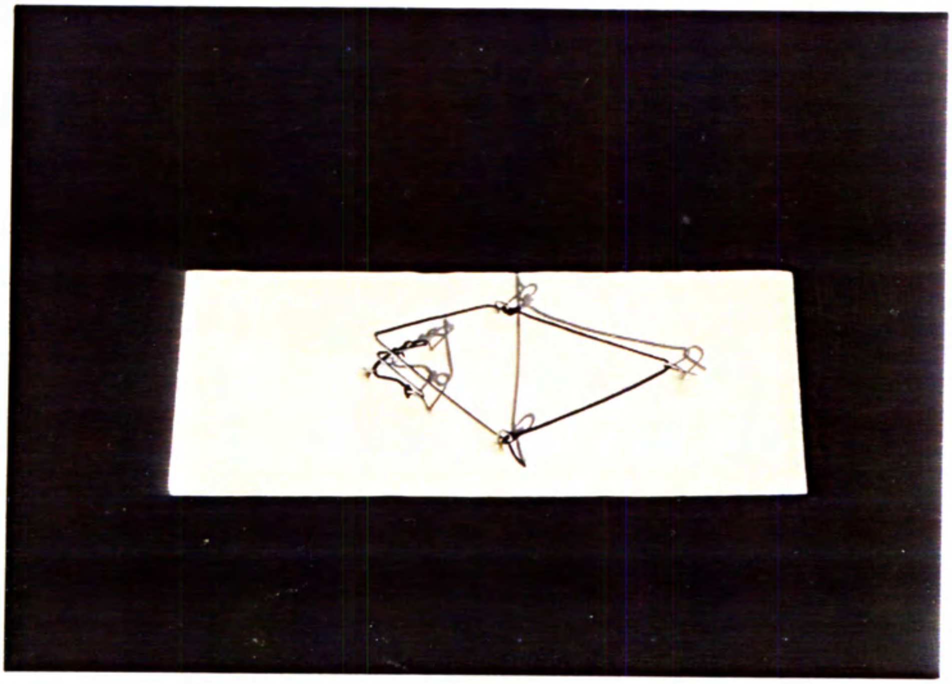


Figure 2 - Soap film model #1

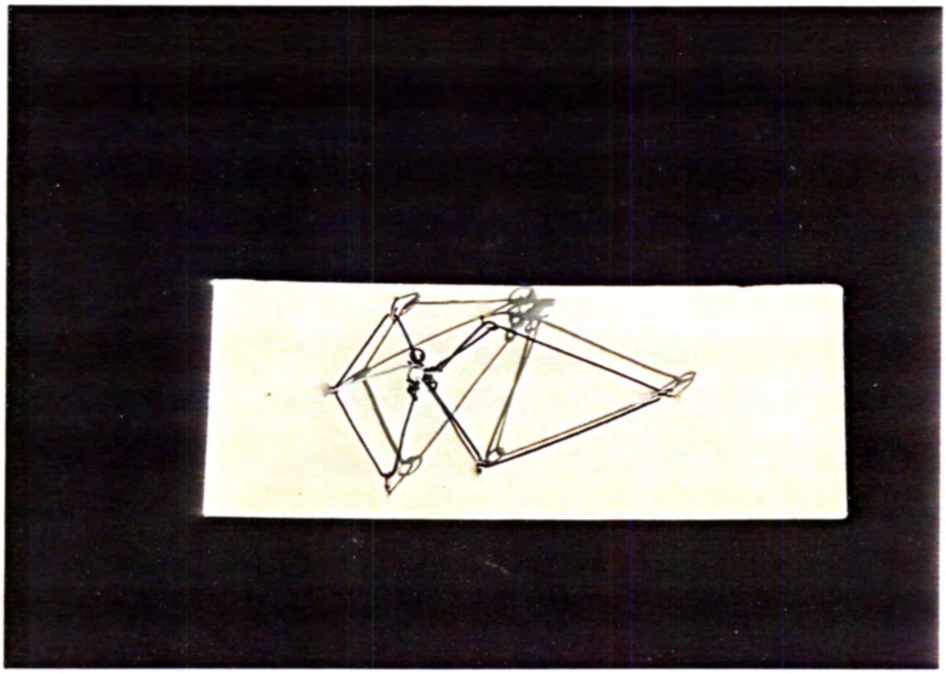


Figure 3 - Soap film model #2

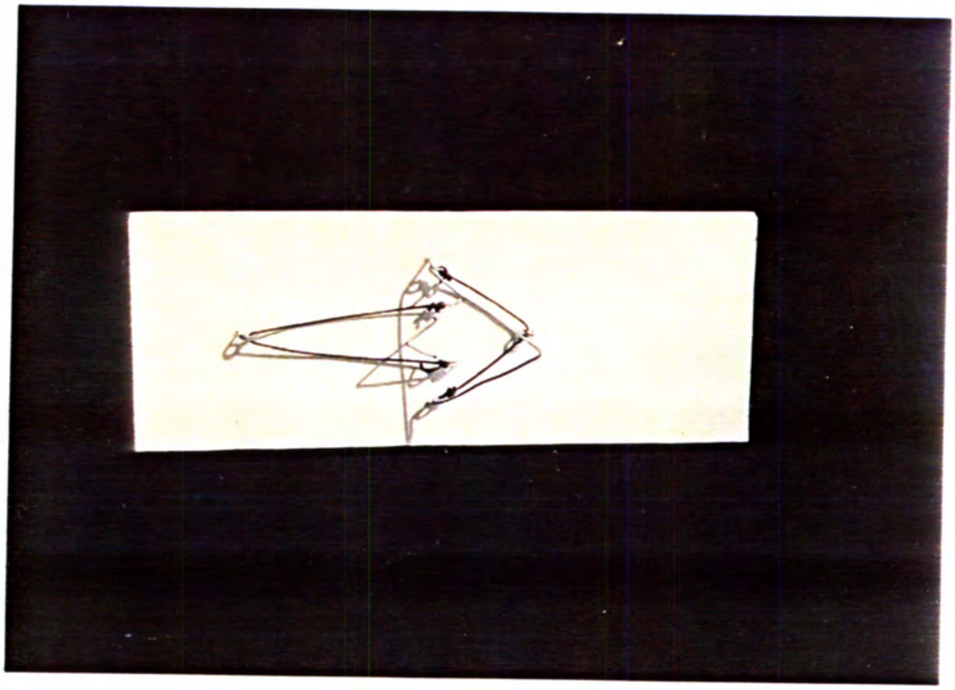


Figure 4 - Soap film model #3

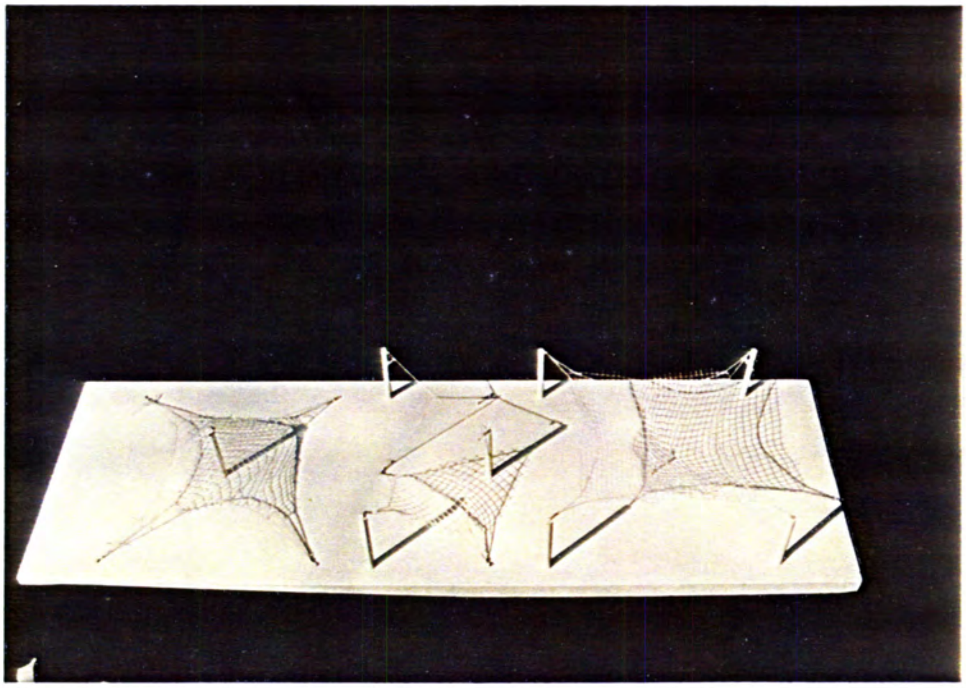


Figure 5 - Study model #1

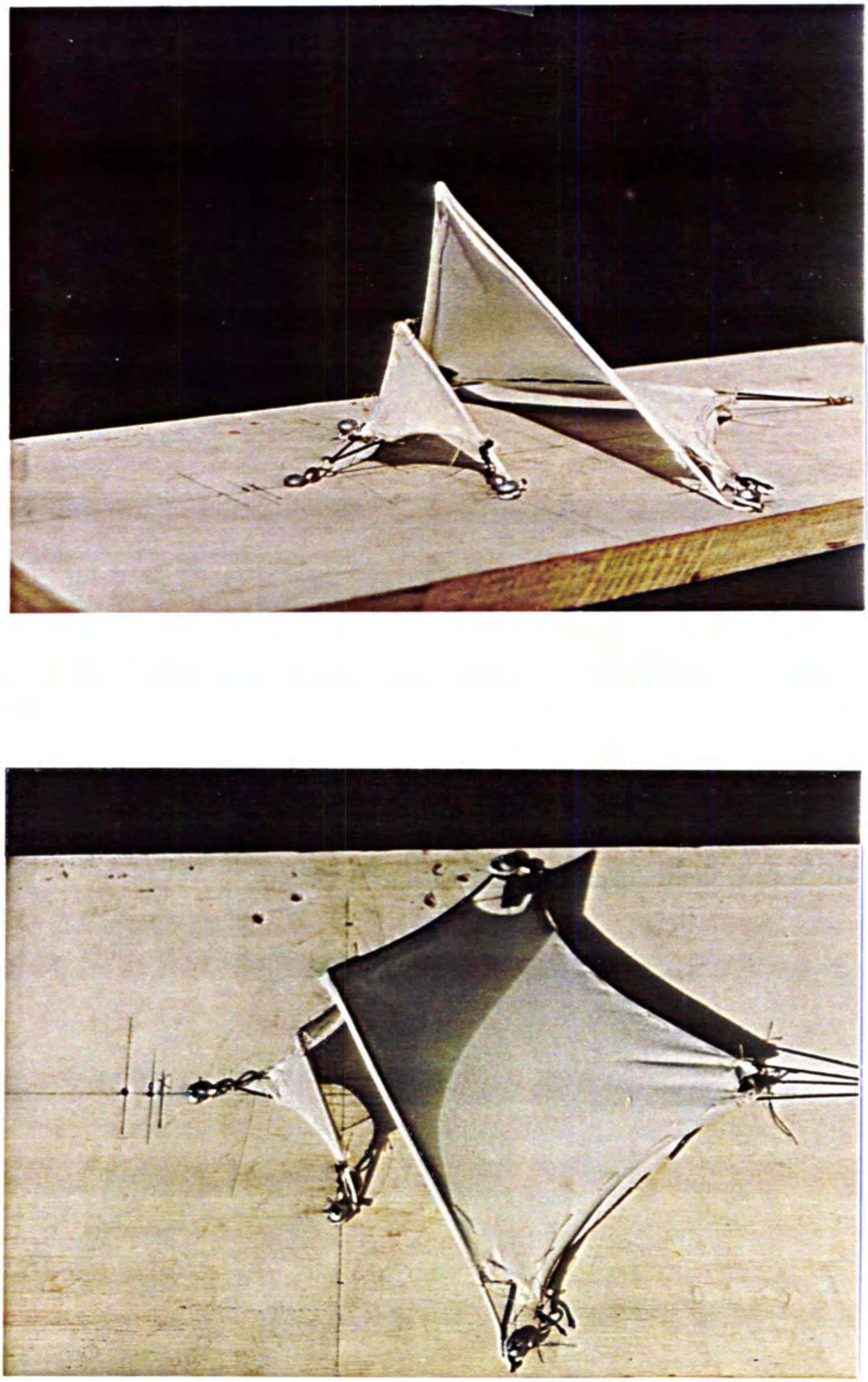
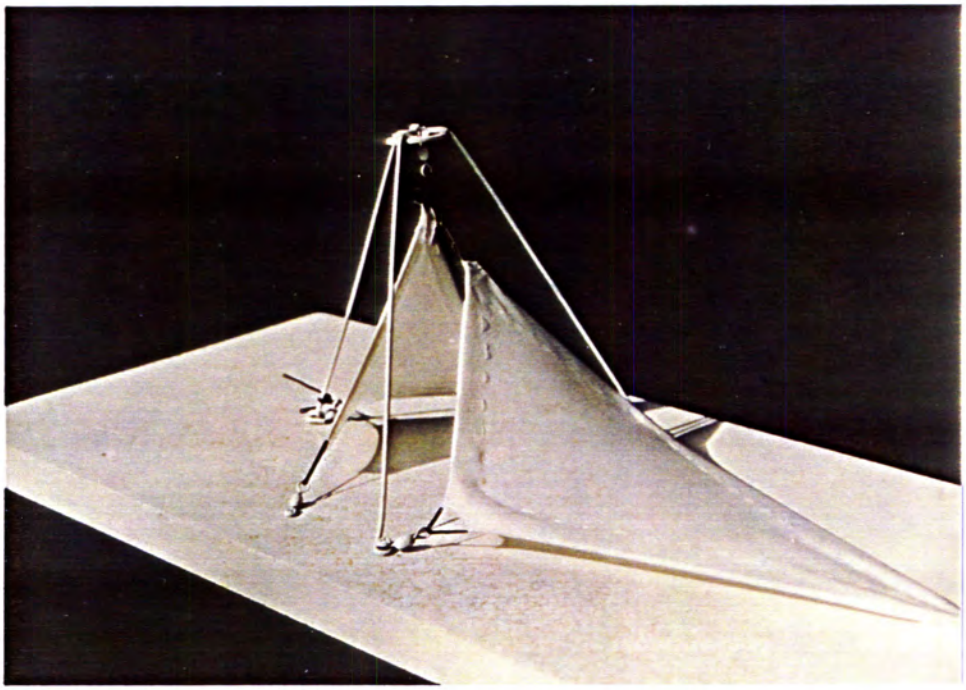


Figure 6 - Study model #2



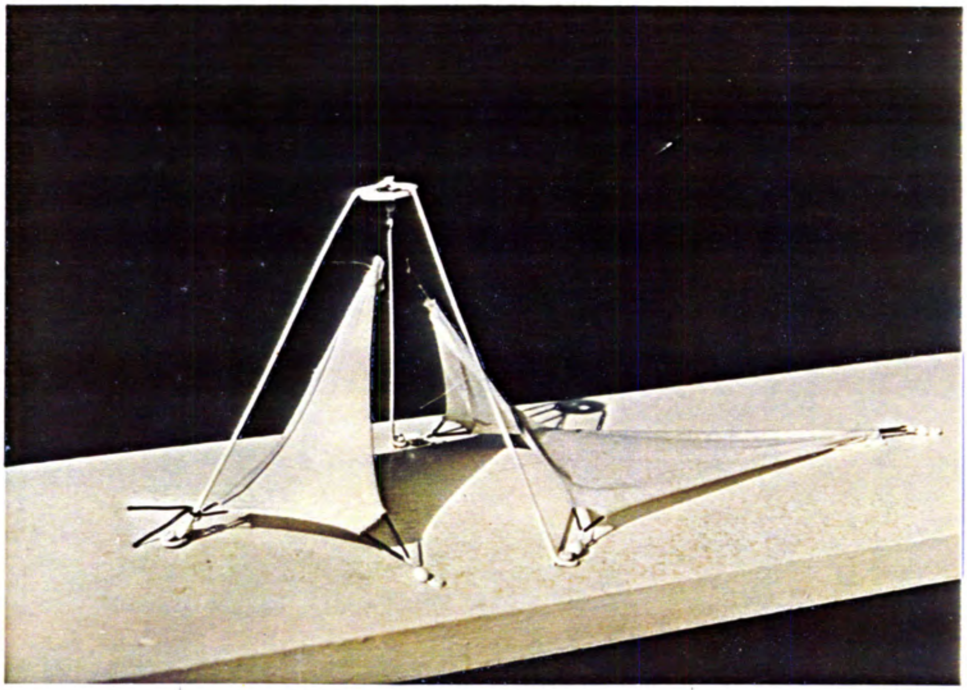


Figure 7 - Study model #3

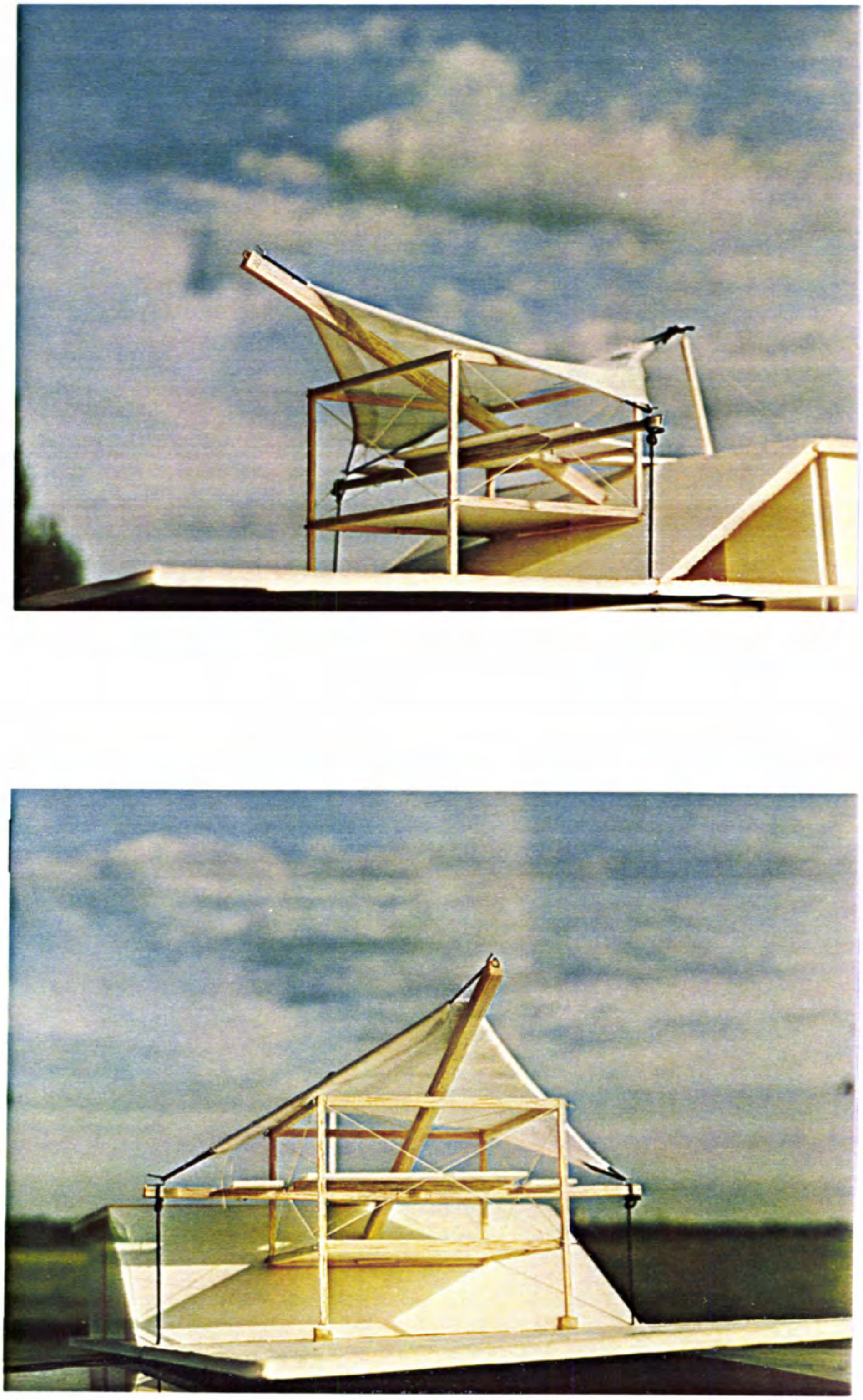


Figure 8 - Vacation house model

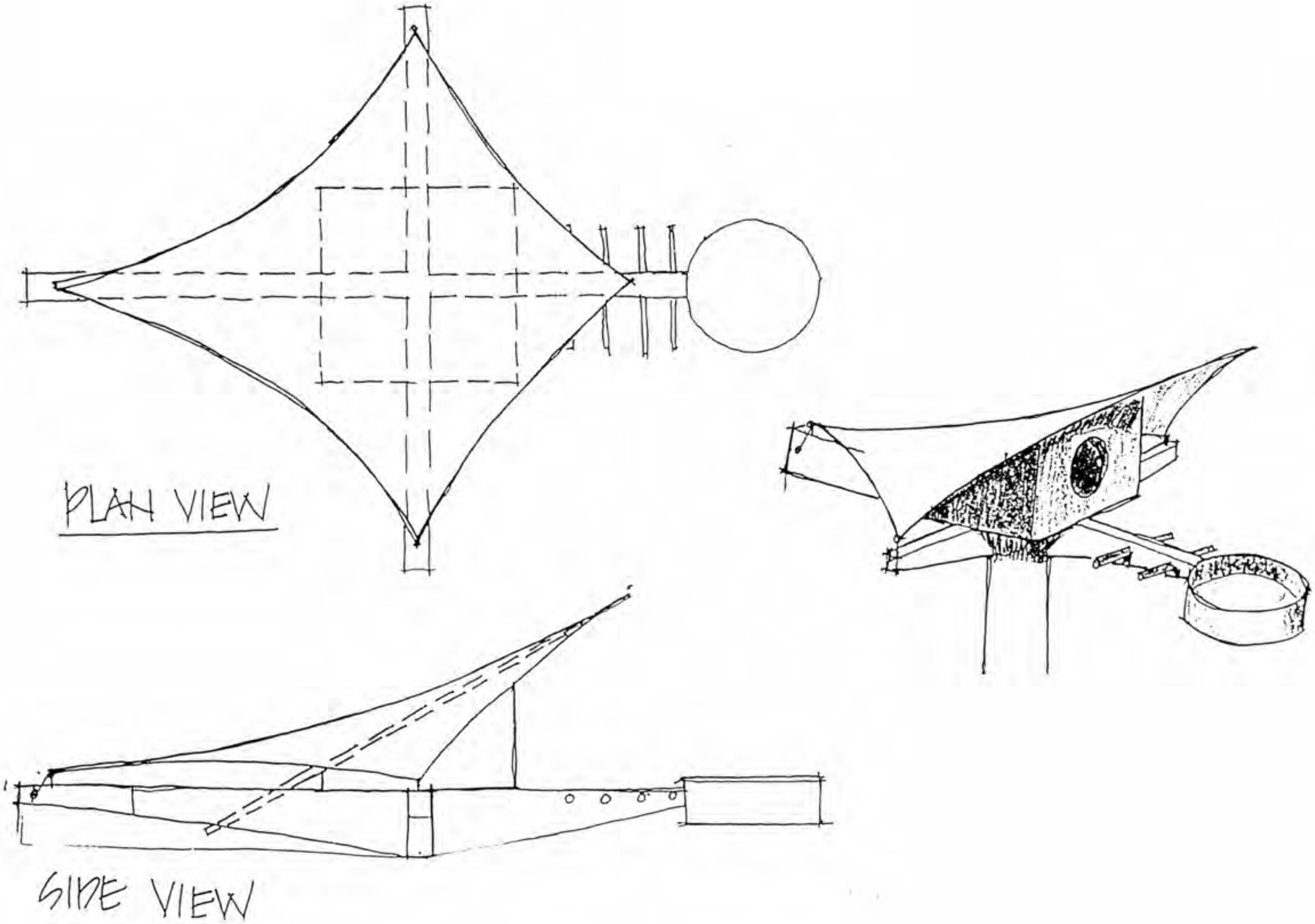
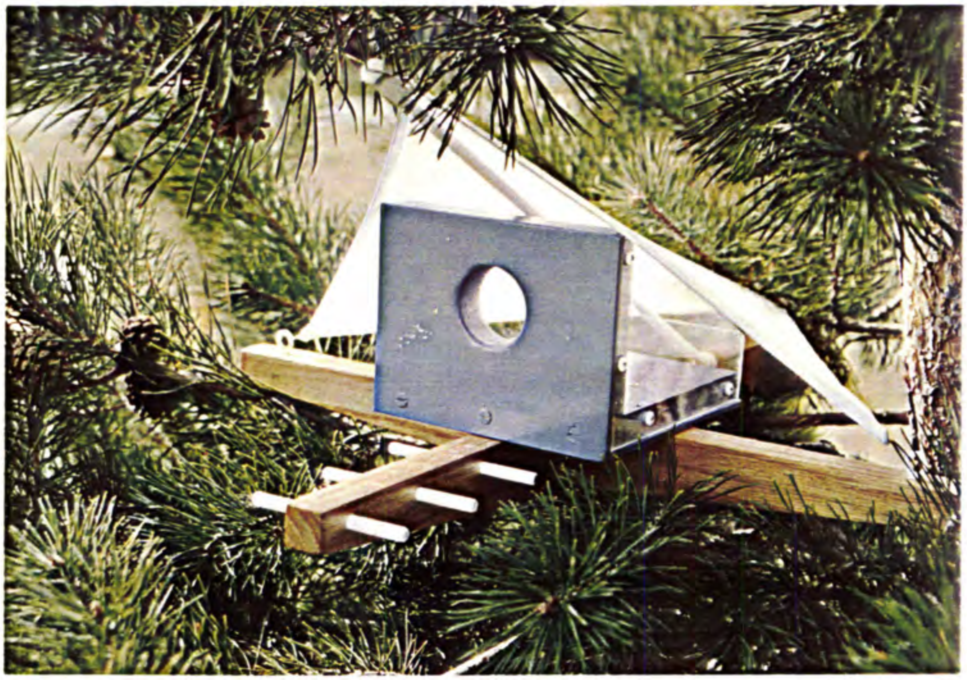


