A Fabric Roof For Denver's New Airport Terminal – Ten Years Later

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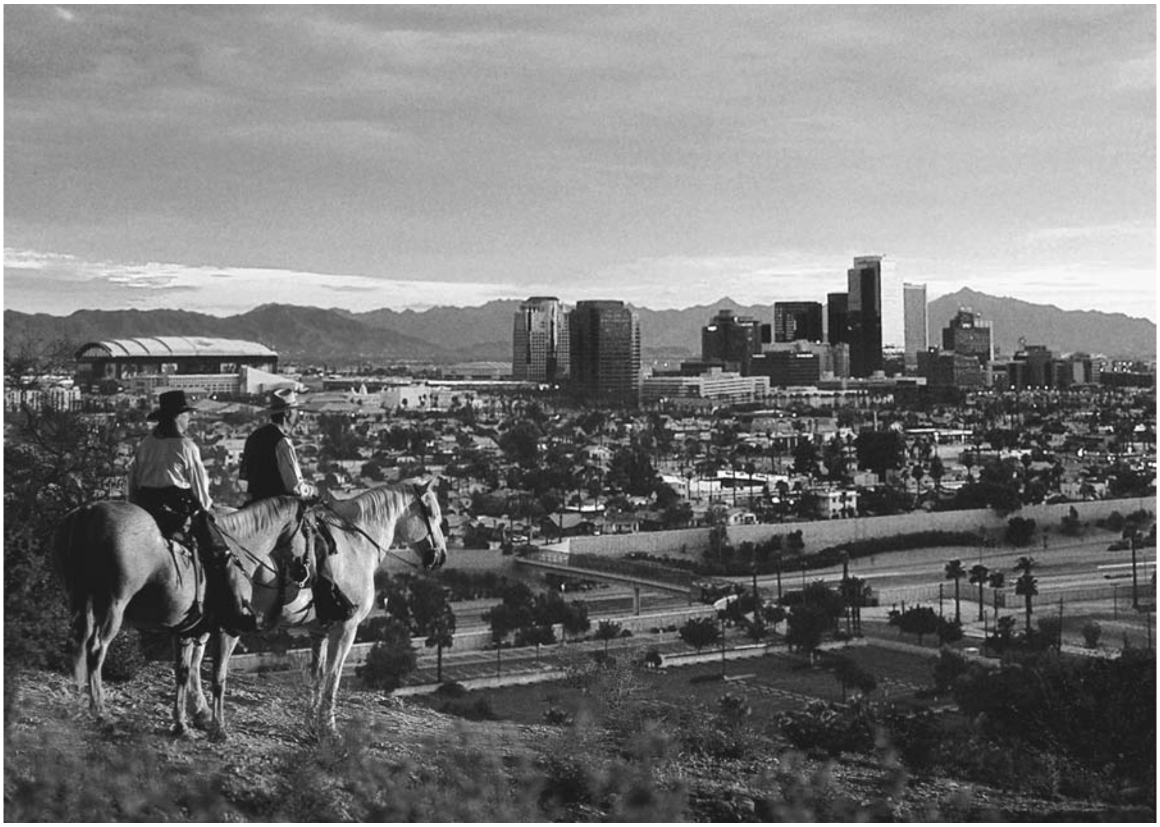

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ABSTRACT

Commonly seen as seasonal or temporary, acceptance of contemporary tensile membrane roof structures as a bonafide building technology has been difficult, primarily due to false assumptions about their permanence, strength, durability, non-combustibility, or energy efficiency. Using a ten-year-old high-visibility project as a case study – Denver International Airport's Jeppesen Terminal – the author will focus on the terminal roof's architectural design, engineering, materials, fabrication, and construction.

SPEAKER

WILLIAM R. BARDEN received an associate degree (1977) from Alfred State College, followed by a bachelor of professional studies (1983) and master of architecture (1985) from the State University of New York at Buffalo. He is a registered architect in New York. Mr. Barden initially associated with the architectural/engineering firm of Cannon Design as a project architect (1985). Since joining Birdair (1996), he has been responsible for the company's business development in lightweight roof structures, establishing and maintaining relations with an international client group of owners, architects, engineers, and contractors. He has spoken on tensile structure building technologies at AIA national and state conventions. A reserve officer, Mr. Barden is a commander in the U.S. Navy's Civil Engineer Corps.

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INTRODUCTION

With sculpted glowing forms, use of lightweight materials, and roots tracing back to the earliest of mankind's shelters, tensile membrane structures represent an aesthetically appealing and imaginative building technology. Efficiently integrating form, structure, and function, tensile architecture responds well to contemporary expectations for environmentally-responsible building design.