Figure 9 - Concept of the bird house



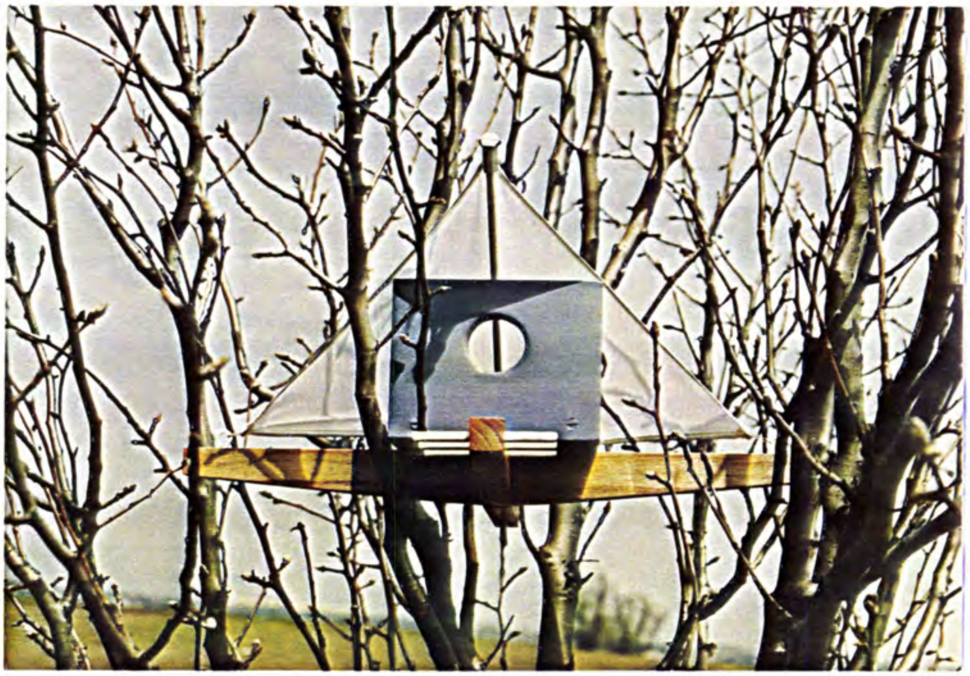


Figure 10 - Bird house

DESIGN PROJECT - AIRPORT

Intent

The airport program was an arbitrary selection to conclude this portion of the study. During the time of the decision, several airports were being constructed or designed utilizing fabric tensile architecture (Denver International Airport and Pearson International Airport). The selection of an airport offered a general, yet authentic program. The appropriateness of the tensile structural system for the project and the area was assumed valid. Although, if the project was genuine, an analysis of structural system and the enclosure system would be required. On the other hand, the intent of the project would not be to invent a new "type" of airport nor would it be intended for the designer to analyze every intricate aspect of how an airport should function. Only basic operational procedures and models of current airports were obtained and studied. Again, if the project was genuine, this information would require full examination.

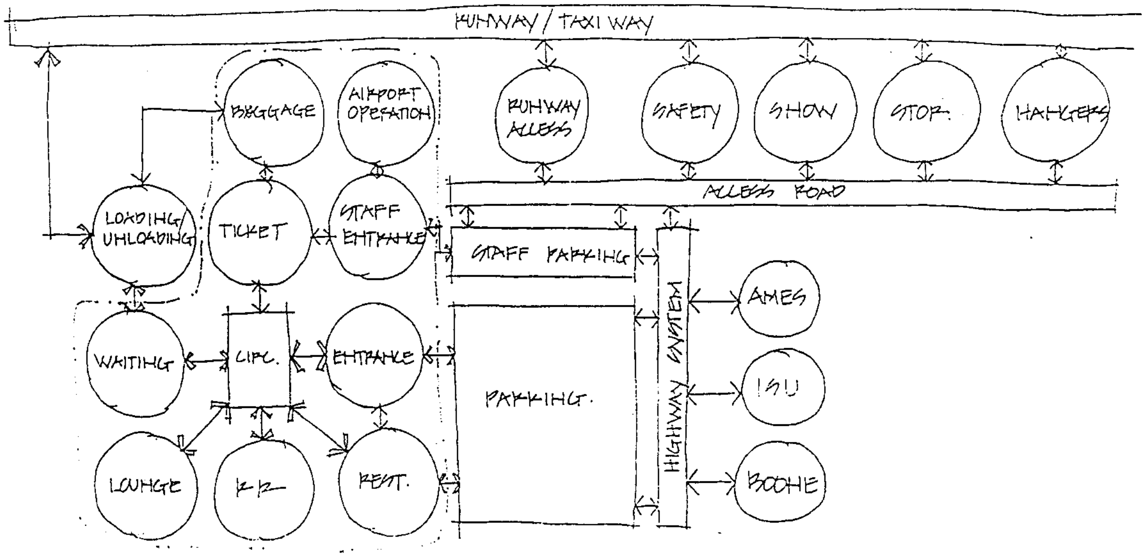
Introduction

The program of the airport was to design an airport in Ames, Iowa, for use by Ames, Boone, and Iowa State University. The site was located west of Ames along Highway 30 leading to Boone. The required structures were divided into two types, the terminal and the airplane hangars with all the supporting functions. The terminal would include the functions of ticket procurement, check-in, baggage, waiting, and other normal passenger related functions, in addition to, a restaurant, lounge, and administrative offices. Also included in the terminal would be the airport traffic control. The hangars would house a variety of different types of aircraft along with fire-fighting and aircraft fueling apparatus.

The design process started as any other project would begin, with the flow organization and the requirements of the space (Figure 11). From the information gathered, several concepts and ideas were developed and studied (Figures 12-16). One scheme was an assymetrical solution, staggering the hangars in a line and placing the terminal at the end (Figure 13). Another solution was to place the terminal symmetrically in the center of the hangers. The hangars were arranged radially around the terminal structure (Figures 14 and 15). This configuration allowed for maximum control and security of the parking apron and hangars by the control tower placed above the terminal. It is for this reason, plus aiding the circulation within the terminal, that the symmetrical scheme was selected for design development.

In design development, the chosen concept was refined, studied and given form. This was accomplished by a combination of drawings and study models (Figures 17-40). The study process was difficult since the normal tool for studying form; the perspective drawings, were very time consuming to produce and have questionable accurancy. The process was made easier by producing study models. The first model represented a solution which placed all functions under the fabric roof (Figures 29-31). The concerns with this solution were the control tower which did not have 360 degree visual access to the site and the baggage/storage area roof form appeared to be tacked on. In the subsequent model the control tower was moved to a position above the fabric membrane; this solved the previous observed problem (Figures 36-40).

Flow Organization



- SCHEME #1
- DIAGRAM OF FUNCTIONAL RELATIONSHIPS
- AMES AIRPORT
- 7/25/90

Figure 11 - Flow diagram

Early Concepts

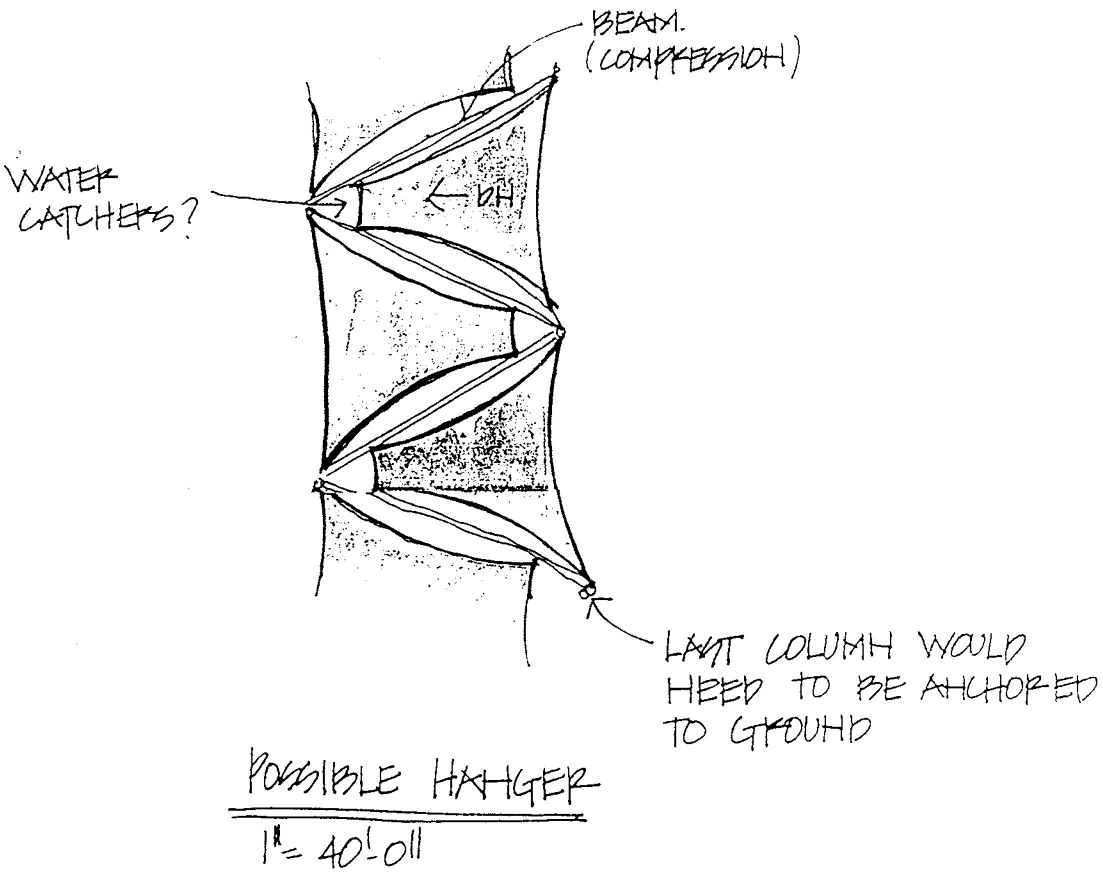
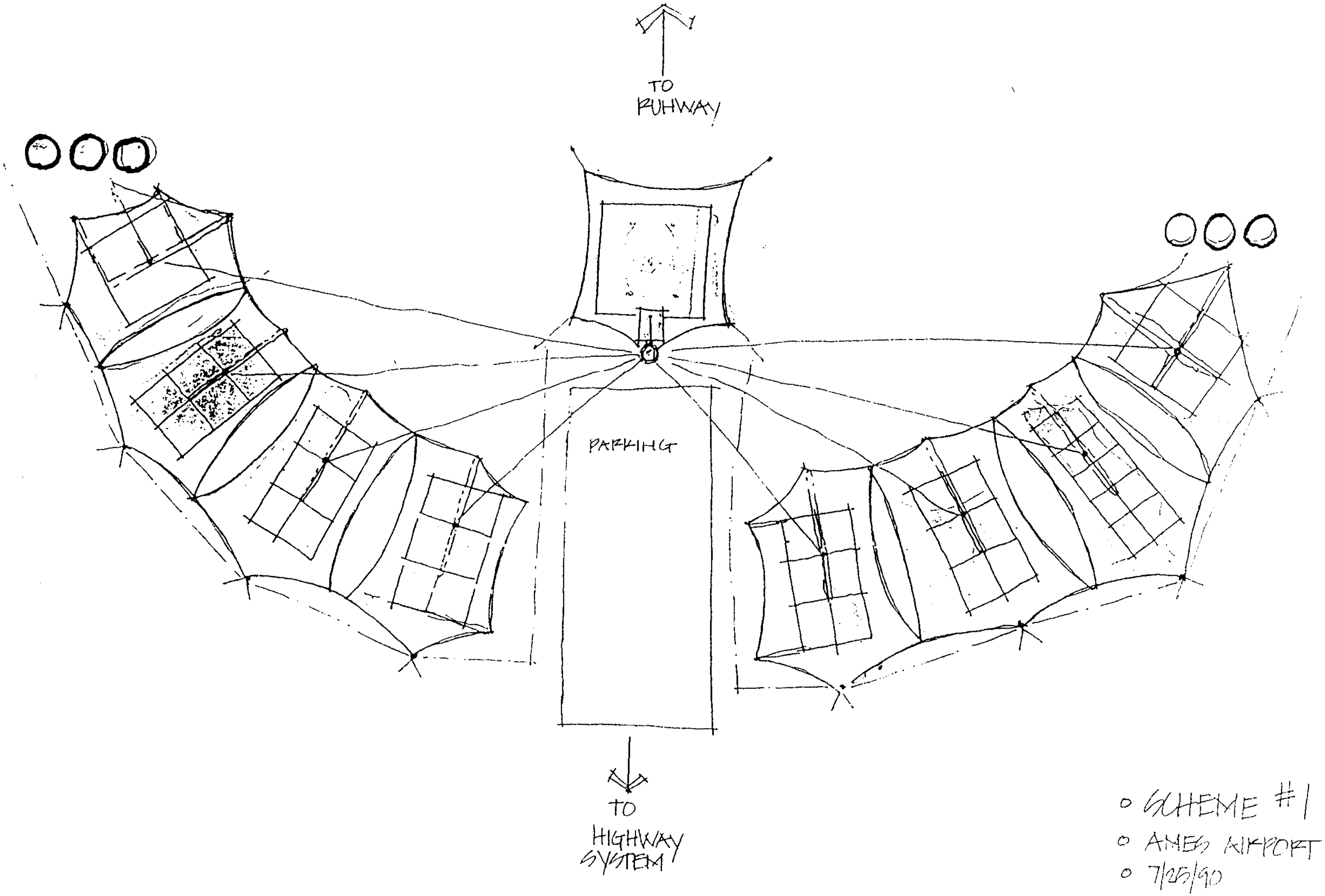


Figure 12 - Conceptual hangar study

Design Development

Figure 13 - Assymetrical solution



- SCHEME #1
- AMES AIRPORT
- 7/25/90

Figure 14 - Symmetrical solution

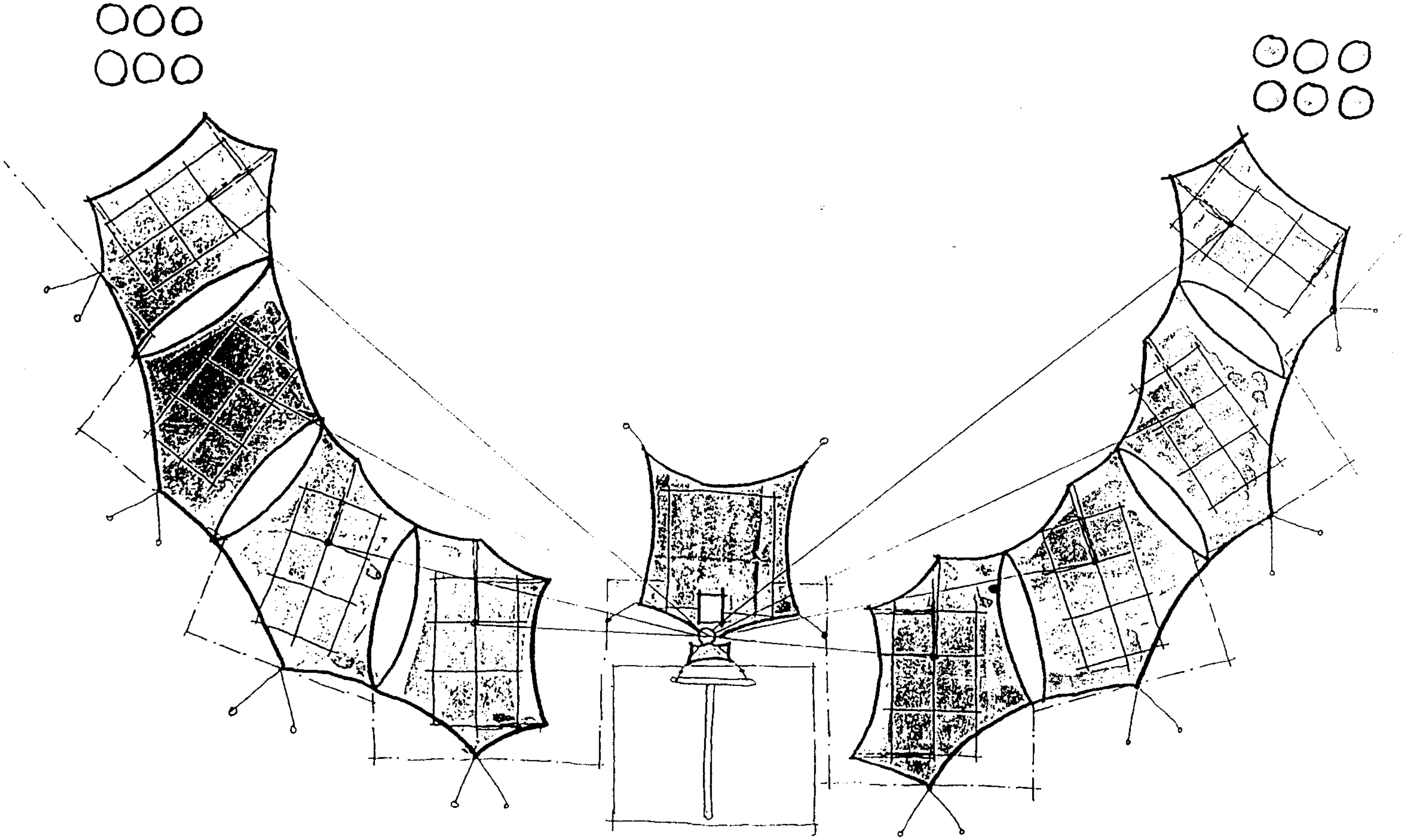


Figure 15 - Alternative symmetrical solution

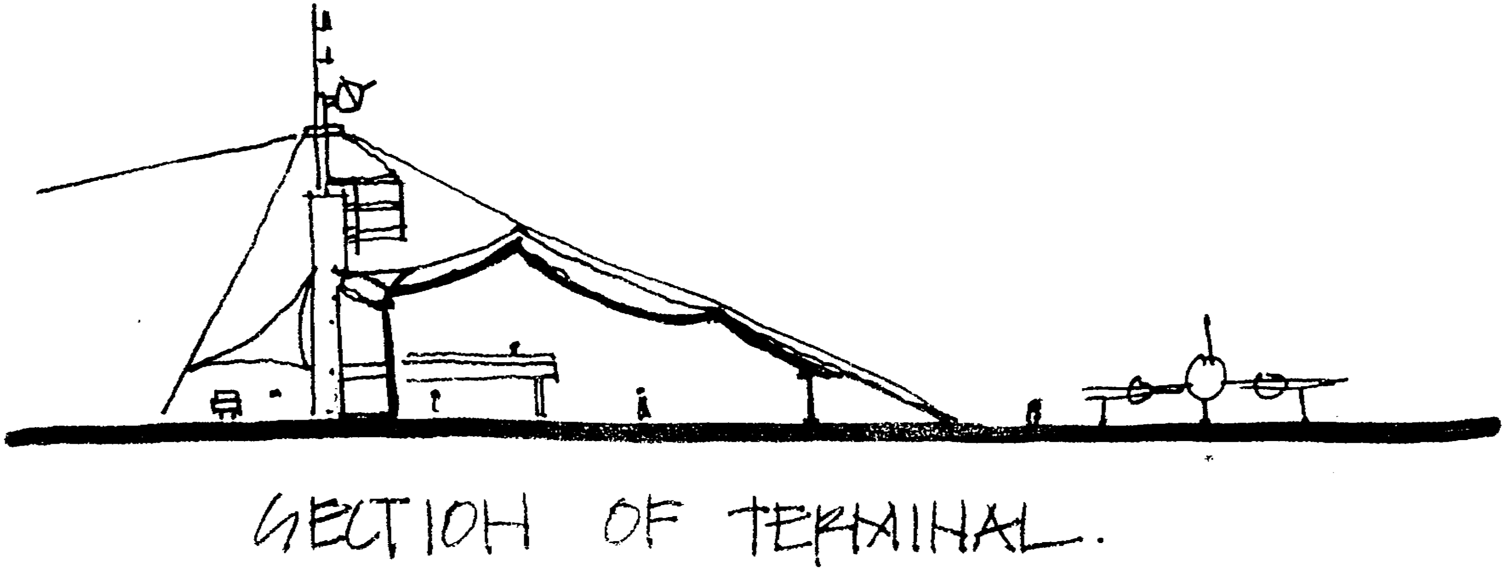


Figure 16 - Conceptual study

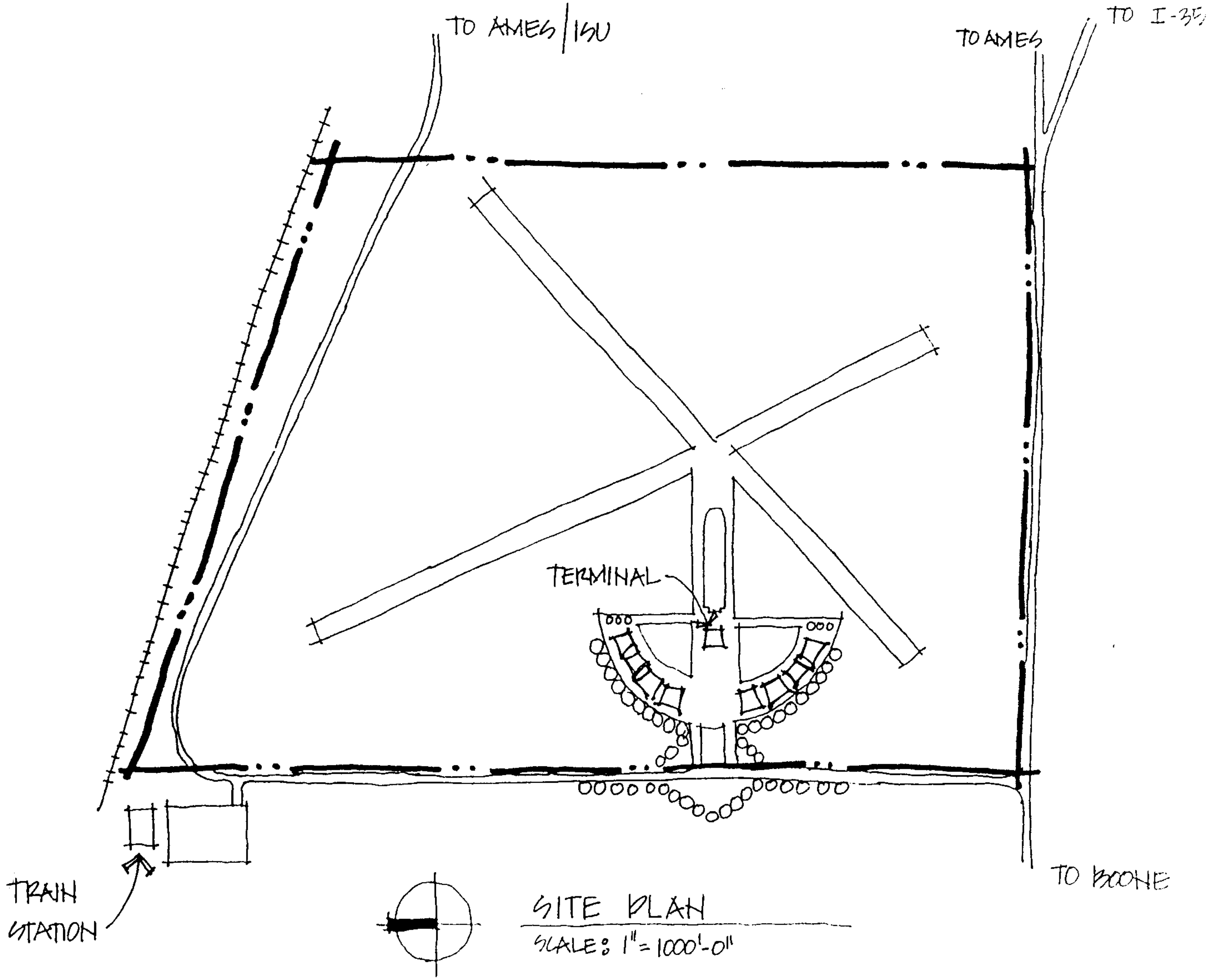


Figure 17 - Design development site plan

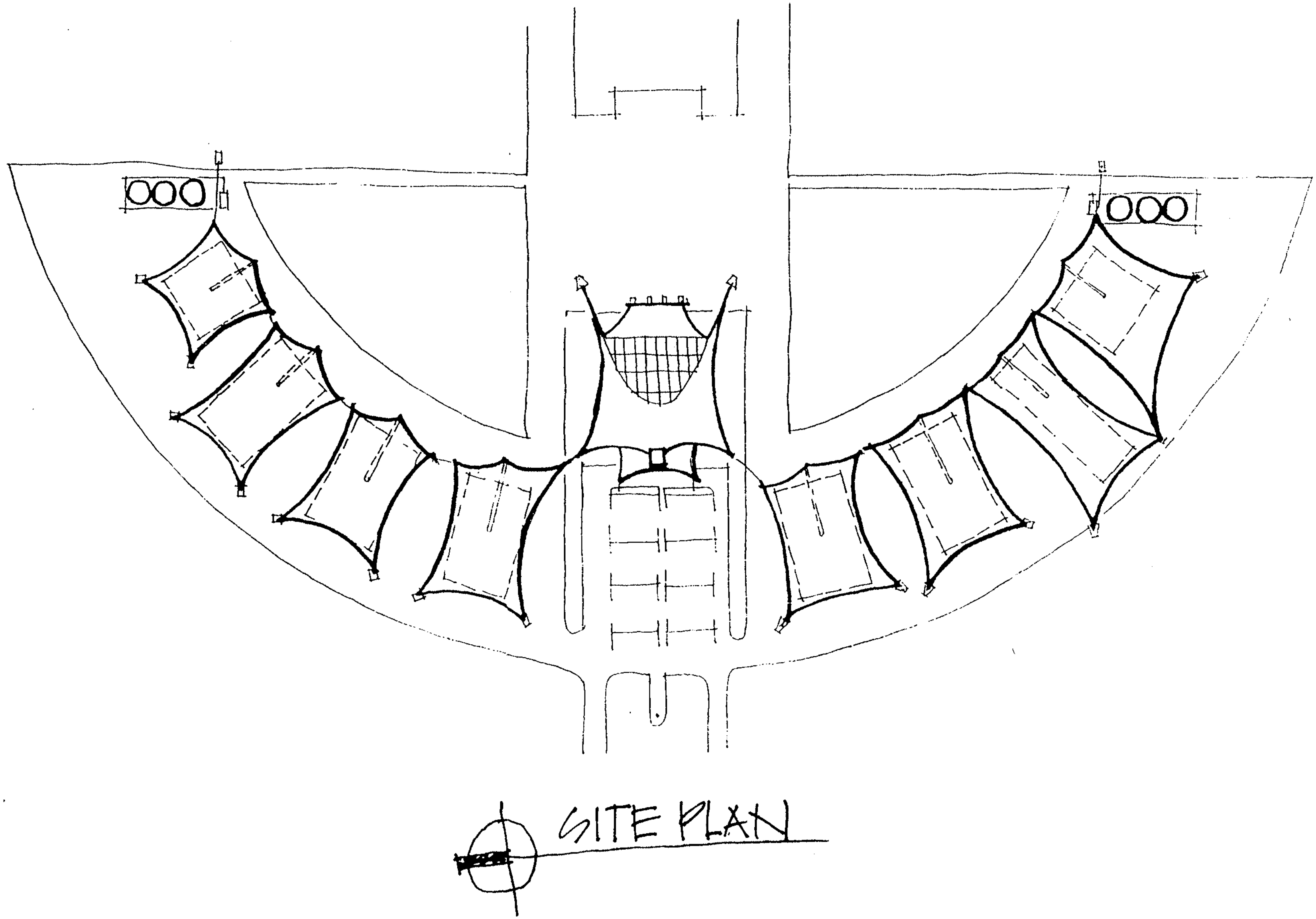


Figure 18 - Design development site plan

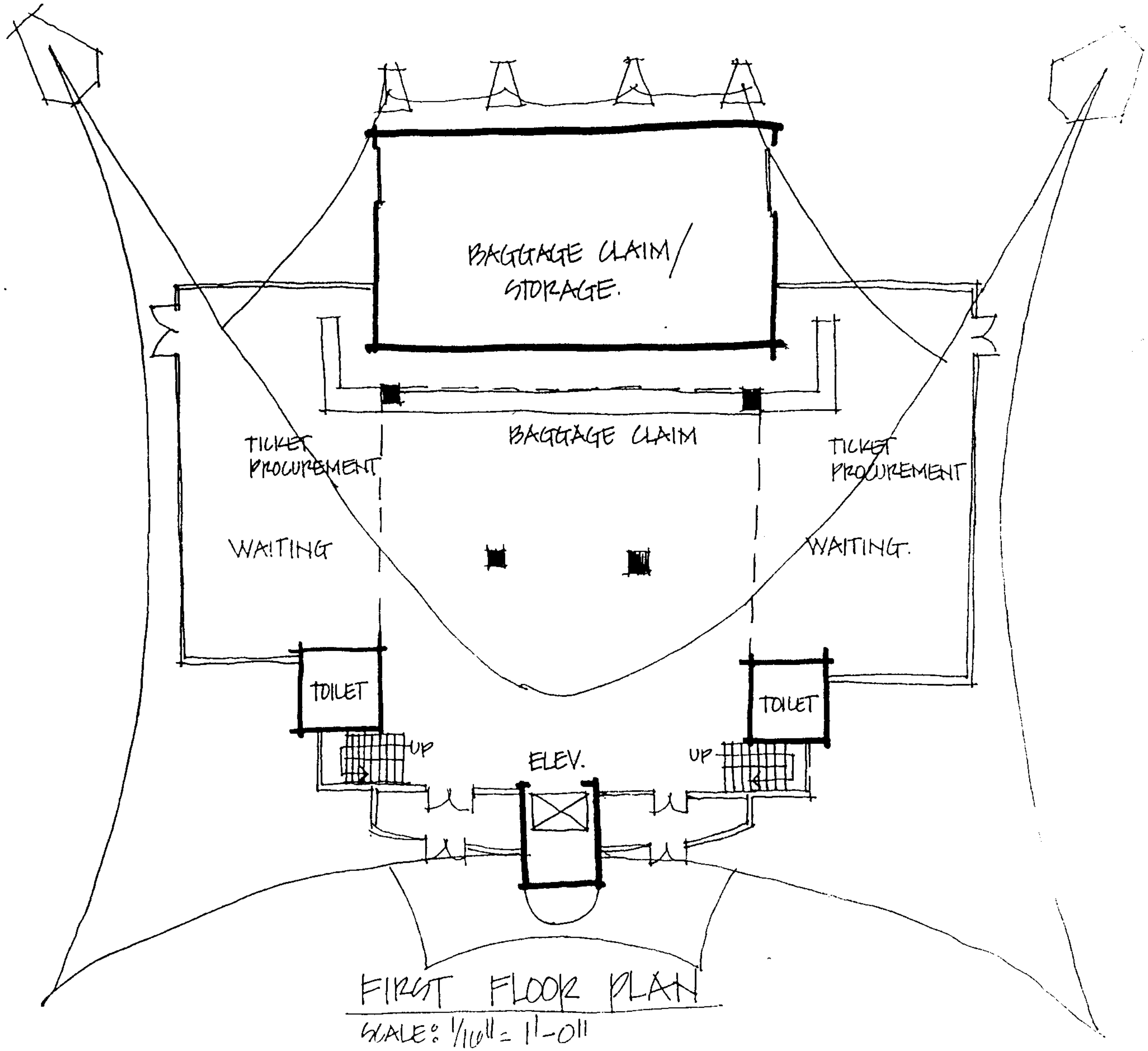


Figure 19 - Design development floor plan

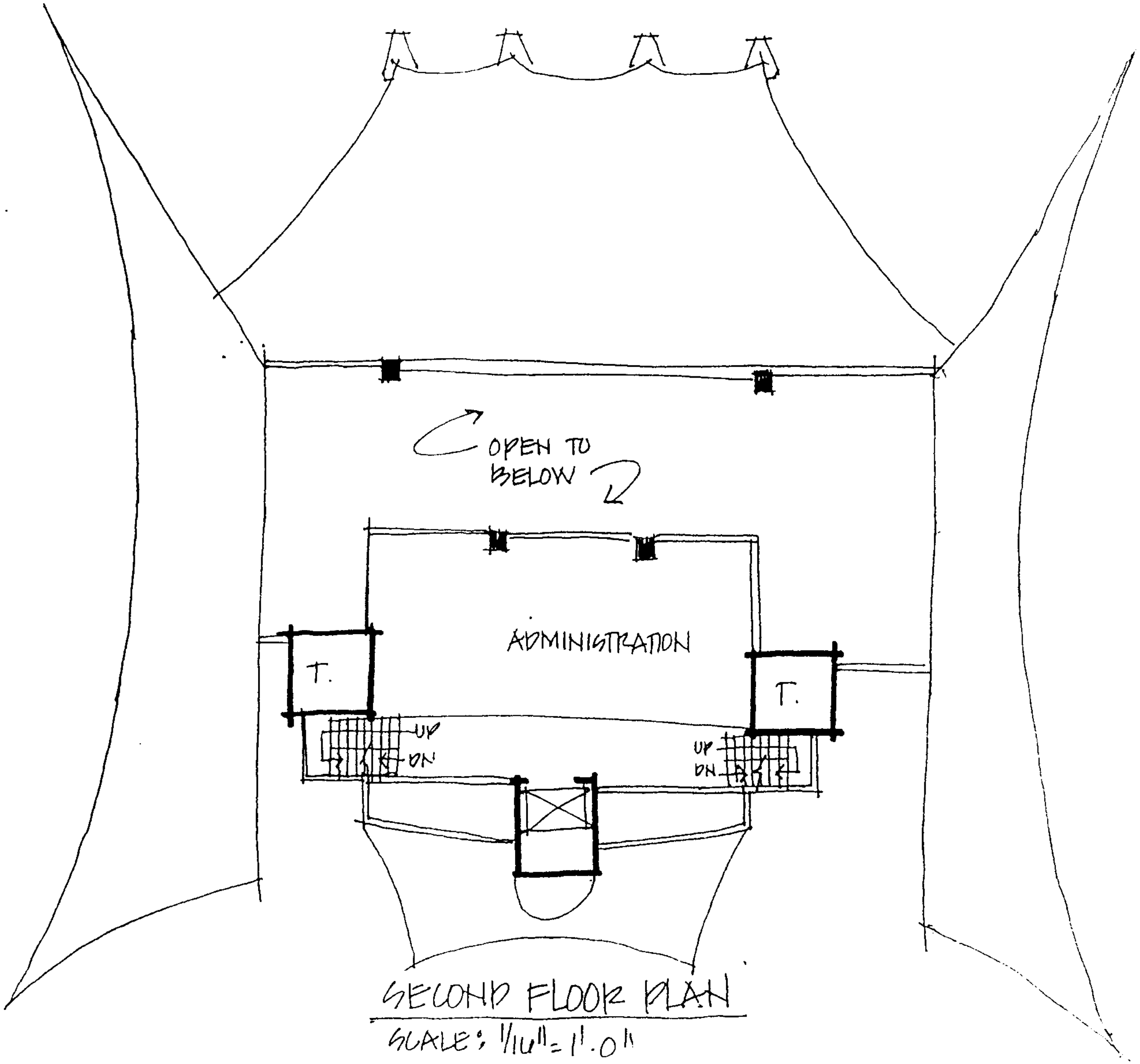


Figure 20 - Design development second floor plan

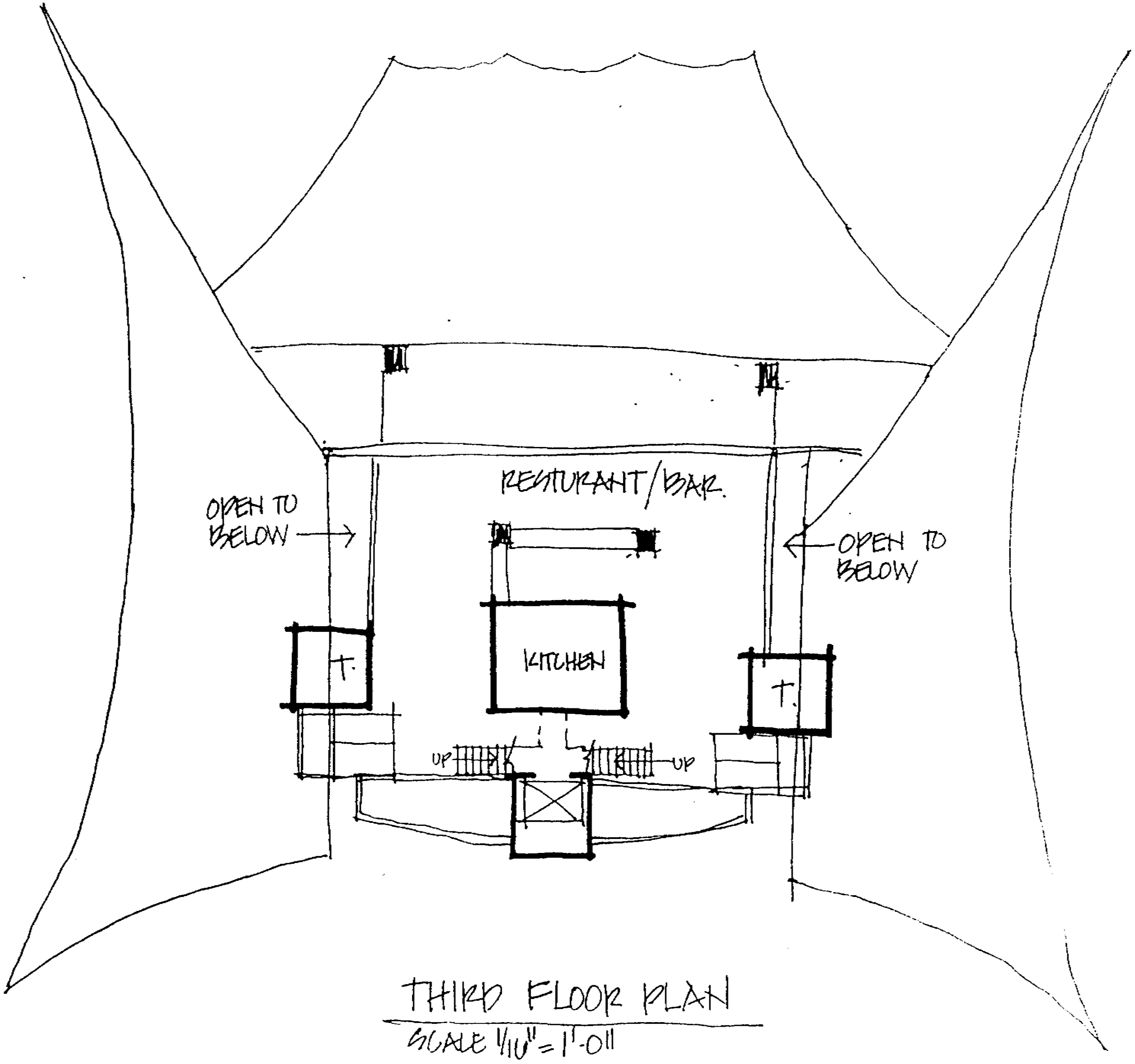


Figure 21 - Design development third floor plan

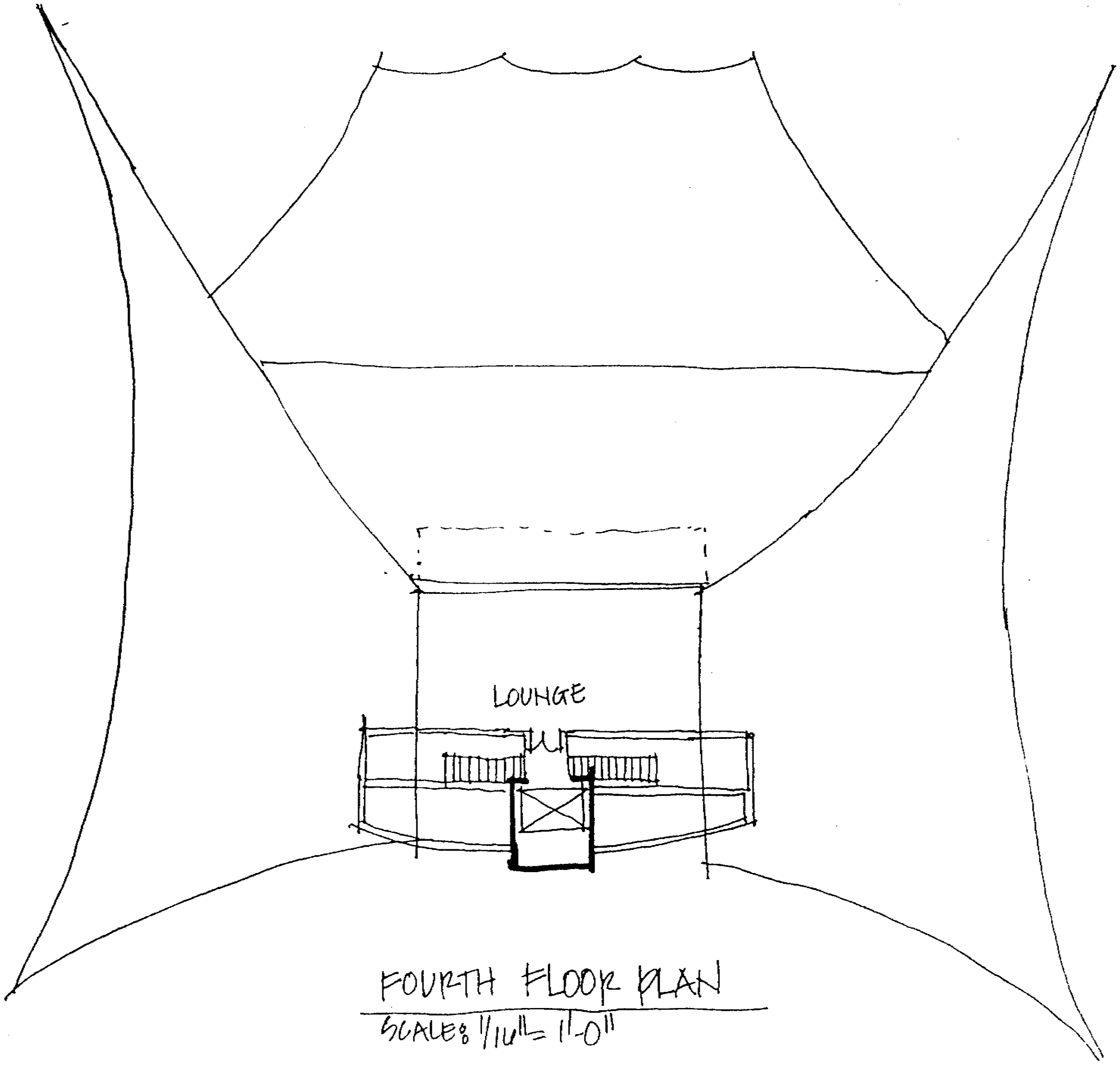
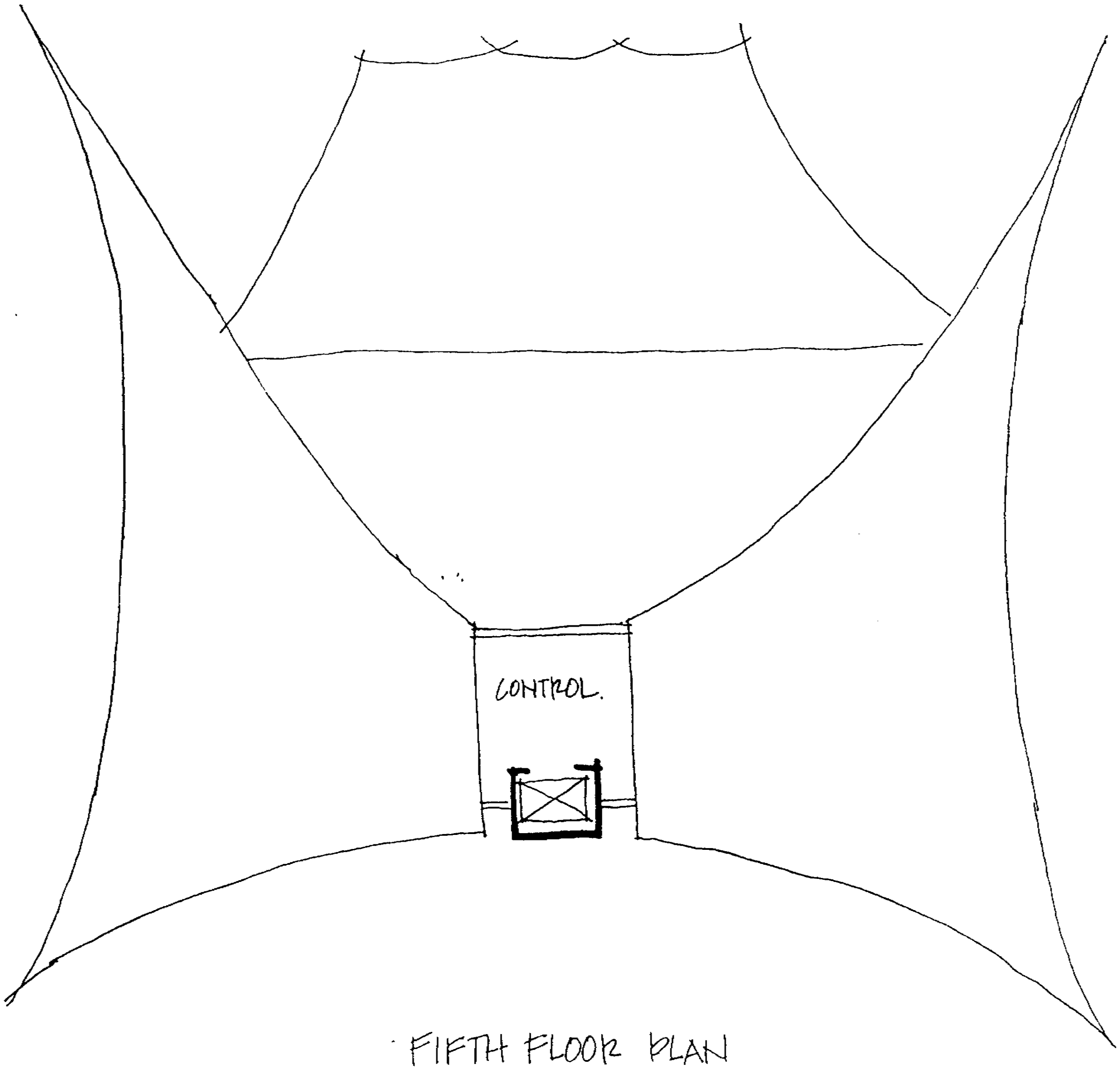