Yet, commonly seen as seasonal or temporary, acceptance of contemporary tensile membrane structures as a bonafide building technology has been difficult, primarily due to false assumptions about their permanence, strength, durability, noncombustibility, or energy efficiency.

Tensile membrane roof structures are excellent examples of sustainable building technologies. Their lightness and accelerated installation time reflect an economy of materials, use of prefabrication methods, and conscientious use of natural resources. With fewer components to erect, they utilize fewer resources during construction and offer significant cost savings, especially as long-span roof enclosures commonly used in voluminous transportation facilities and sports venues. And, their ability to transmit diffused natural light while reflecting excessive solar heat gain results in reduced energy costs for artificial lighting and cooling.

Using a well-known facility as a case study – the Denver International Airport's passenger terminal - we will focus on the signature tensile membrane roof: its design and engineering, daylighting and energy efficiency characteristics, fabrication, and construction. We will try to demystify terminology, techniques, materials, and processes associated with tensile structures and shed light on the unique relationship of tensile architecture to high-performance design and construction.

BACKGROUND

When it opened on February 28, 1995, Denver's $4.5 billion international airport was the first major airport built in the United States since Dallas/Fort Worth was constructed in 1974. The initial build-out phase of Denver International Airport – or DIA, as referred to locally – consisted of five runways (since increased to six), one passenger terminal, three concourses hosting 84 gates and 40 commuter positions, 12,000 parking spaces, and an office building. This expansive airport is situated on about 34,000 acres (or 53 square miles), an area greater than any other airport site in the world. Throughout its 11 years of operations, DIA has become a significant economic generator for the Rocky Mountain region. The Colorado Department of Transportation recently estimated that DIA annually contributes $17 billion to the regional economy. In 2004 – with over 42 million passengers, 24 airlines, and 34,000 tons of cargo handled – DIA maintained its ranking as the fifth busiest airport in North America and the tenth busiest in the world.

The planning for this world-class airport began in 1985 when former Denver Mayor Federico Peña (later to become U.S. Secretary of Transportation) decided against expanding Stapleton Airport in favor of a plan to establish a new facility on land 20 miles northwest of Denver. In 1989, the City and County of Denver commissioned Fentress Bradburn Architects as designer of the new Passenger Terminal Complex at DIA, which later came to be known as the Elrey B. Jeppesen Terminal.

Developing the terminal's comprehensive master plan and initial design standards, concepts, and programming were responsibilities of a different design firm that was not intended to be the architect-of-record. However, early reviews of their efforts were not favorable – the project was hampered by questions of cost overruns (estimated to be $78 million), scheduling (forecast to be 38 to 40 months too long), and aesthetics (it was deemed “not memorable”) - and so a second opinion was sought. Fentress Bradburn was subsequently selected as architect-of-record to build upon the concept depicted in the master plan and see the project through to completion.

To address the problems of severe cost and scheduling overruns as well as develop a striking image for the Terminal, new design concepts were called for. The first order of business for Fentress Bradburn was to host a design charrette aimed at solving these functional and aesthetic dilemmas. In striving towards meeting Mayor Peña's goal of creating a memorable and significant piece of civic architecture, Fentress Bradburn settled on forms and materials indigenous to the environment and culture of the Rocky Mountain region surrounding the airport complex to create a unique sense of place. Motivation for the roof's unique shape, material, and color stemmed from the architects' desire to bring the Colorado outdoors inside. Harmony between the interior and exterior was achieved through the fusion of two natural elements: form and light. The architects settled on a fabric and cable solution for the Terminal roof.

On a practical level, the unique tensile membrane roof design resulted in sufficient cost cutting to fit the Terminal's project budget; reduced construction time that would achieve the planned opening date of late 1993; and improved energy efficiency.

As proposed and developed by Fentress Bradburn over an intense three-week charrette, a tensile membrane roof was thus substituted for the Terminal's original design concept of a boxy form with a flat, conventionally-built roof.

> “As we were looking at possible structural systems and roof materials, Jim Bradburn suggested that the most efficient solution for spanning the space, especially with the form being considered, was a lightweight cable and fabric structure.”
>
> *– Curt Fentress, FAIA, Senior Principal, Fentress Bradburn Architects*

The fabric roof enclosing the 210-foot wide by 900-foot long Great Hall of DIA's Jeppesen Terminal is truly a milestone for the tensile membrane structure industry. The world's largest transportation terminal enclosed by a tensile membrane roof unites structural engineering with architectural design to produce a magnificent and expansive interior space with a volume three times that of New York City's Grand Central Station. The nine-acre roof's dramatic peaks and valleys give it a unique shape emulating the profile of the Rocky Mountains that are synonymous with Denver and provide a striking backdrop to the Terminal's western view.