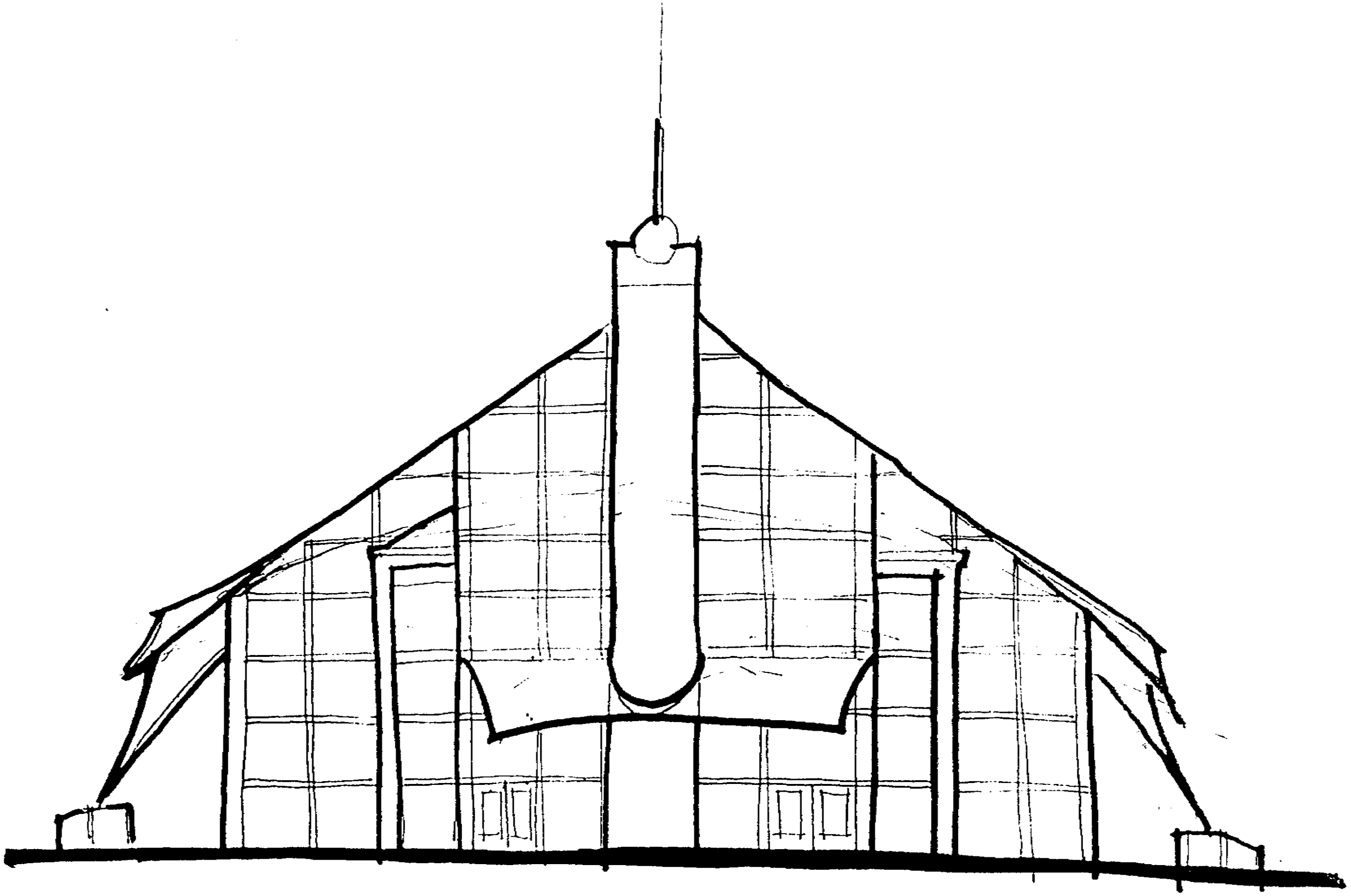
Figure 22 - Design development fourth floor



FIFTH FLOOR PLAN

SCALE: 1/16" = 1'-0"

Figure 23 - Design development fifth floor



FRONT ELEVATION

SCALE: 1/16":1'-0"

Figure 24 - Design development front elevation

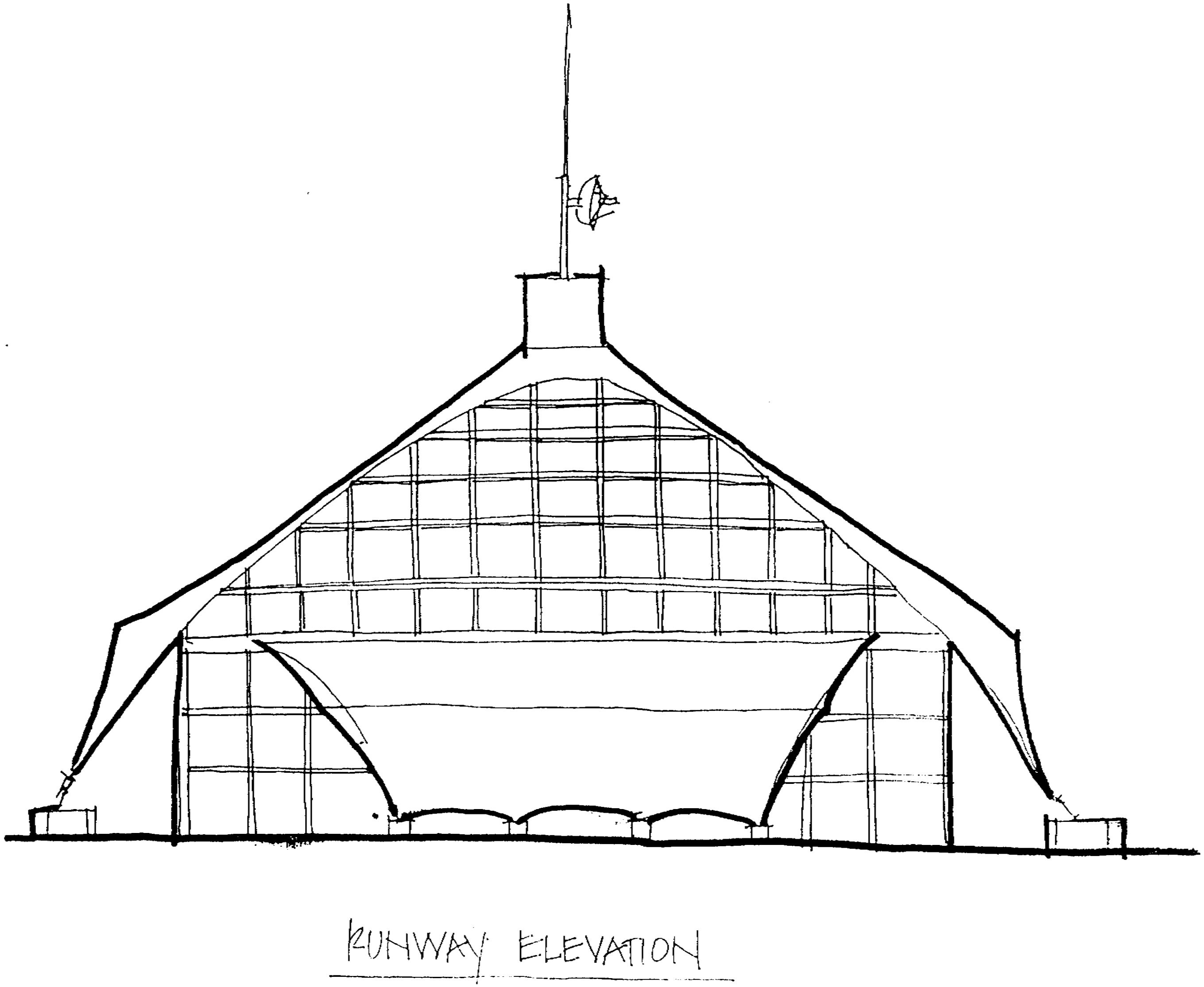


Figure 25 - Design development runway elevation

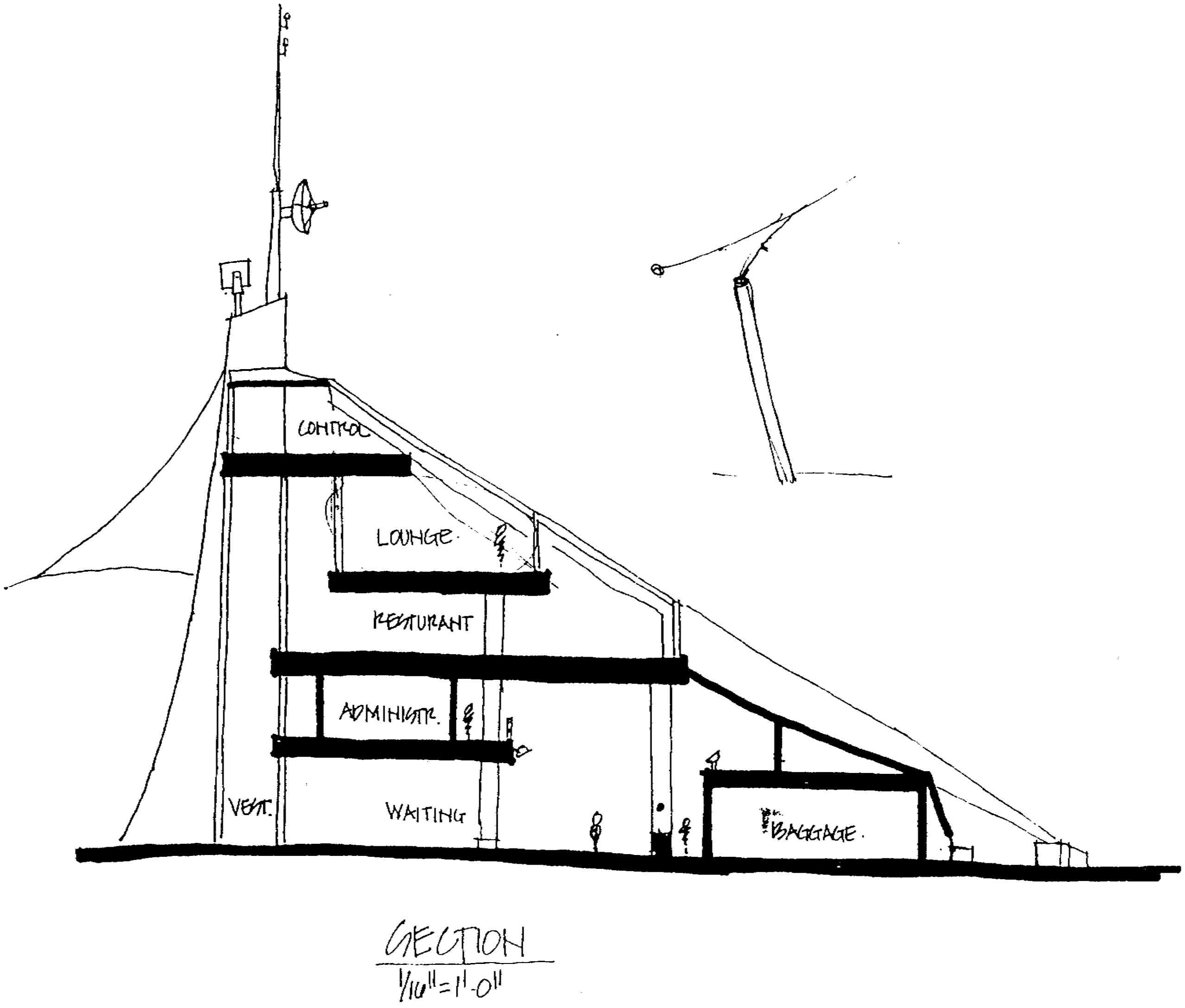


Figure 26 - Design development section through terminal

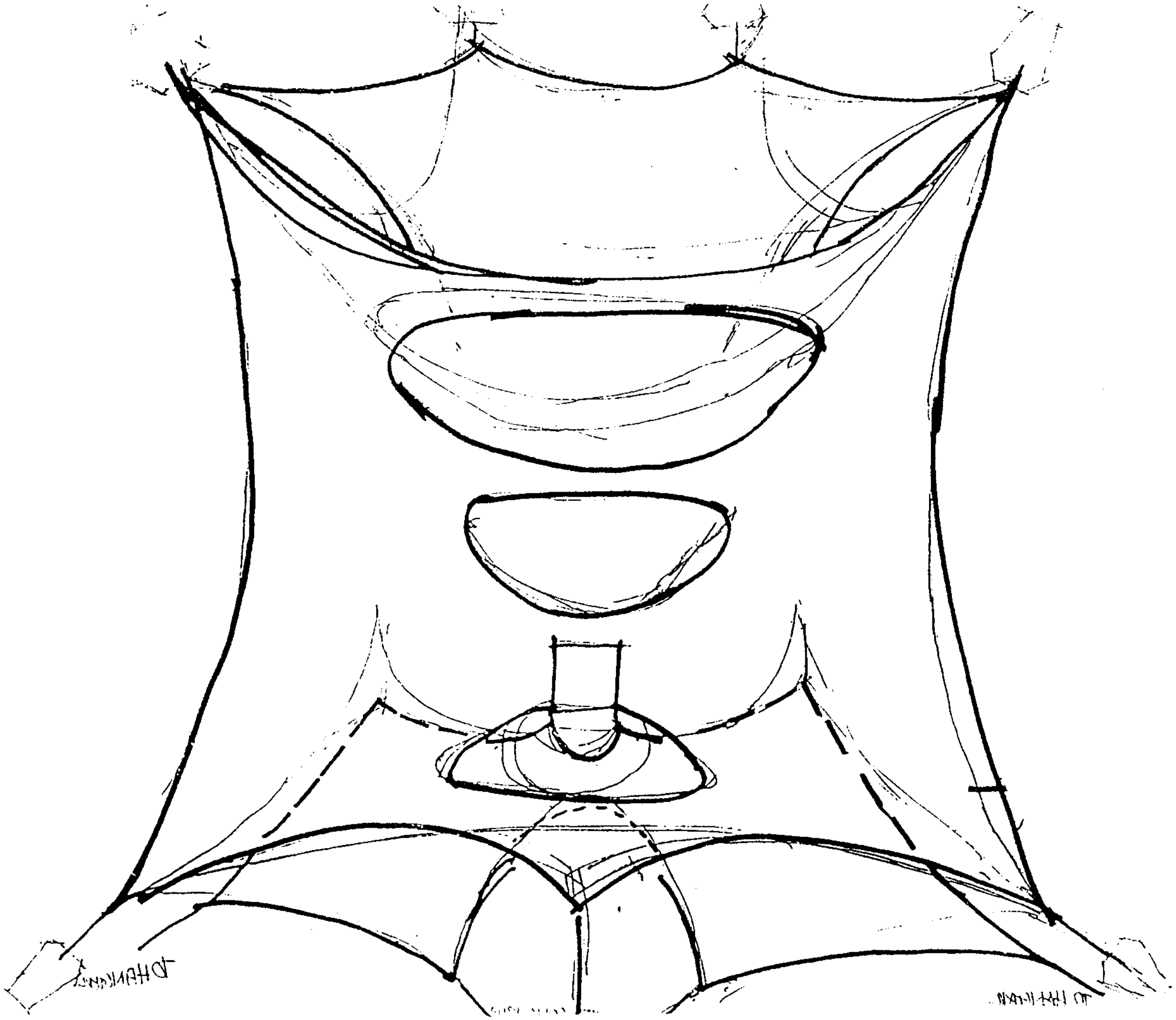


Figure 27 - Roof membrane study

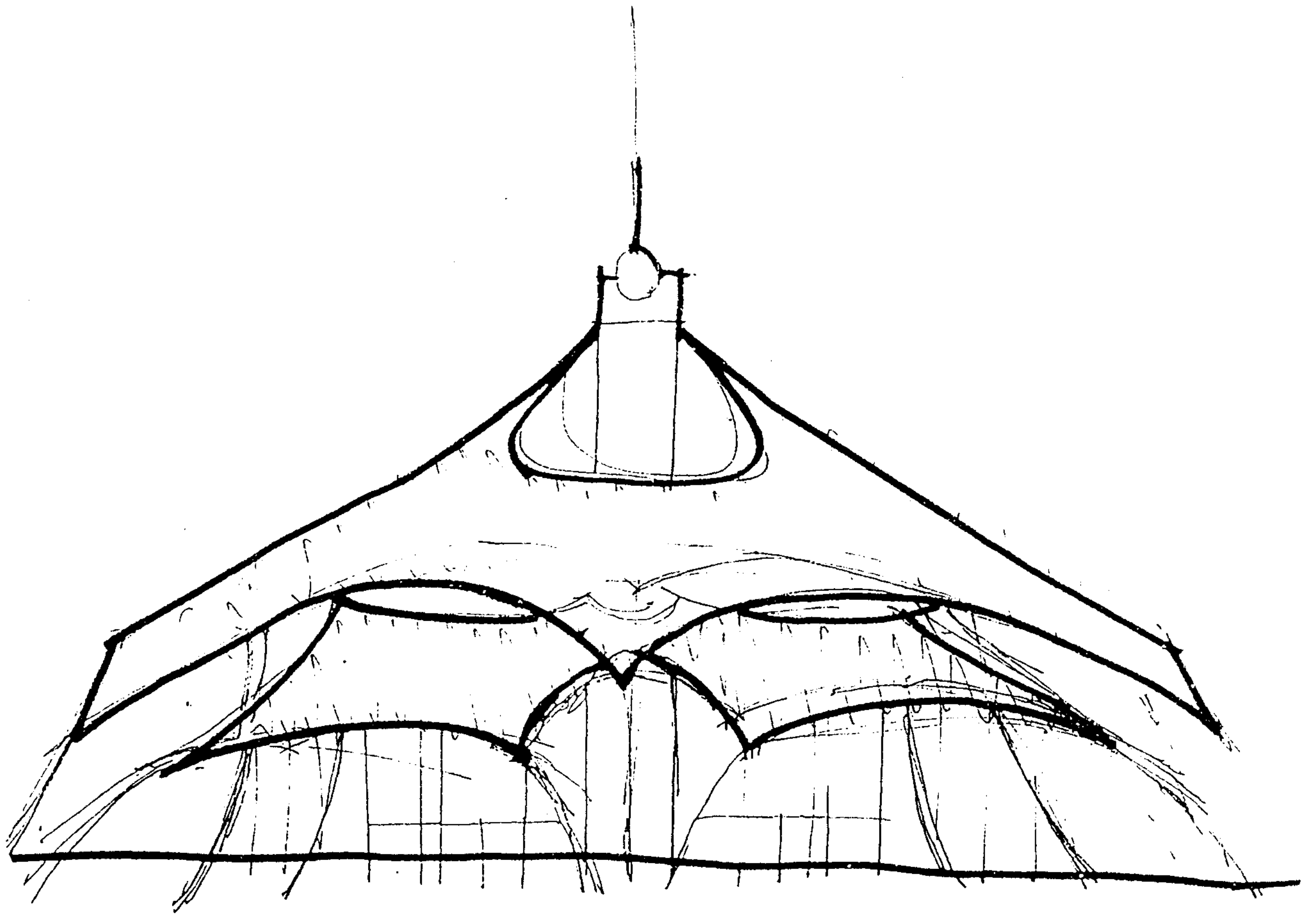


Figure 28 - Elevation study

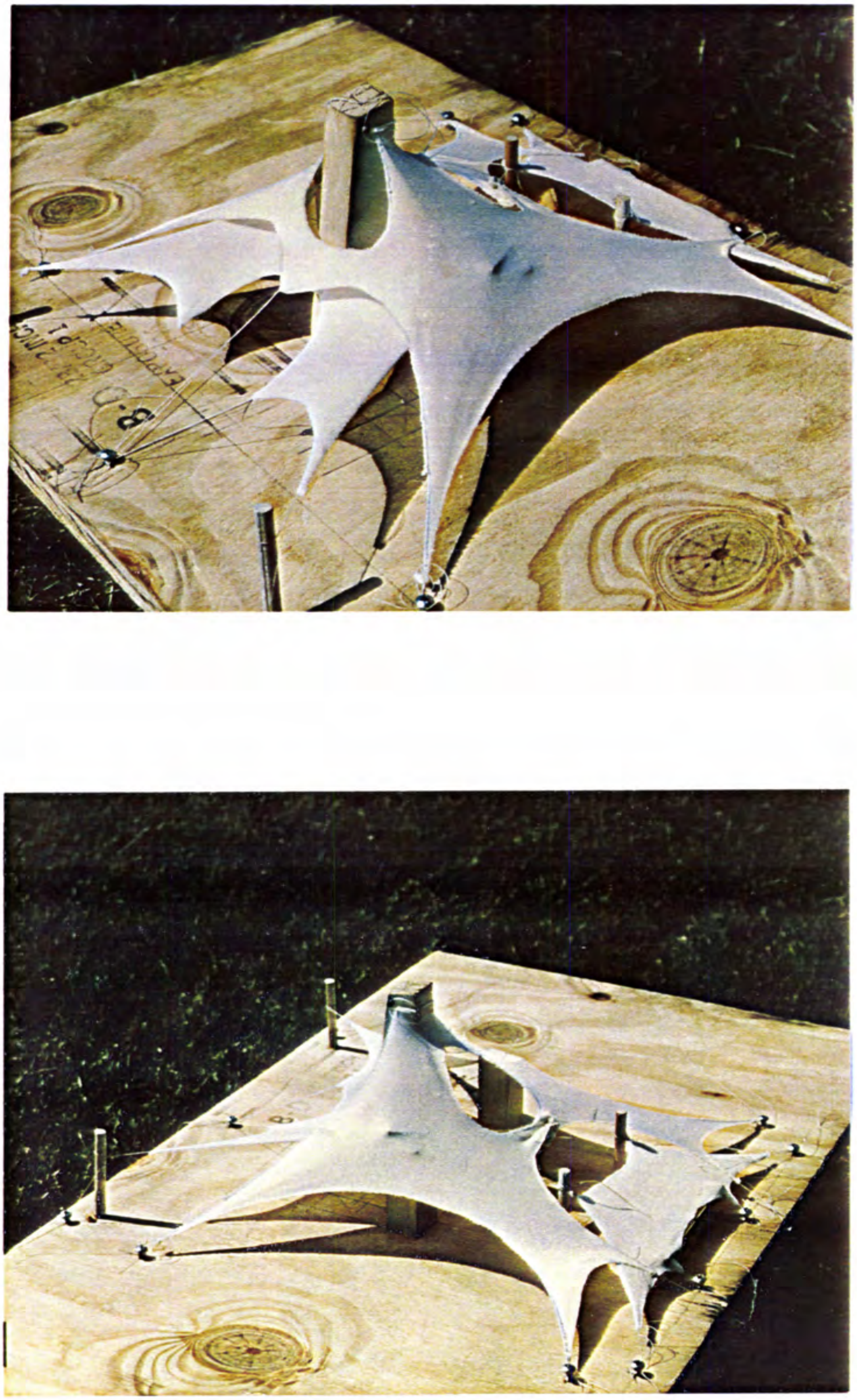


Figure 29 - Terminal study model

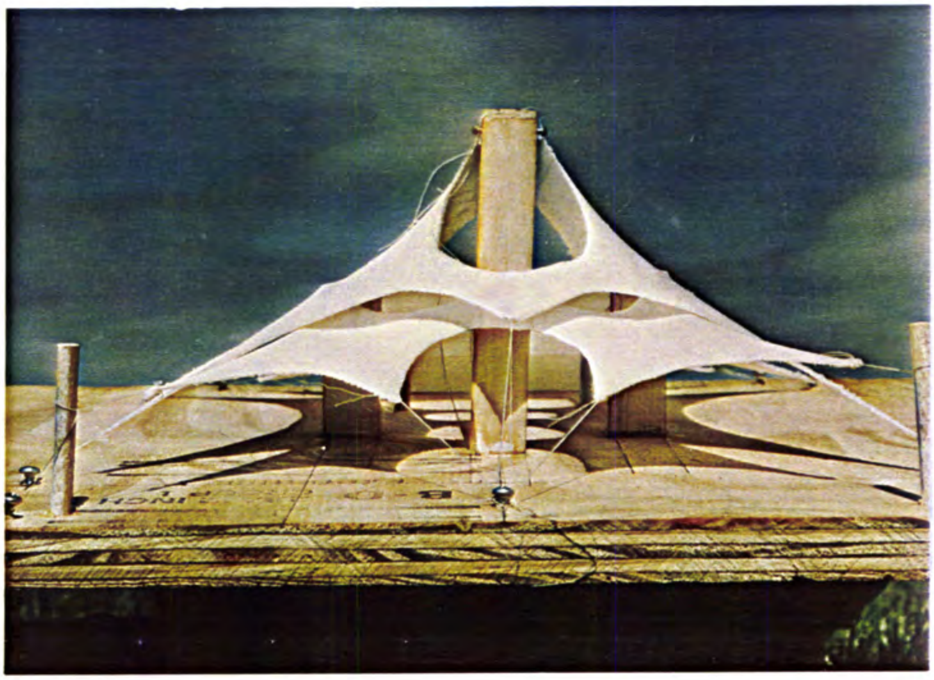


Figure 30 - Terminal study model - passanger entrance

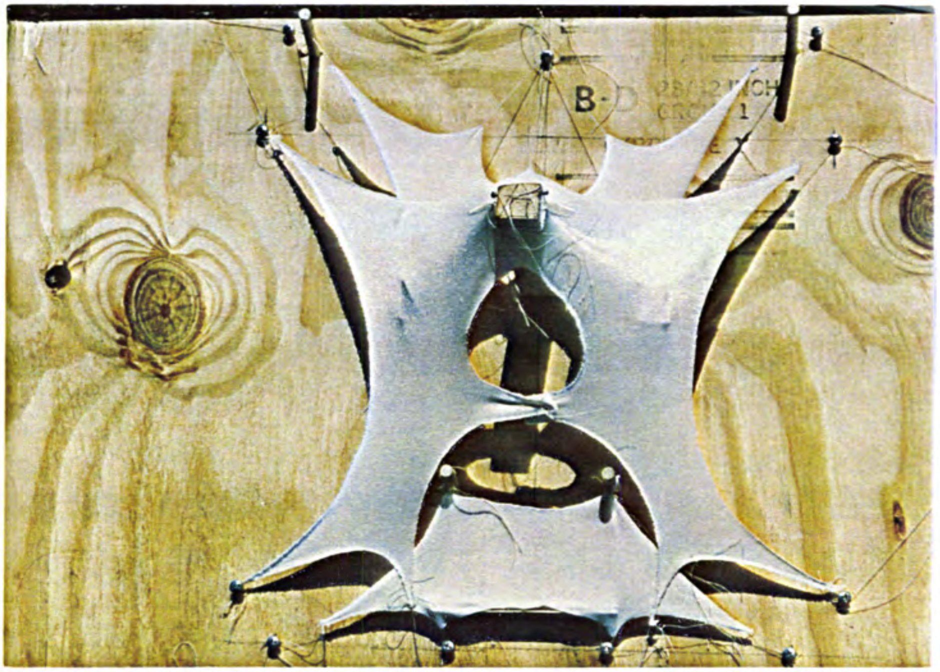


Figure 31 - Terminal study model - top view

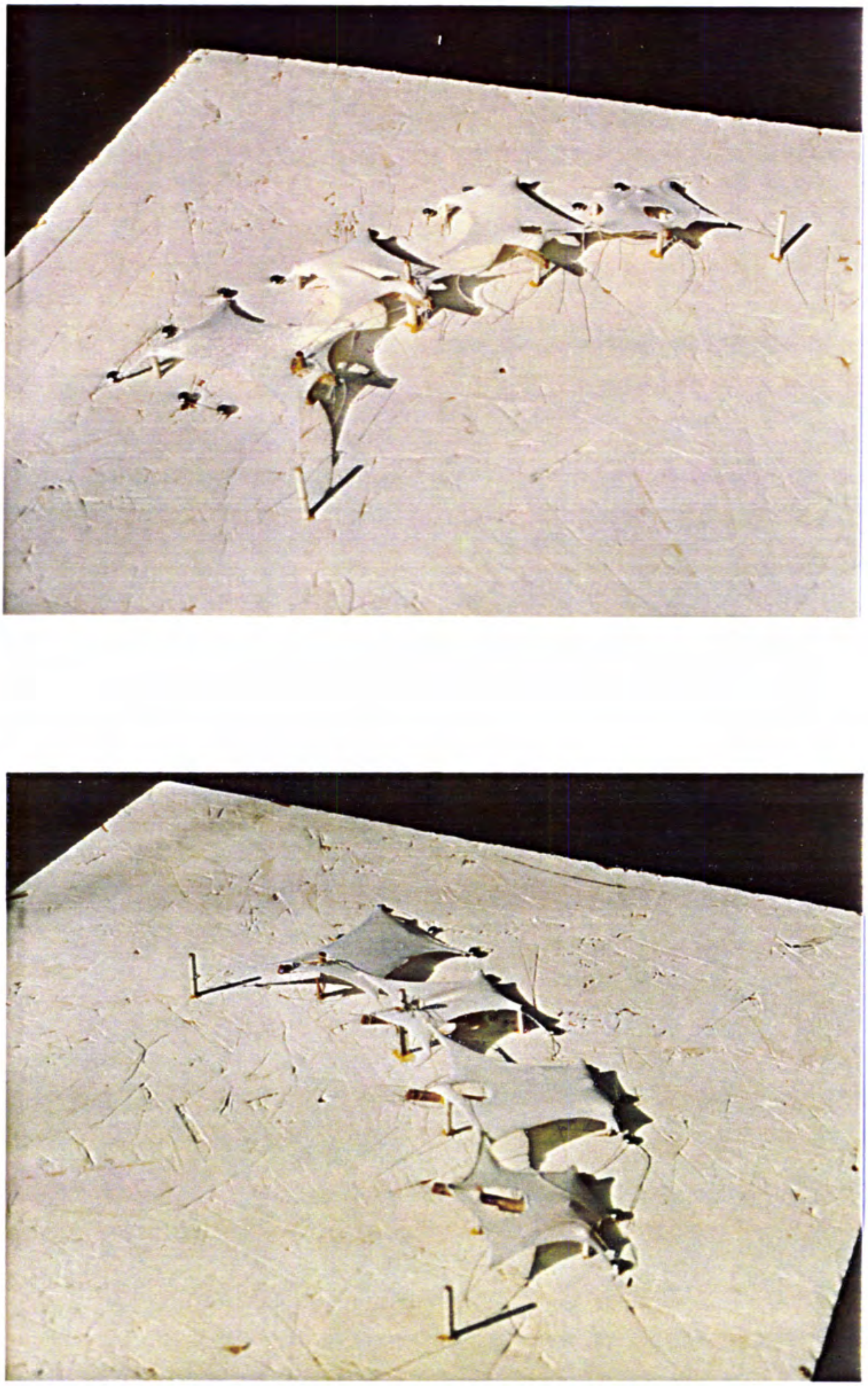


Figure 32 - Hangar study model

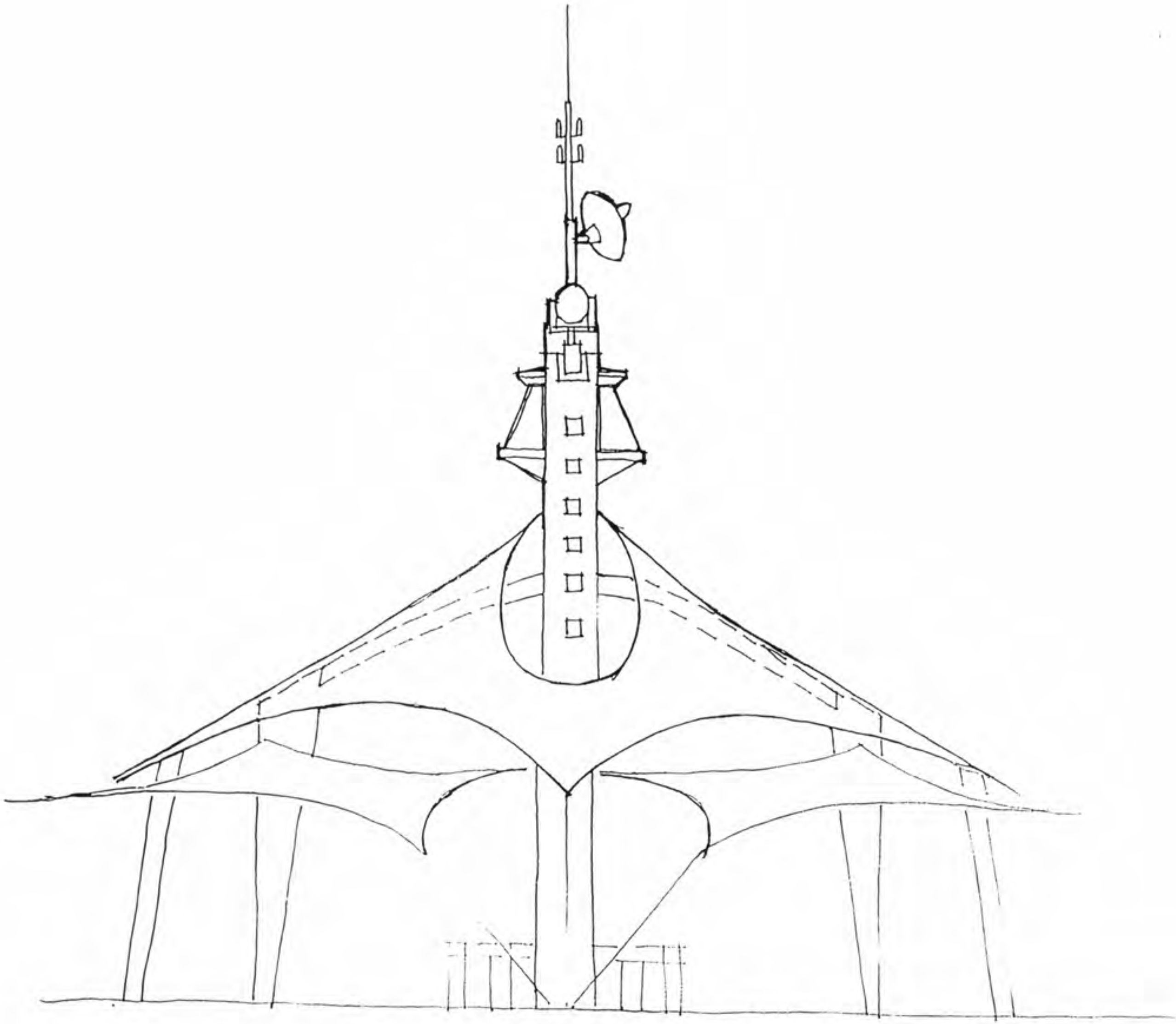


Figure 33 - Elevation study

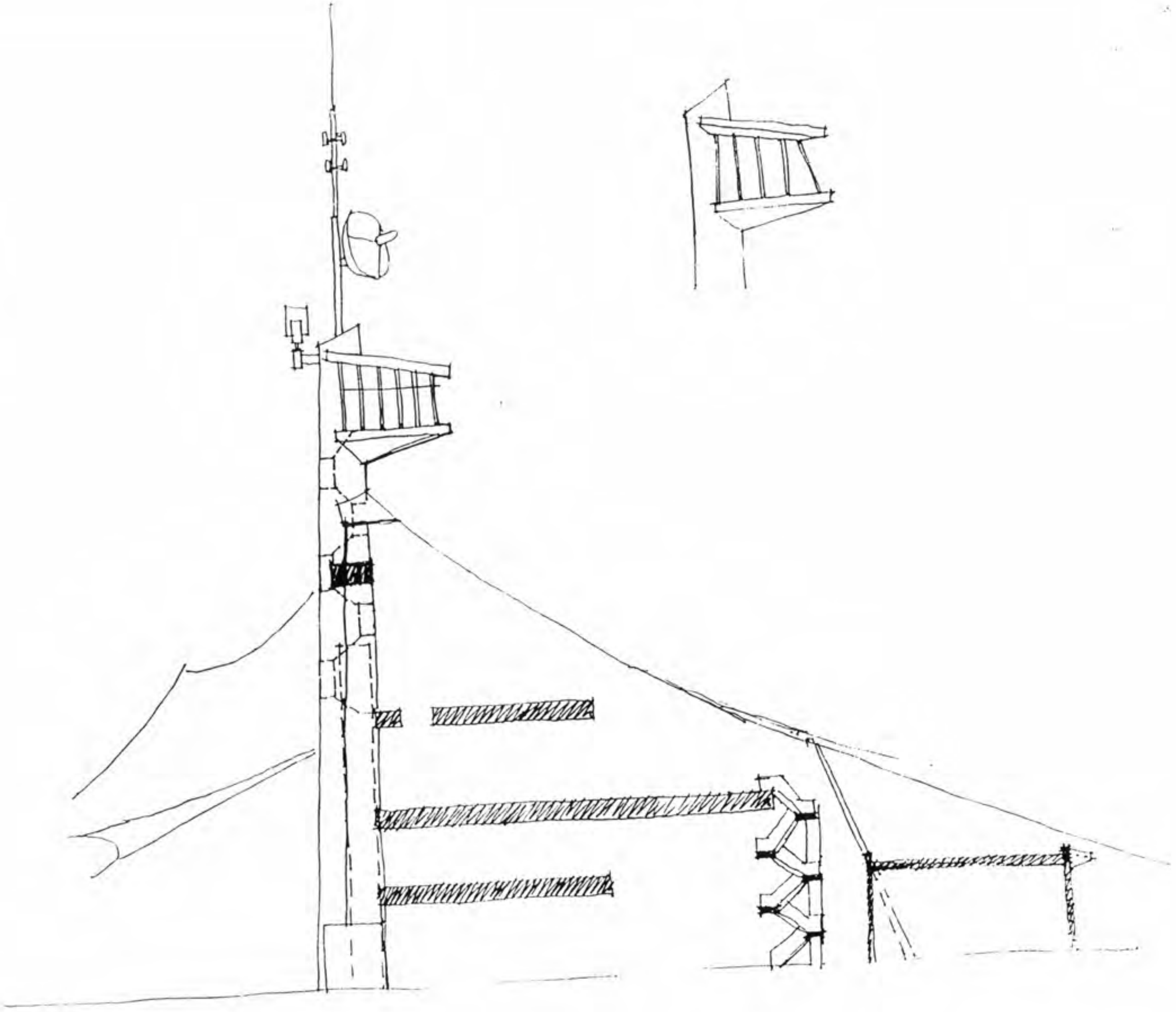


Figure 34 - Section study

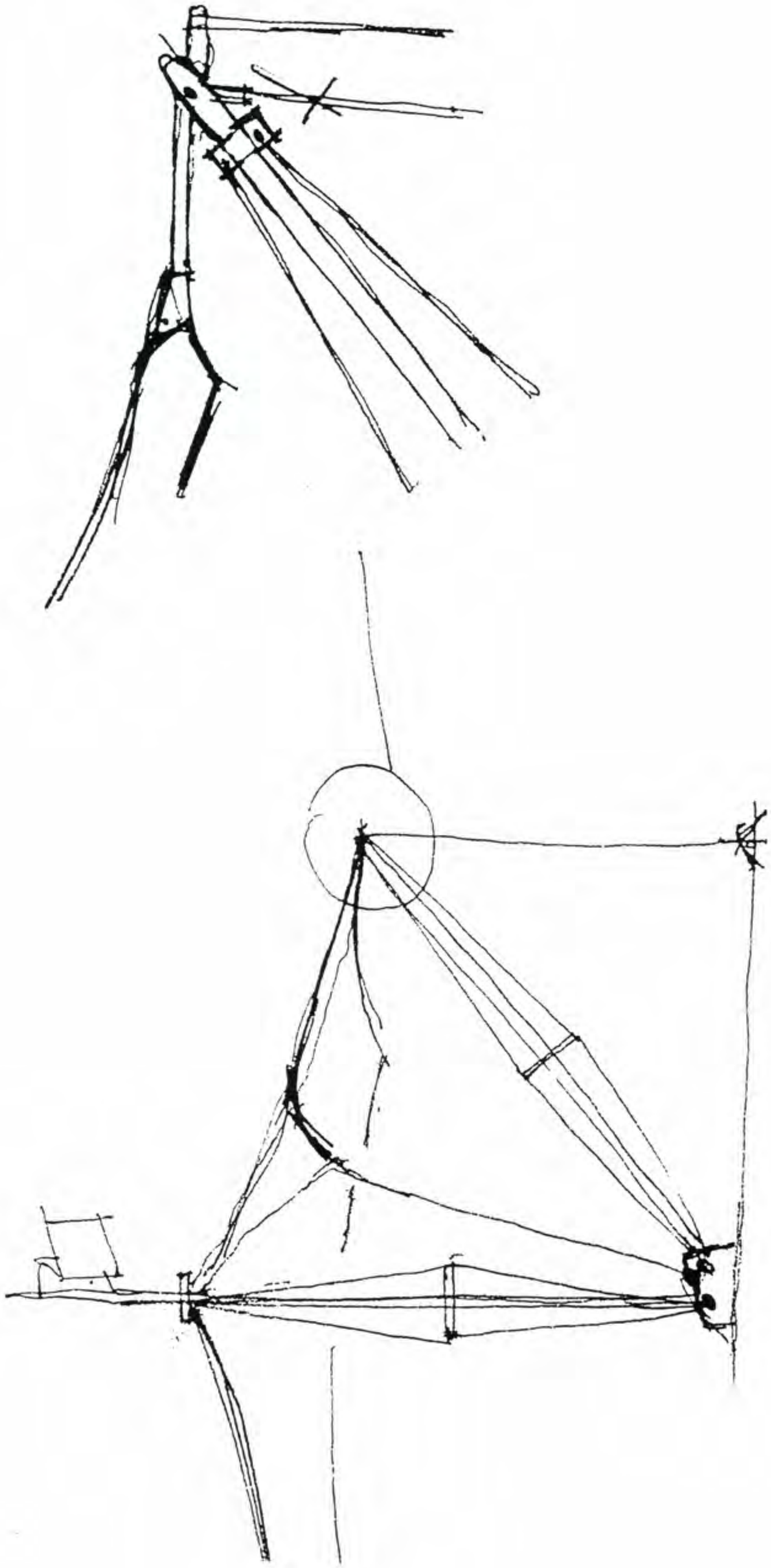


Figure 35 - Detail studies

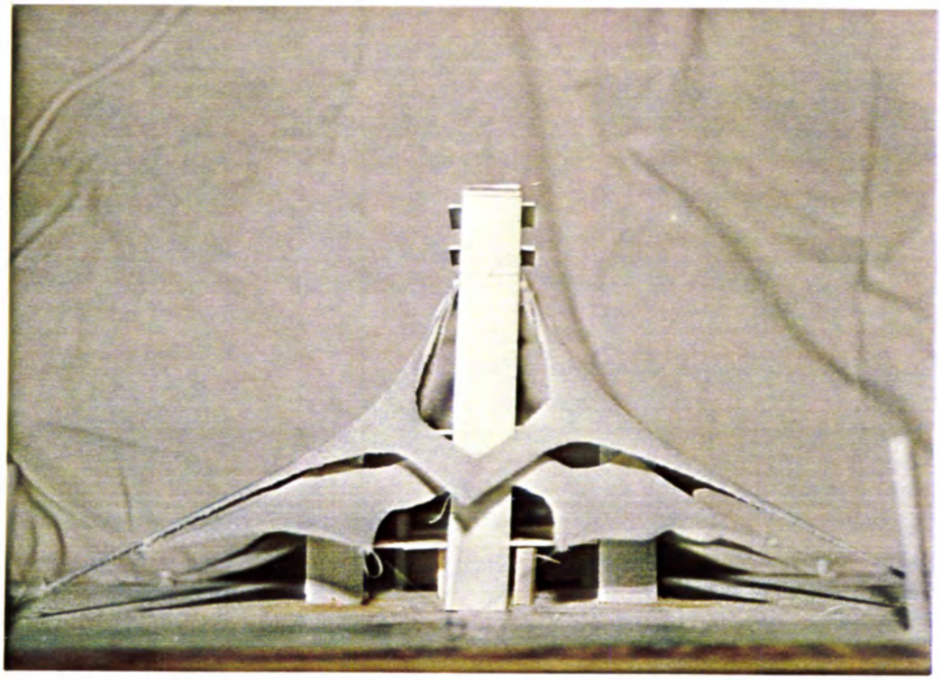


Figure 36 - Terminal study model - passanger entrance

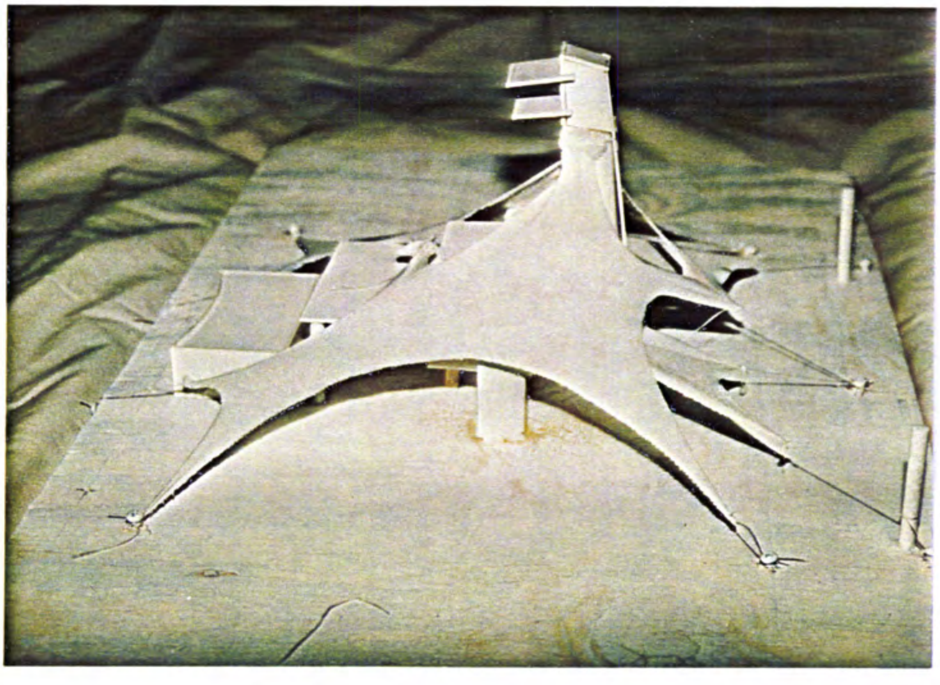


Figure 37 - Terminal study model - side elevation

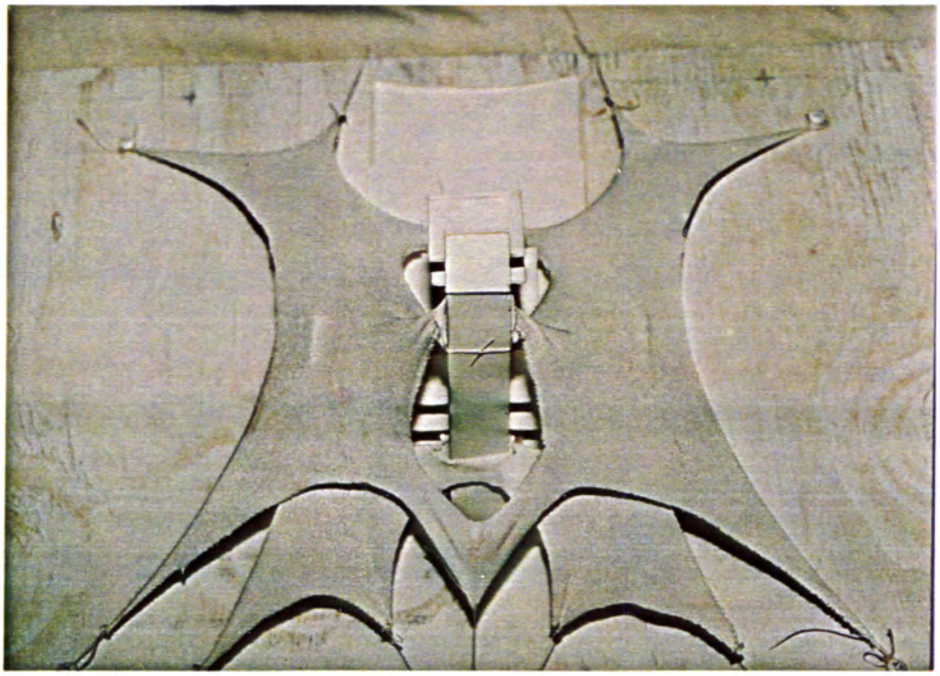


Figure 38 - Terminal study model - top view

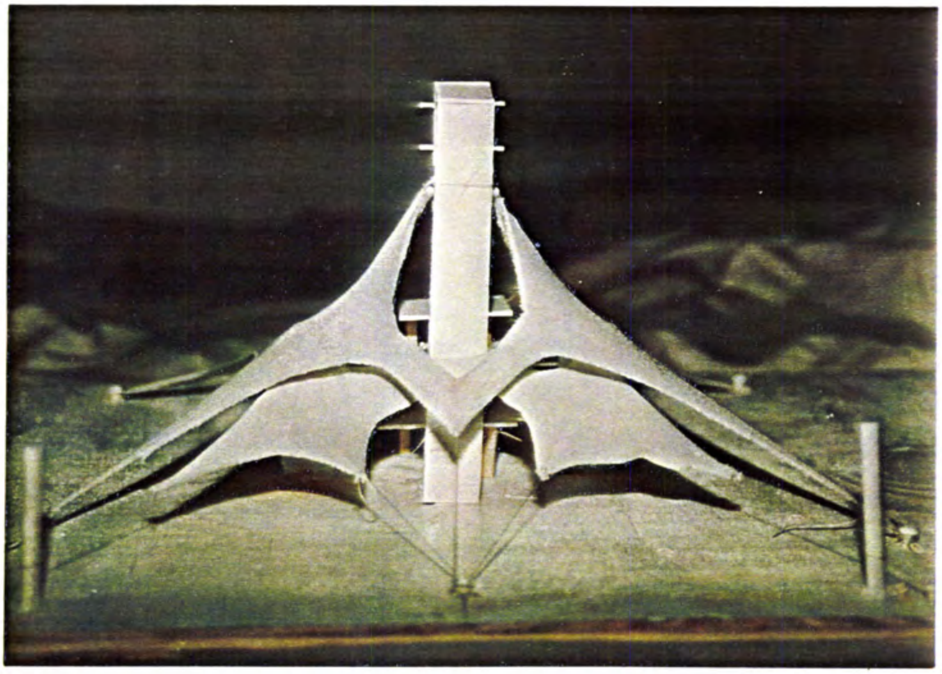


Figure 39 - Terminal study model

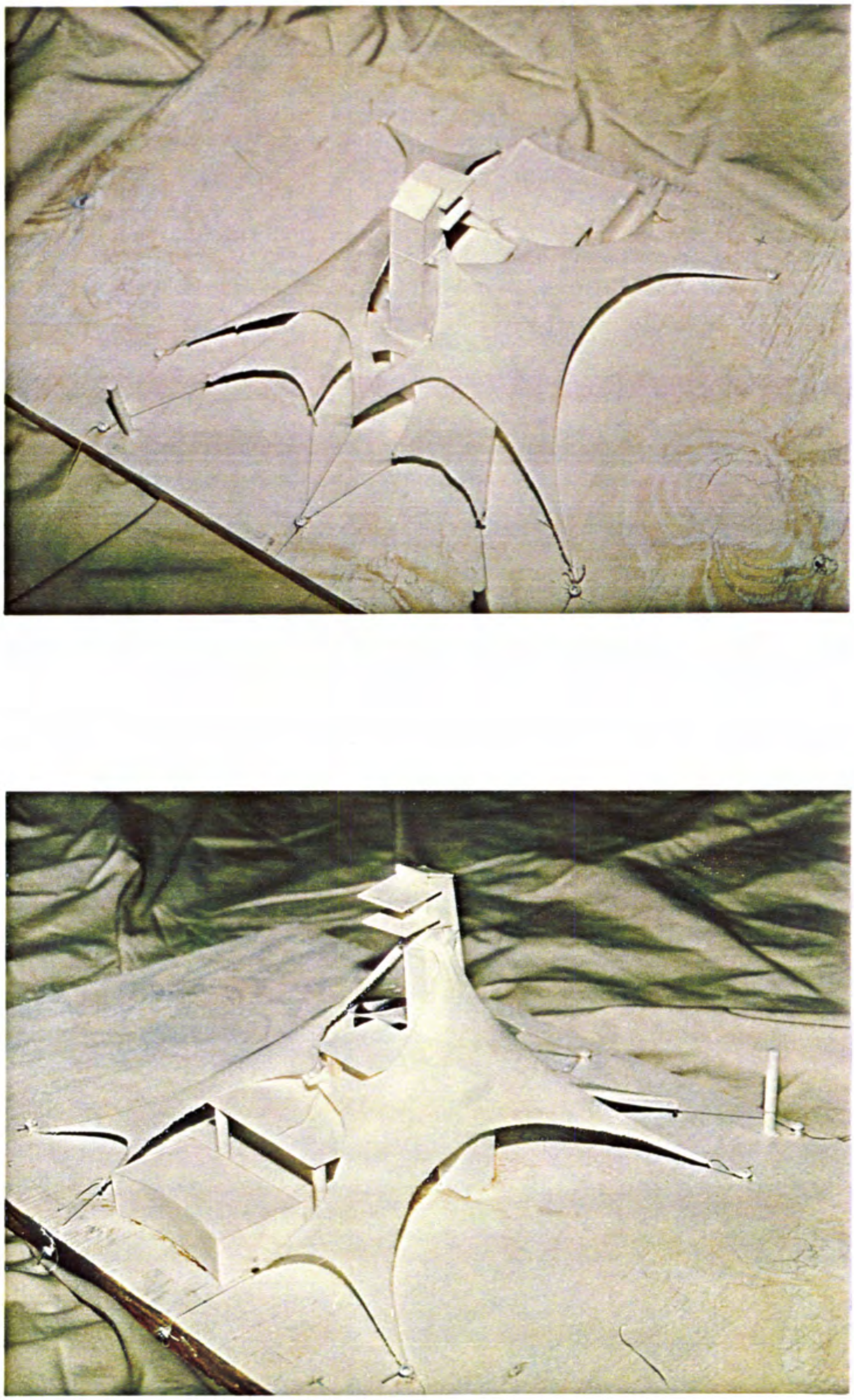


Figure 40 - Terminal study model

Final Solution

The final solution (Figures 41 - 55) would be to place the terminal and hangers as far away from the runways as the site would allow (Figure 41). Also, the terminal would be located so it would not be directly in line with the runways. This would reduce the level of sound reaching the terminal from departing planes. The taxiway would be aligned with the intersection of the runways with the terminal centered on the taxiway. This arrangement would allow for a logical progression for the aircraft, hanger, apron, passenger loading, taxiway, runway, and finally the wild blue yonder. Automobile parking would be placed between the hanger wings as close to the terminal as possible reducing travel distance with overloaded luggage. A covered drop-off would be provided at the main entrance with easy access to the parking area.

Inside the terminal, an open main floor plan would be utilized with all the related passenger functions (Figure 42). This would provide for visual access of the entire area by the passengers in order to easily determine the location of their desired destination. It also would provided unobstructed circulation for any sudden influx of passengers. The open plan would be accomplished by use of of the tension fabric which could span long distances without the use of supporting columns which otherwise would be present if conventional construction were used. The only columns needed within the space would be those required to support the upper floors which would consist of concrete waffle slabs.

Since the complex would be arranged symmetrically, the terminal would also be arranged symmetrically. The elevator would be placed on the centerline of the structure along with a stair and a baggage/storage space. At the sides of the elevator shaft would be placed a set of entrance doors leading through a vestibule to a large common lobby area. Ticket procurement, baggage claim, waiting area, and passenger loading areas would be placed on each side of the centerline so that two flights could be readied and depart simultaneously. This symmetrical arrangement would be continued to the exterior by providing two taxiways, on each side of the centerline, separated by a pond (this would augment the view from the lounge and restaurant areas).

The second floor would contain the airport administrative offices (Figure 43). The offices would overlook the public main floor to allow for the observation of the activities below. On the third floor, the restaurant would be placed to provide an elevated view of the runway, pond, and surrounding countryside (Figure 43). The lounge would be placed above the restaurant to provide a good view (Figure 43). The control tower would be placed at the top (Figure 43).

The form of this terminal is within the morphology of fabric structures which Harry Daugherty calls a cone. The elevator shaft also would serve as a mast to suspend the fabric membrane. The fabric would be tensioned at the perimeter by cables anchored to concrete pier footings located below grade level. The hangars also would use the same morphology and perimeter attachment cables. They would also be open-sided. The mast for the hangers would be a truss column. The columns would consist of slender pipes braced from deflection by four prestressed cables each. All of this would require a structural engineer to determine the component sizes and connections.

The proposed membrane for the terminal would be 20-26 ounce laminated fabric, consisting of polyester mesh with a teflon film. This fabric would provide adequate strength and durability as well as economy and would have less elongation than other available fabrics. The teflon coating will protect the polyester fabric from the sun's harmful rays as well as eliminate the accumulation of dirt on the membrane. In order to increase the thermal resistance of the roof membrane a light weight fabric inner liner and batt insulation would be placed below the main roof membrane. For condensation a vapor barrier and gutter system would be installed. Over the restaurant and lounge a transparent film would be used as a window onto the view outside. The fabric for the hangers could be the same material as the terminal.

An inherent quality of fabric is its light weight appearance. To further emphasize the lightness of the fabric, all materials would be selected for their visual qualities and the connections and elements detailed as minimal as possible. The fabric would be anchored by perimeter cables. The pier footings' heavy mass would be removed from sight. The elevator shaft/mast would be engineered to be as slender as possible and cladded in partially transparent panels of some type. Below the fabric membrane, the enclosure walls would be set back from the edge. Since the walls would not be required to be structural, the walls do not necessarily need to be vertical, so they would be tilted. The walls would be constructed of clear plate insulating glazing units in aluminum framing. The glass would be butt glazed to reduce the visual impact of the aluminum framing.

Heating and cooling of the fabric roofed terminal would be a challenge. The mechanical ducts would not be hung from the roof structure as they would be from a conventional structure, although ducts could be hung from the concrete slabs of the upper floors and buried below the slab on the main floor. A mechanical room would be placed under the lobby area, which would contain the required air handling equipment. Two main duct risers would extend from the mechanical room to the top floor. The duct system for each floor would tie into one of the main ducts in order to remove heat from under the membrane and to provide for exhaust air. A second duct system would be placed next to the main supply ducts. This duct would return the air to the mechanical room for retreatment and redistribution or to be exhausted directly outside through a pair of exhaust air ducts located by the main entrances.

Fresh air would be obtained from intake air ducts located next to the exhaust air ducts with care taken not to recirculate the exhausted air. The air conditioning condensing unit would be located outside the baggage/storage area.

To illuminate the areas within the terminal a combination of indirect and direct lighting methods would be used. The underside of the fabric membrane would be used to reflect and diffuse light down to the areas below. Where the indirect light could not reach direct lighting would be used. Also, where additional illumination would be required, direct lighting would supplement the indirect lighting.

Summary

Although the design is presented as a final solution, it is far from being finalized. There are several areas which will need additional studies, calculations, and tests. First, several consultants will need to be added to the design team: a mechanical engineer, an electrical engineer, a structural engineer, and a landscape architect as well as a fabric roof consultant, airport consultant, and a food service consultant (for the restaurant's kitchen).

A further area of study would be the final determination of the form of the hangars. It appears that the membrane is too flat, not producing enough stability to withstand the imposed loads (especially the Iowa snow loads). To remedy this potential problem, the center mast should be extended to produce more curvature in the membrane. The mast should still remain shorther than the peak of the terminal to maintain the prominence of the terminal.

Another area in need of study would be the connection between the curtain wall and the cable net of the roof structure. With the potential of high deflection in the cable net, the connection would be required to be flexible and waterproof, yet still withstand the windloads.

Following the fine tuning of the form and the connections, wind tunnel tests or computer generated models would require analysis to determine the structural performance during expected windloads. This would especially apply to the hangars since they would be open-sided. The patterning of the fabric membrane would have an influence on the visual appearance.

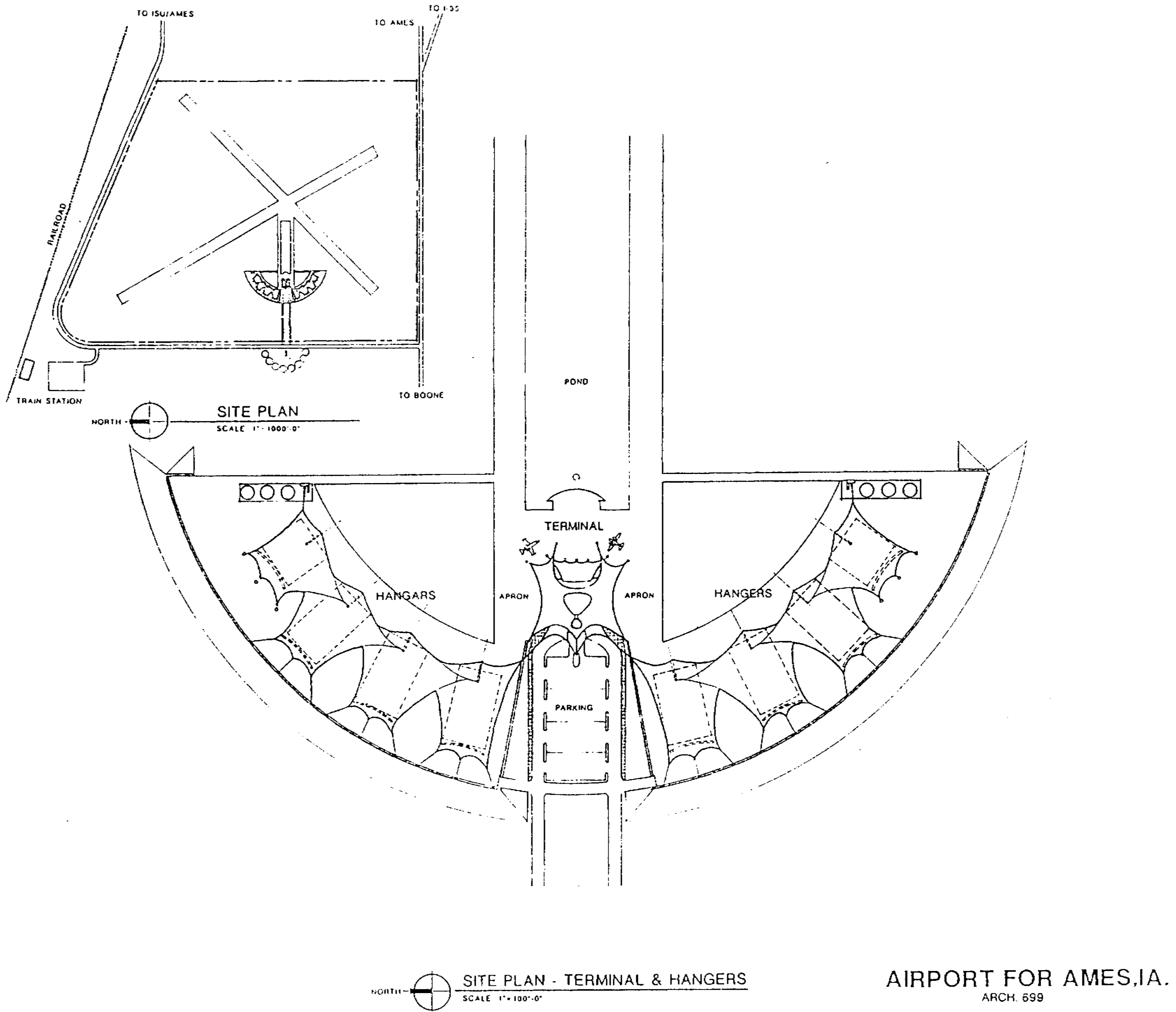


Figure 41 - Final solution site plan

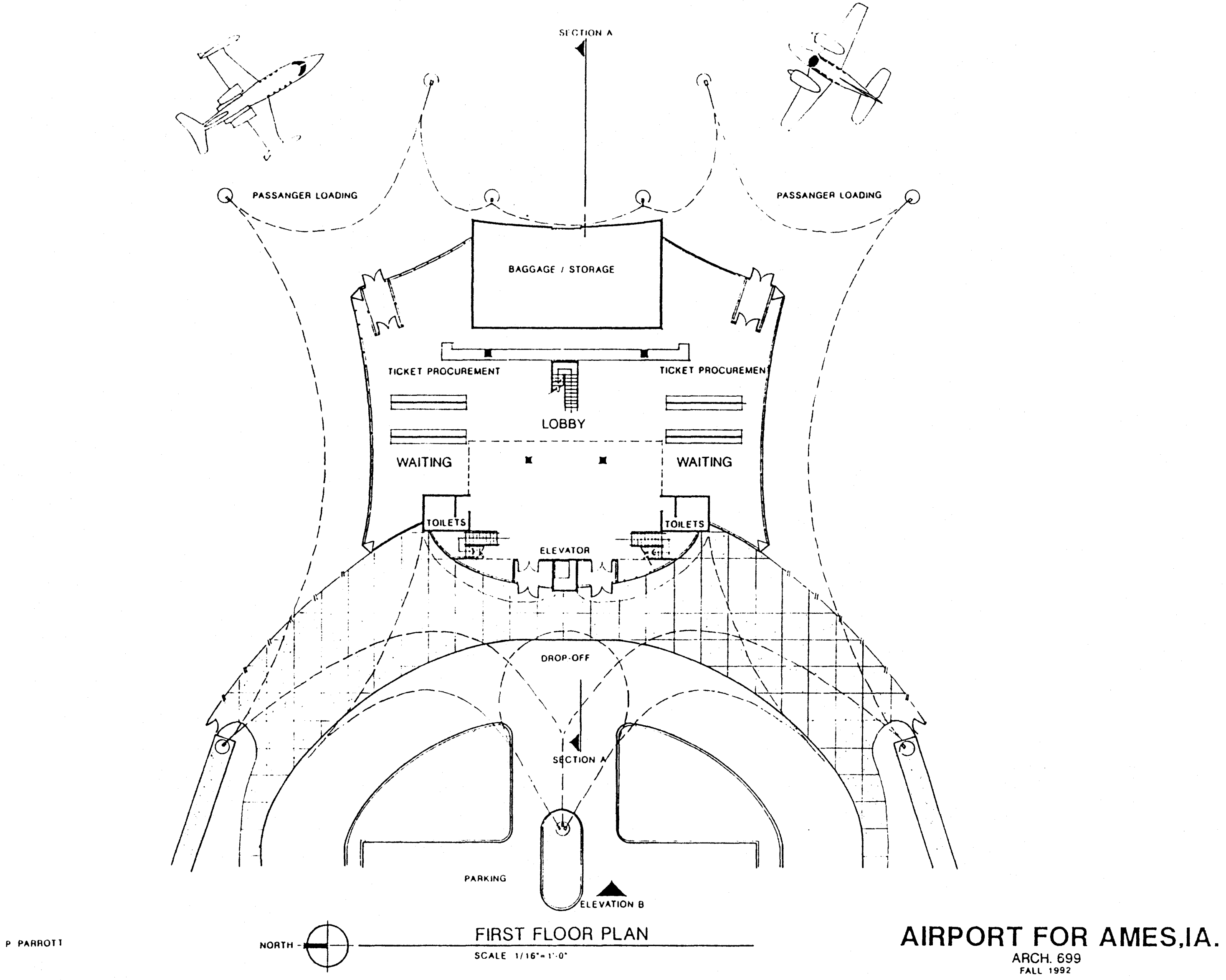


Figure 42 - Final solution first floor plan

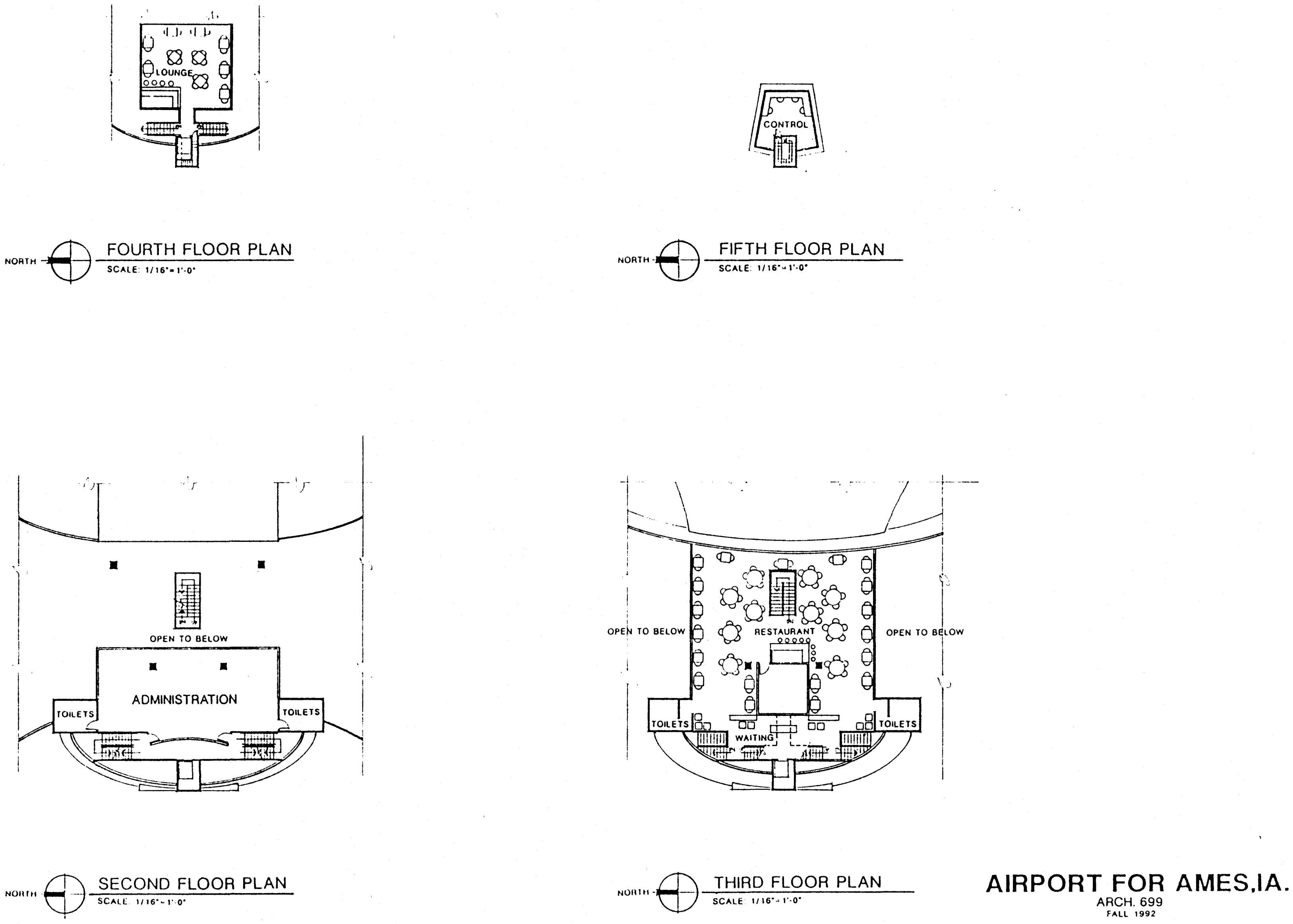


Figure 43 - Final solution upper floor plans

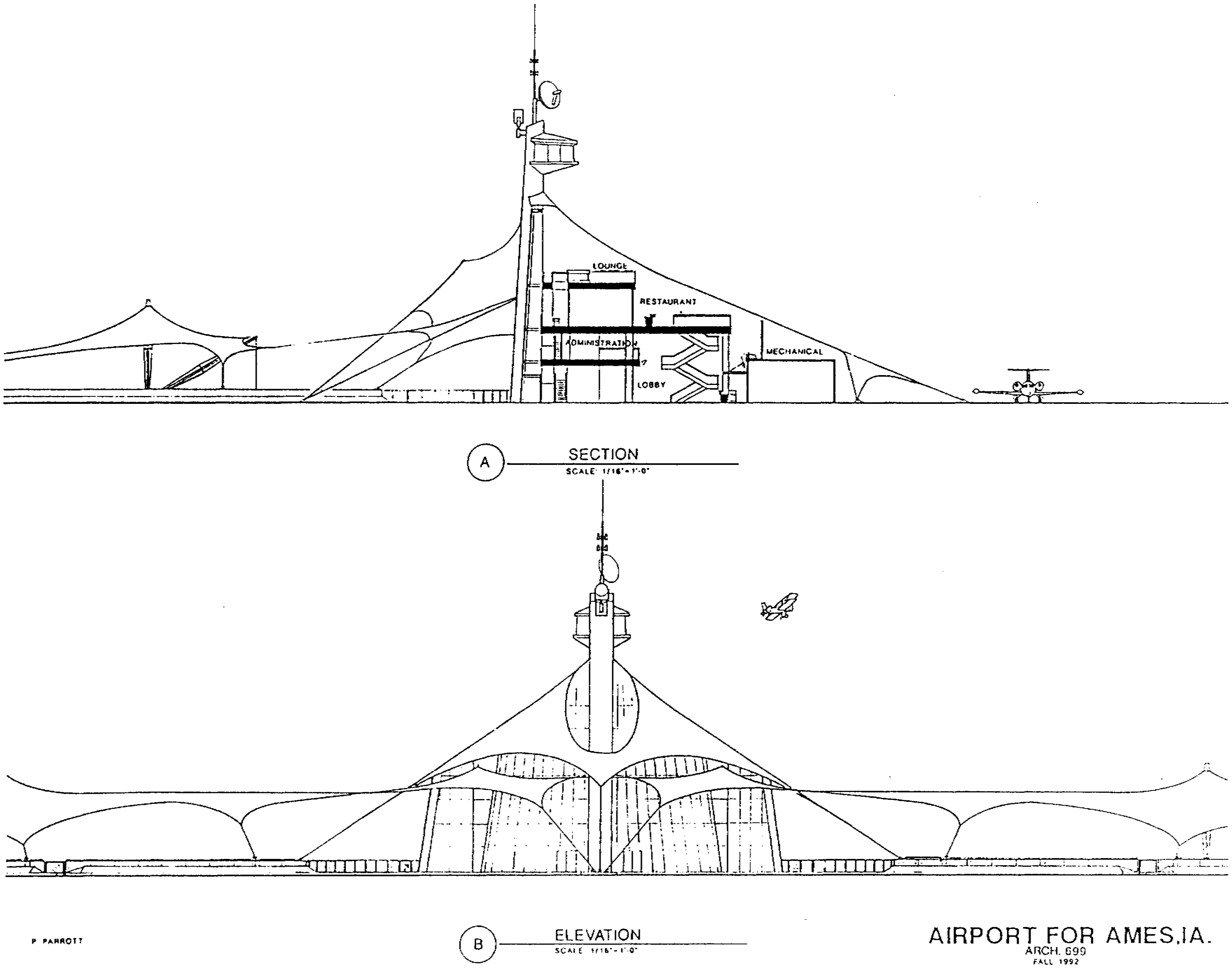


Figure 44 - Final solution section and elevation

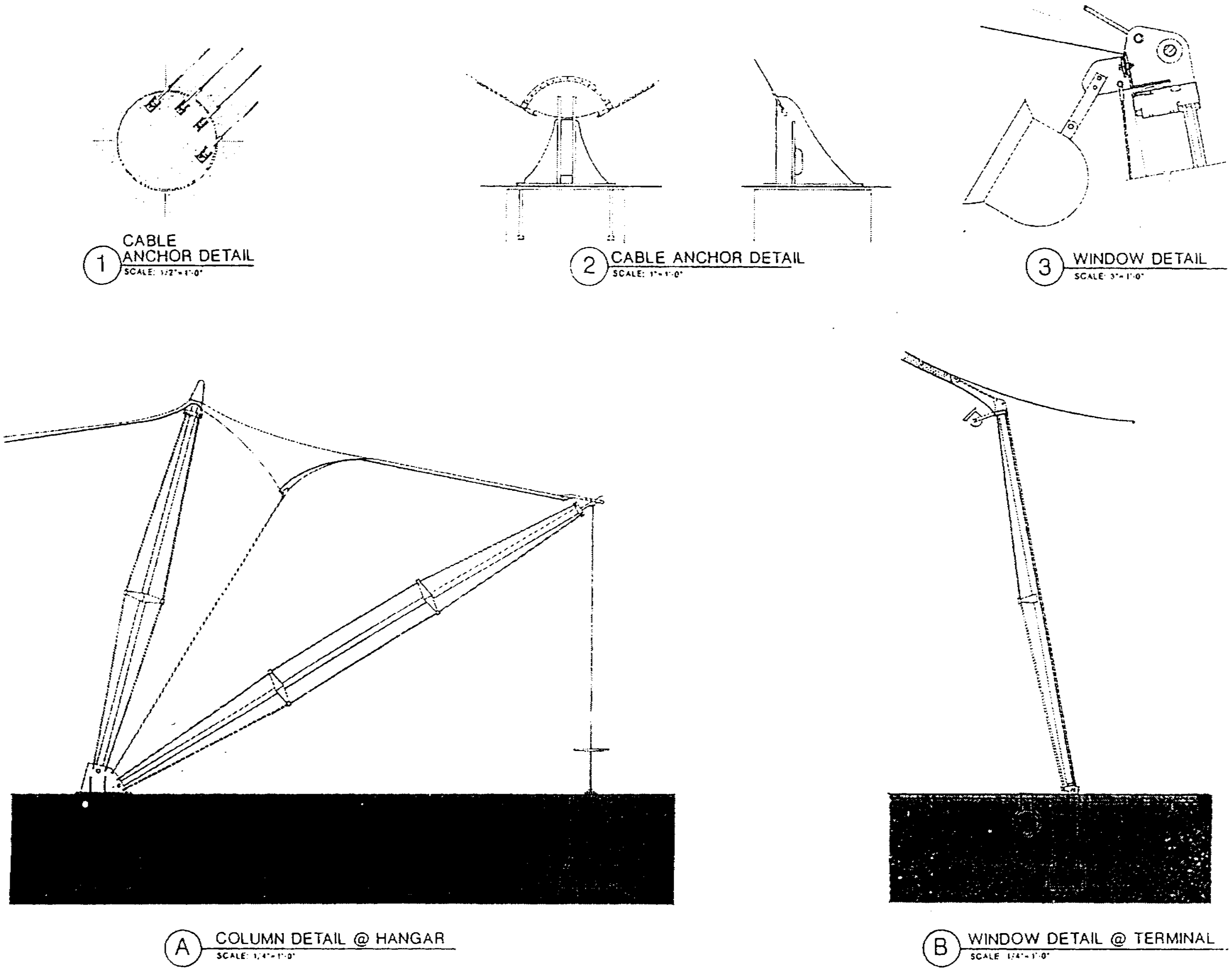


Figure 45 - Final solution sections and details

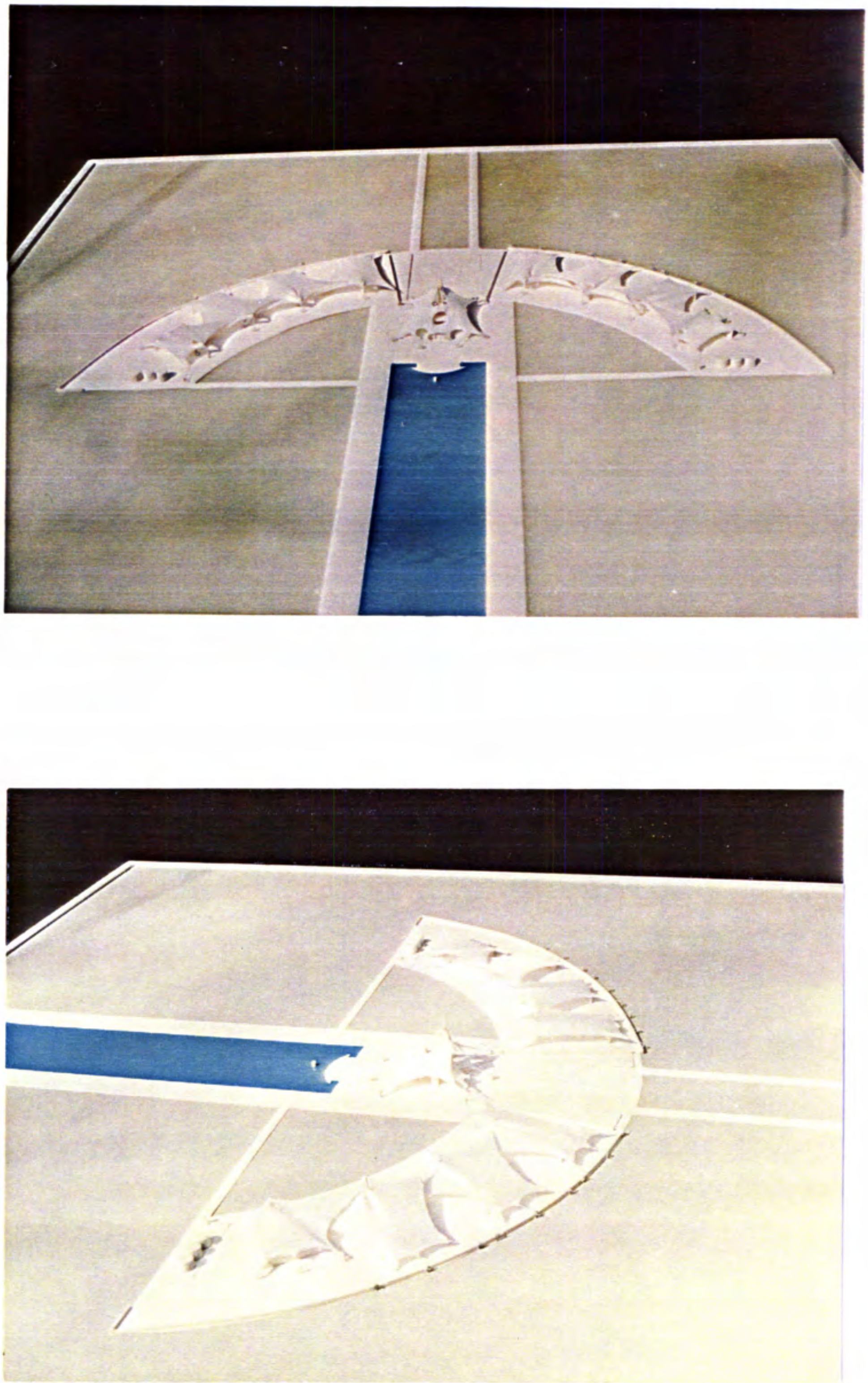


Figure 46 - Site model

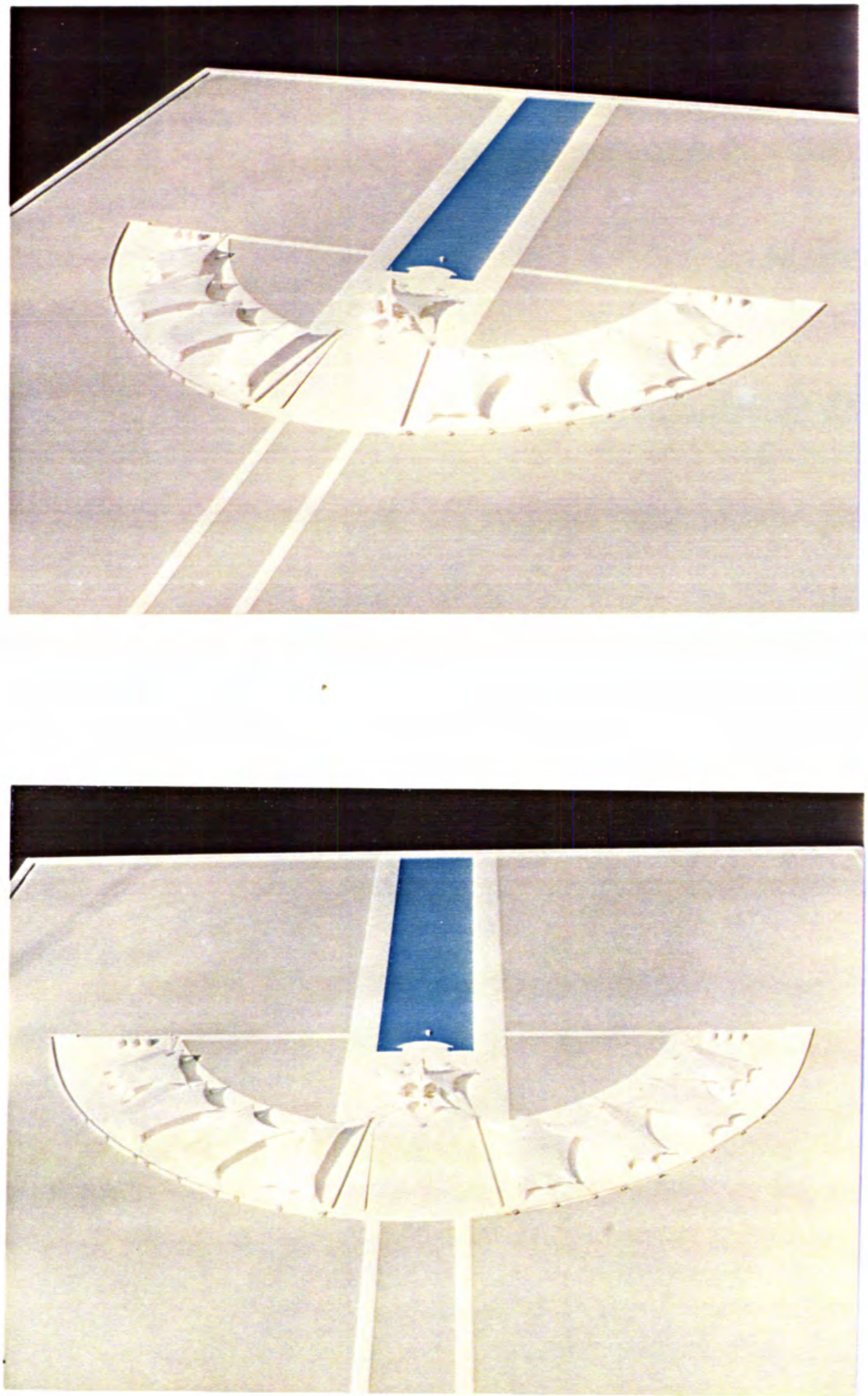
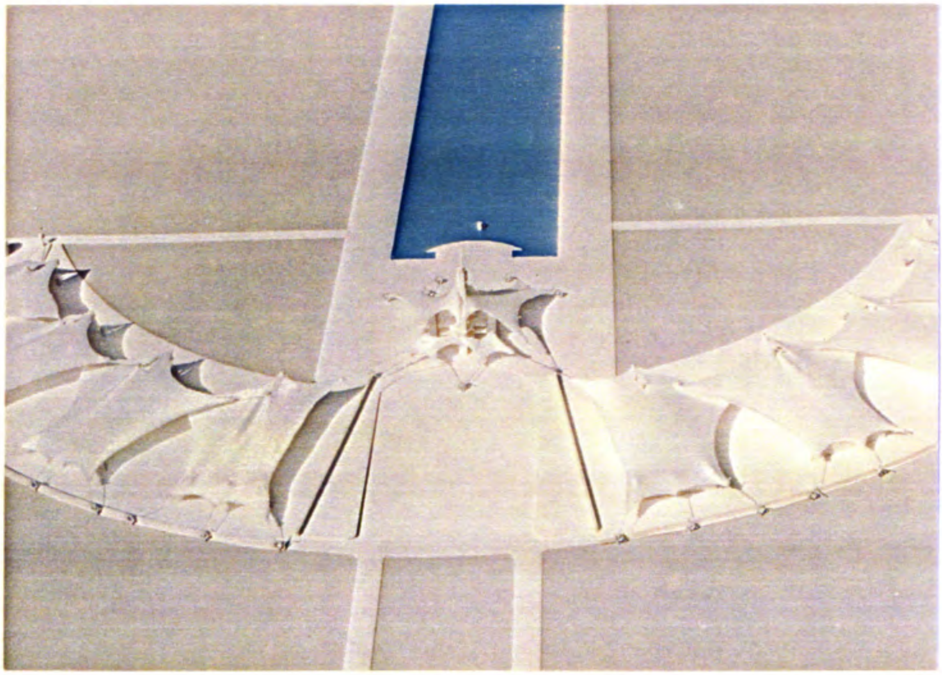


Figure 47 - Site model



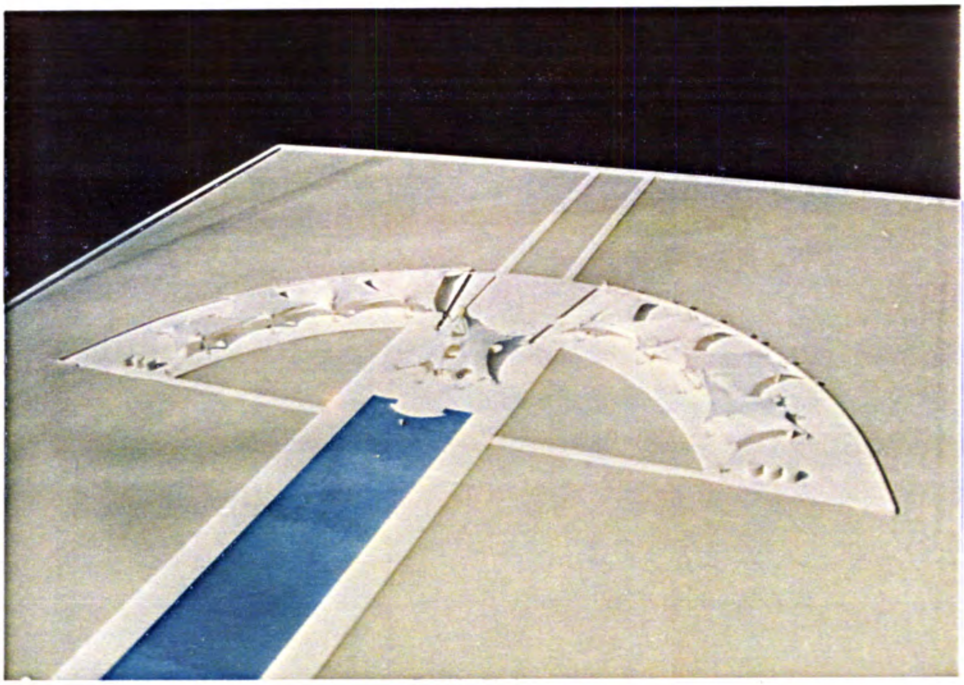


Figure 48 - Site model

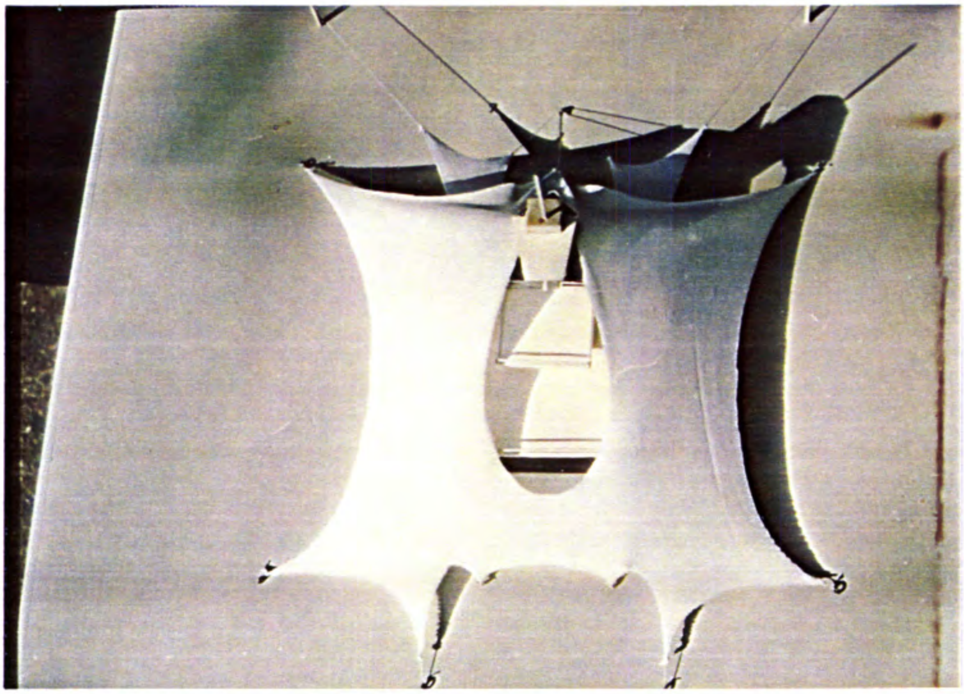


Figure 49 - Terminal model - top view

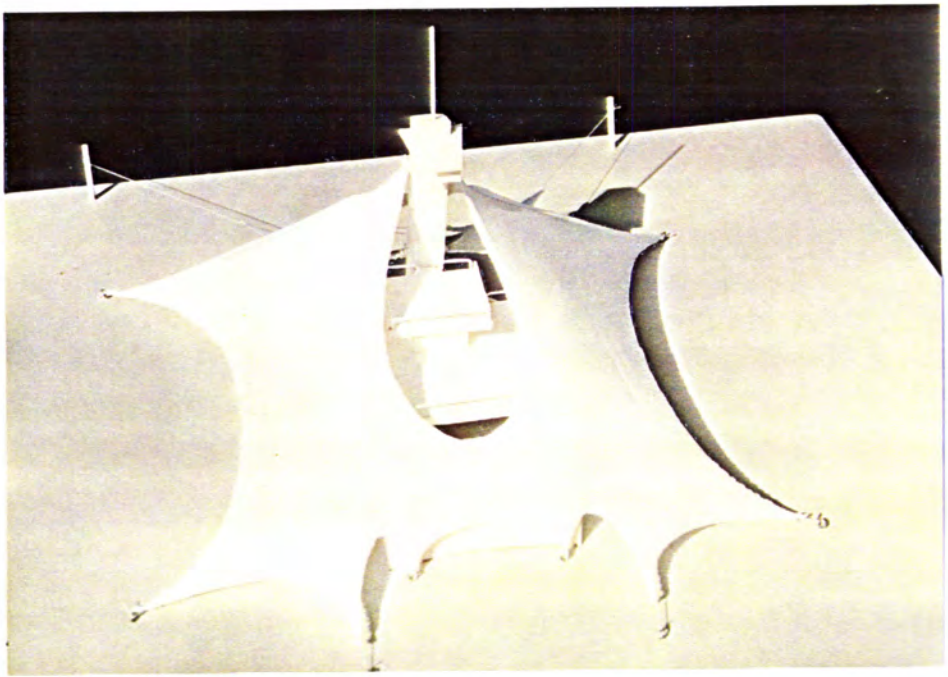


Figure 50 - Terminal model - runway side

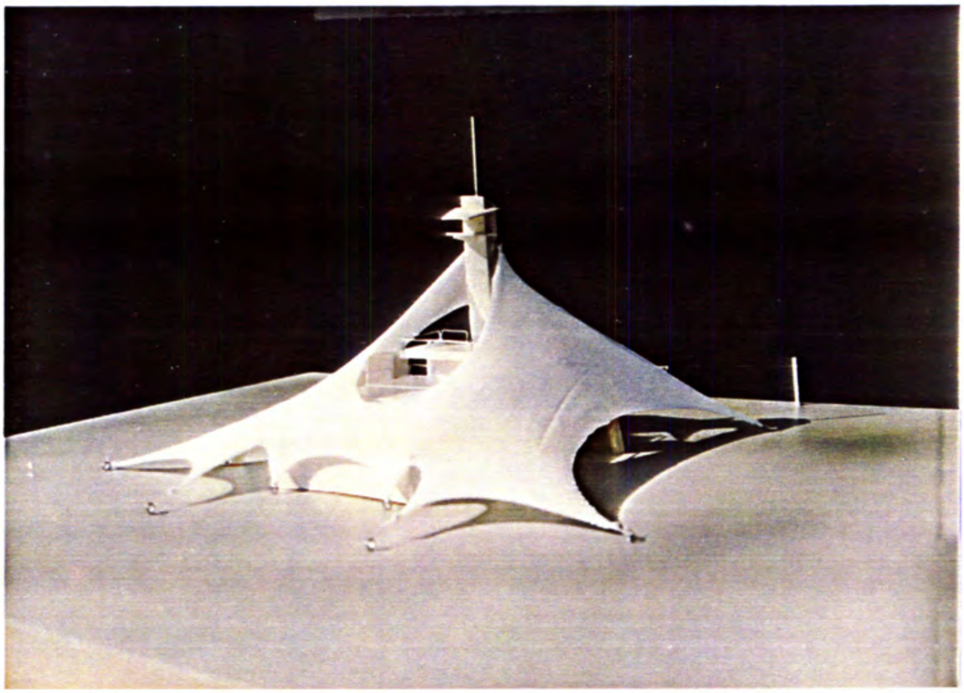


Figure 51 - Terminal model

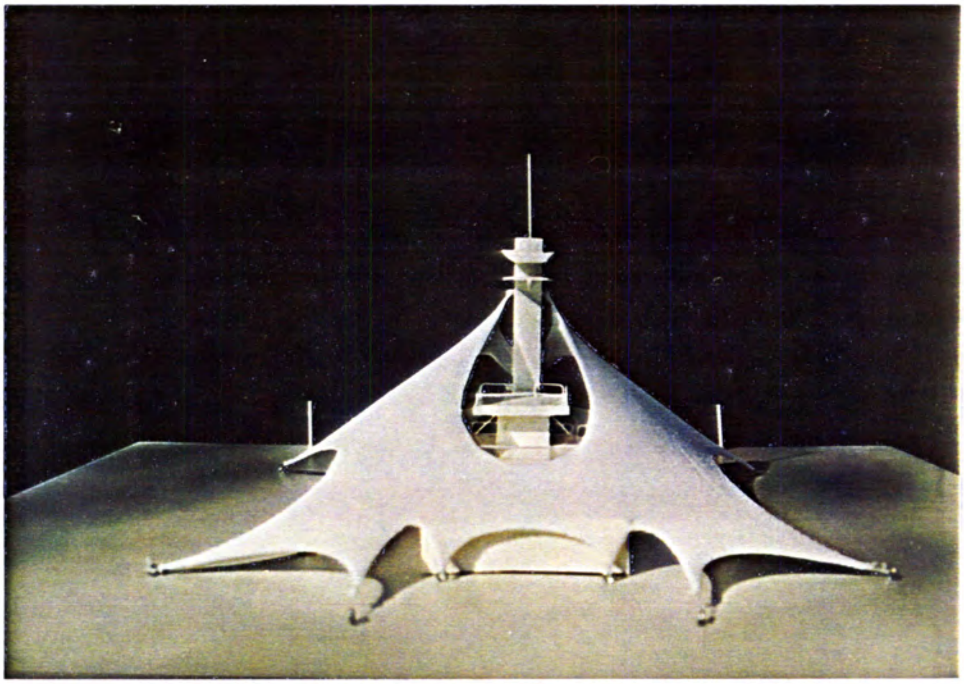


Figure 52 - Terminal model - runway elevation

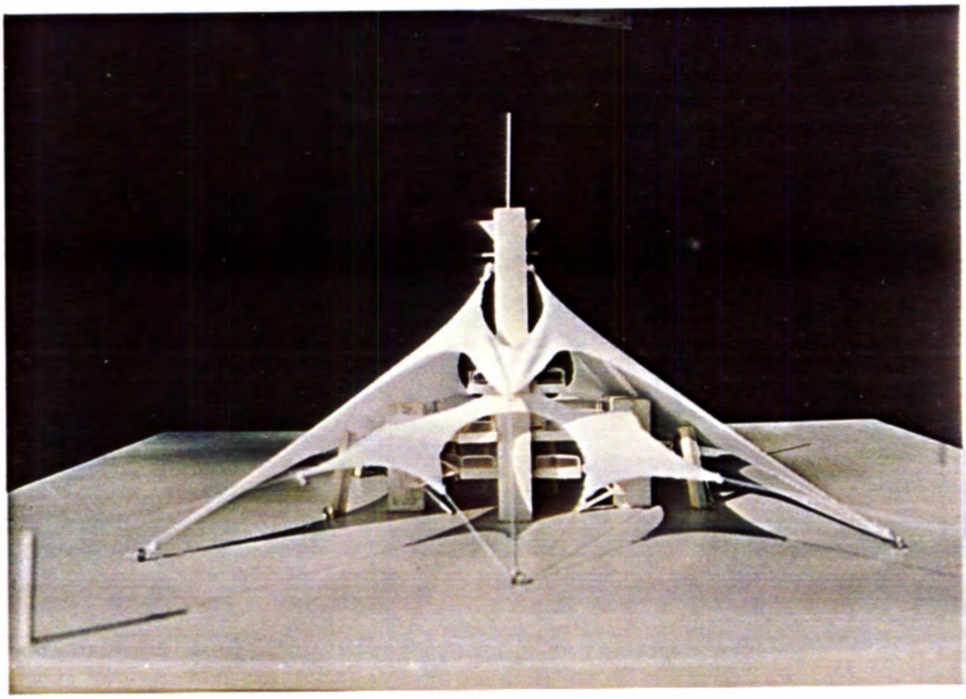


Figure 53 - Terminal model - passanger entrance

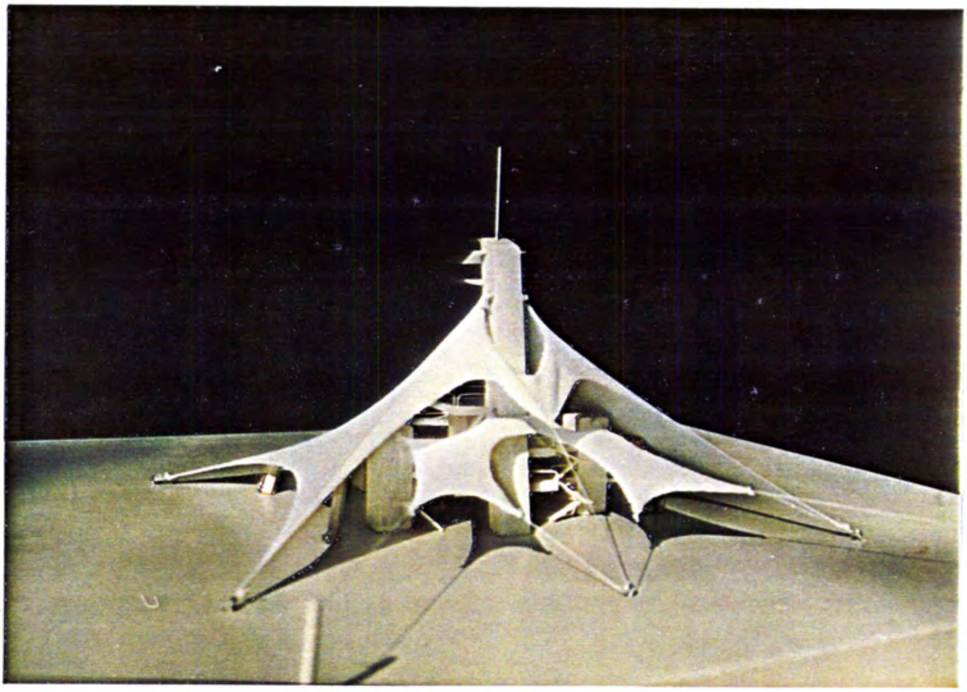


Figure 54 - Terminal model

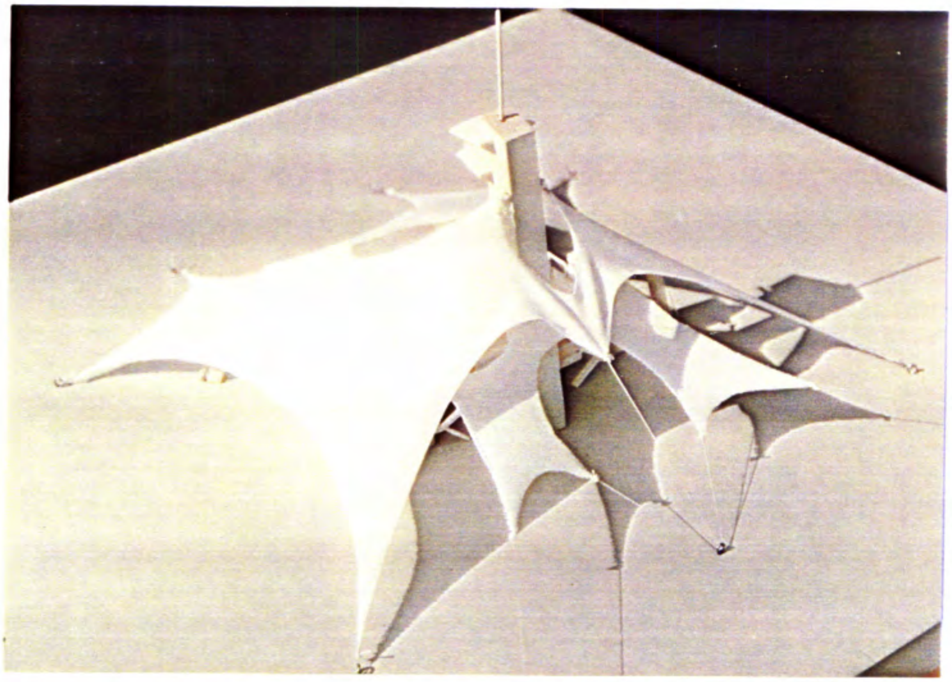


Figure 55 - Terminal model

CONCLUSION

Back in 1980, Architectural Record wrote:[1]

> The significance of the new fabric tension structures in the world of architecture is clearly major. Horst Berger feels that the openness of spaces, the abundance of daylight, and the sculptural quality make for 'a new architecture.' ... fabric tension structures take the edge of the harsher expression of nature and make the environment livable with minimum materials and at low cost.

This was echoed by Horst Berger in 1989 "Architecture is posed on the verge of a fabric revolution" (Rebeck, 1989, p.23). Considering projects such as the Georgia Dome, the Suncoast Dome, the Pier 6 Concert Pavilion, the San Diego Convention Center, and the Denver International Airport which have been recently or are currently being constructed, it appears that the new architecture has arrived.

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David A. Block and P.O.S. Committee

Frevert-Ramsey-Kobes, Architects-Engineers, P.C. (A.S.D.)

APPENDIX

PARTIAL LIST OF PROJECTS INCORPORATING FABRIC TENSILE STRUCTURES

Arranged chronologically

1. Raleigh Arena
Raleigh,North Carolina
Matthew Nowicki
1952

2. David S. Ingalls Skating Rink
Yale University
New Haven, Conn.
Design: Eero Saarinen and Assoc.
1953-1958

3. Federal Garden Exhibition
Cassel, Germany
Design: Frei Otto
1955

4. Federal Garden Exhibition
Cologne
Design: Frei Otto
1957

5. Interbau Building Exhibition
Berlin, Germany
Design: Frei Otto
1957

6. Sidney Myer Music Bowl
Melborne, Australia
Design: Yuncken, Freeman, Griffiths & Simpson
Engineering: Irving & Associates
1958

7. Federal Garden Exhibition
Saarbrucken, Germany
Design: Frei Otto
1958

8. Marie-Thumas Restaurant
Brussels, Belgium
Design: Rene Sarger
1958

9. International Horticultural Exhibition
   Hamburg, Germany
   Design: Frei Otto
   1963

10. Tokyo-Yoyogi Arena
    Tokyo, Japan
    Kenzo Tange
    1961-1964

11. Snow & Rocks
    Swiss National Pavilion
    Lausanne
    Design: Frei Otto
    1964

12. Convertible Roof
    Palm Beach Casino
    Cannes, France
    Design: Frei Otto with R. Taillibert
    1965

13. German Pavilion
    Expo 1967
    Montreal, Canada
    Design: Otto, Leonhardt, Kendel, Kies, Medlin
    1967

14. The Munich Aviary
    Munich, Germany
    Design: Jorg Gribi & Frei Otto

15. Convertible Roof
    Open-Air Theatre, Abbey Ruin
    Bad Hersfeld, Germany
    Design: Frei Otto
    1968

16. Sports Centre
    Kuwait
    Design: Frei Otto
    1969

17. Convertible Roof
    Hoechst Stadium
    Hanover, Germany
    Design: Frei Otto
    1970

18. Stadium & Arenas
    XX Olympic Games
    Munich, Germany
    Design: Behnisch & Partners Architects
    Roof Consultant: Frei Otto
    1972

19. Tensile Structures
    University of Cincinnati
    Cincinnati, Ohio
    Design: Students of Gerald Larson
    1975

20. Pontiac Silverdome
    Pontiac, Michigan
    Design: O'Dell, Hewlett & Luchenback and
    Geiger-Berger Associates
    1975

21. Park District Recreation Complex
    Hanover Park, Illinois
    1976

22. Bullock Department Store
    San Mateo, California
    Design: Horst Berger
    1981

23. Tropical Forest Pavilion
    Franklin Park Zoo
    Boston, Massachusetts
    Design: Huggens & Tappel
    and Weidlinger Associates
    1981

24. Haj Terminal
    Jeddah, Saudi Arabia
    Architect: Skidmore, Ownings & Merrill
    Structural Engineer: Horst Berger
    1981

25. University of Florida Student Center
    Gainesville, Florida
    Architect: CRS, Inc.
    Structural Design: Geiger-Berger Associates
    1981

26. Concert Paviliion (Replaced by Pier Six)
    Baltimore, Maryland
    Design: Future Tents
    1981

27. Tennessee State Amphitheatre
    Knoxville, Tennessee
    Architect: McCarty, Bullock & Holsaple, Inc.
    Structural Engineer: Geiger-Berger Associates
    1982

28. International Stadium
    Riyadh, Saudi Arabia
    Design: Fraser, Roberts Partners and
    Geiger-Berger Associates

29. Hangar One
    Tampa International Airport
    Tampa, Florida
    Design: Rowe Holmes & Birdair Structures
    1982

30. Lindsay Park Aquatic Center
    Calgary, Alberta
    Design: Chandler Kennedy and
    Geiger-Berger Associates
    1983

31. East Area Health Center
    Detroit, Michigan
    Design: Smith Hinchman & Grylls and
    Chrysalis Corp. Architects (Kent Hubbel)
    1983

32. Queeney Park Pavilion
    St. Louis, Missouri
    Design: Jones/Mayer Associates
    Consultant: Geiger Berger Associates
    1983

33. Crown Center Square Pavilion
    Kansas City, Missouri
    Design: Geiger Berger Associates
    1983

34. Sea World
    San Deigo, California
    Design/Engineer: Geiger Berger Associates
    1983

35. The Royal National Eisteddfod Mobile Theatre
    Wales
    Architect: John Dangerfield Associates
    Structural Engineer: Buro Happold
    1983

36. Sports Facility
King Adbul Aziz University
Jeddah, Saudi Arabia
Design: Buro Gutbord
Consultant: Frei Otto
1983

37. The Tokyo Dome
Tokyo, Japan
Design: Gieger Berger
1983

38. Arena Theatre - International Garden Festival
Liverpool, England
Architect: Cass Associates
Structural Engineer: Ward, Ashcroft & Parkman
1984

39. Tensile Structures
University of Cincinnati
Cincinnati, Ohio
Design: Students of Gerald Larson
1984

40. Thomas E. Leavey Activities Center
Harold L. Toso Pavilion Complex
University of Santa Clara
Santa Clara, California
Architect: Caudill Rowlett Scott with
Albert A. Hoover & Associates
1985

41. Canada Place - Expo 86
Vancouver, British Columbia, Canada
Architect: Zeidler Roberts Partnership/Architects
1986

42. Ontario Pavilion - Expo 86
Vancouver, British Columbia, Canada
Architect: Zeidler Roberts Partnership/Architects
1986

43. Bradford Exchange
Chicago, Illinois
Architect: Weese Hickey Weese
1986

44. Marylebone Cricket Club Mound Stand
Marylebone, England
Design: Michael Hopkins & Partners
Consultant: Ove Arup & Partners
1986

45. Schlumberger Plant
Montrouge, France
Design: Renzo Piano
Structrual: Peter Rice
1987

46. Schlumberger Cambridge Research Center
Cambridge, England
Design: Micheal Hopkins and Partners
1986

47. The Chapel for Hunter Ministries
Texas
Design: Armco Atlantic
1987

48. Knott Athletic Recreation/Convocation Complex
Maryland
Architect: Bohlin Powell Larkin Cynwinski
Roof Design: Horst Berger Partners
1989

49. The Riverfront Amphitheater
Riverfront Park
Little Rock, Arkansas
Architect: Rousseau Fennell Associates
Structural Engineer: Harry Daugherty, P.E.
1989

50. The Second Season Golf Center
Lakeville, Minnesota
Architect: Architects Plus
1990

51. The Proctor & Gamble Performance Pavilion
and Riverfront Auditorium
Little Rock, Arkansas
Architect: Schervish, Vogel, Merz, P.C.
Fabric Design: Kent L. Hubbell Architects
1990

52. Georgia Dome
Atlanta, Georgia
Architect: Heery International
Dome Design: Weidlinger Associates, Inc.
1990

53. Shading Structure
Private Residence, Rockport, Maine
Design: Charles Bryant
1990

54. The Suncoast Dome
St. Petersburg, Florida
Architect: Hok Sports Facilities, Inc.
1990

55. Shade Structure
Talieson West
Scottsdale, Arizona
Design: Mick Granlund
1990

56. Sherway Gardens
Etobicoke, Ontario, Canada
Architect: Zeidler Roberts Partnership/Architects
1990

57. Olympic Plaza
Calgary, Alberta, Canada
Design: Warner Shelter Systms Ltd.
1990

58. Cynthia Woods Mitchell Pavilion for the Performing Arts
The Woodlands, Texas
Design: Horst Berger
1990

59. Forks Market
Winnipeg, Manitoba, Canada
Design: Steve Cohlmeyer
1990

60. Crary Park
Petersborough
Design: Leslie Rebanks
1990

61. Showroom
Design: FTL Associates
1990

62. Mitsui-Toshiba Pavilion
International Garden & Greenery Exposition
Osaka, Japan
Design: Kisho Kurokawa
1990

63. Chene Park Preforming Arts Complex
Detroit, Michigan
Design: Kent L. Hubbell

64. Carlos Moseley Music Pavilion Portable Orchestra Shell
Architect: FTL Associates
1991

65. Sculpture
Design: Bill Moss
1991

66. The Imagination Building
London, England
Design: Herron Associates
Structural Engineer: Buro Happold
1991

67. Motorized Banner Mobile & Roof Structure
Park City Center
Lancaster, Pennsylvania
Design: Cope Linder Associates
1991

68. Minnesota State Fair's Visitor Plaza
Design: Toltz, King, Duvall, Anderson
and Associates, Inc.
1991

69. San Diego Convention Center
San Diego, California
Architect: Arthur Erickson
Deems Lewis McKinley with
Loschky, Marquardf & Nesholm
Consultant: Horst Berger Associates
1991

70. Weesner Family Amphitheater
Apple Valley, Minnesota
Architect: Hammel Green and Abrahamson
1992

71. Pier Six Concert Pavilion
Baltimore, Maryland
Architect: FTL Architects
1992

72. Grand Rapids Symphony Pavilion
Grand Rapids, Michigan
Architect: Kent Hubbell
Not Constructed

73. The German Pavilion - Expo 92
Seville, Spain
Design: IPL Ingenieurplanung Leichtbau GMBH
1992

74. Palenque - Expo 92
Seville, Spain
Design: Jose Miguel De Prada Poole
Structural Engineer: IPL Ingenieurplanung Leichtbau GMBH
1992

75. Oleada - Expo 92
Seville, Spain
Design and
Structural Engineer: IPL Ingenieurplanung Leichtbau GMBH
1992

76. Diadema - Expo 92
Seville, Spain
Design and
Structural Engineer: IPL Ingenieurplanung Leichtbau GMBH
1992

77. Bioclimatic Rotunda - Expo 92
Seville, Spain
Design and
Structural Engineer: IPL Ingenieurplanung Leichtbau GMBH
1992

78. Pabellon De Jarez - Expo 92
Seville, Spain
Design: D. Ignacio De La Peña Muños, D. Ramón Gonzales
De La Peña, D. José Luis Manzanares, Arquitectos
Structural Engineer: IPL Ingenieurplanung Leichtbau GMBH

79. Shading Structure
Private Residence, Phoenix, Arizona
Design: Bill Moss
1992

80. Venafro Research Centre - Expo 92
Seville, Spain
Design: Samyn, L'European Avendia
1992

81. Denver International Airport
Denver, Colorado
Design: C.W. Fentress, J.H. Bradburn and Associates
Roof Design: Horst Berger & Severud Associates
Under Construction

82. Pearson International Airport
Toronto, Canda
Architect: Zeidler Roberts Partnership/Architects
On Drawing Boards