The project team for DIA's Passenger Terminal Complex consisted primarily of:

- **Owner**: City and County of Denver.
- **Architect**: Fentress Bradburn Architects (Denver, CO).
- **Roof Structural Engineer**: Severud Associates (New York, NY), with specialized roof design and engineering by Horst Berger (New York, NY).
- **Daylighting/Energy Consultant**: Architectural Energy Corp. (Boulder, CO).
- **Architectural Lighting/ Daylighting Consultant**: Lam Partners (Cambridge, MA).
- **Microclimate Consultant**: Rowan Williams Davies Irwin (Guelph, ON).
- **Acoustical Consultant**: Shen Milsom & Wilke (New York, NY).
- **General Contractor**: Joint venture of PCL Construction Services and BL Harbert.

THE ROOF

The double-layer fabric roof over the terminal's Great Hall is best described as a folded-plate design of 17 modules, which are supported by steel masts 60 feet on center and set 150 feet apart. From terminal floor to the top of the masts the roof elevation ranges from 106 to 126 feet in height. Ridge cables slung from the tops of the 17 pairs of masts carry such downward forces as wind and snow loads as well as the weight of the structure, stabilize the masts, and help achieve the distinctive forms visible from the Terminal's exterior. Valley cables anchored outside the Terminal hold the membrane down, resist wind uplift (which is predominantly upward and outward suction), and provide positive roof drainage. Catenary cables around the perimeter are anchored to either the ground or adjacent conventional construction to help tension the roof structure. The lightweight Teflon® PTFE-coated fiberglass membrane roof which lends the Jeppesen Terminal's distinctive form allows for greater spans than traditional roofing systems, decreases construction and maintenance costs, and increases durability. Plus, even in the Rocky Mountains' climate of cold temperatures and heavy snowfalls, the tensile membrane roof promised to be an energy-efficient solution.

> "The functional aspects of utilizing a fabric roof, as opposed to a conventional roof, are most apparent from a structural standpoint. At two pounds per square foot, the lightweight and flexible qualities of a Teflon-coated fiberglass tensile-membrane roof eliminated 300 tons of steel and 200,000 linear feet of concrete shear wall from the early concept plan."
>
> – *Fentress Bradburn Architects' Gateway to the West*

At 400 tons, the roof consists of 34 steel masts, ten miles of structural steel cable, 3.8 miles of aluminum clamping, and 660,000 square feet of PTFE fiberglass architectural membrane. The masts are topped by molded fiberglass reinforced plastic caps in two sizes: 6' x 8' and 12' x 28'. The Terminal's entire roof structure - including structural steel masts, cables, and double-layer fabric roof – was constructed in about nine months using an average installation crew size of 50 men.

Additionally, at the Level 4 East and West Arrivals, tensile membrane canopies provide curbside weather protection for passengers being dropped off. Each of these conical canopies is about 40 feet in width and 900 feet in length.

> "If daylighting can provide the majority of ambient lighting for the atrium, ticketing, baggage claim, and circulation spaces during the day, the simultaneous demand from the peak cooling load and full electric lights can be avoided."
>
> – Energy consultant Michael Holtz, AIA, in *Fentress Bradburn Architects' Gateway to the West*

Daylighting was indeed a major architectural and energy efficiency design strategy of the Jeppesen Terminal. The design objective was for natural light to provide the majority of daytime ambient lighting for the terminal's Great Hall, ticketing, baggage claim, and circulation spaces in order to eliminate simultaneous demand from the peak cooling load and full electric lights. Due to the translucent nature of the tensile membrane roof structure, transmission of sufficient diffused daylight in the Great Hall was assured. However, the design team also wanted to retain views and visual contact with the sky as an indicator of weather, time of day, and as a means to bring in direct sunlight to add visual interest during the daytime. Transparent glass skylights were thus incorporated at several of the main fabric roof mast tops, and glass clerestories and curtainwalls line the east, west, and south edges of the Great Hall. These "vision-preserving" glazing elements provide direct sunlight and a psychological connection to the outdoors.

The white-colored PTFE fiberglass membrane reflects about 76% of all incident solar radiation landing on its surface. This high level of reflectivity reduces daytime heat gain (saving air conditioning costs and comparing favorably to conventional glazing) while enabling the use of energy-efficient indirect lighting to illuminate nighttime interiors. Due to its low thermal mass, the tensile membrane roof does not heat up nor radiate heat into the space below like most conventional roofing systems. Combined with this membrane's very low shading coefficient of 0.14, the Great Hall's cooling requirements are significantly reduced. Of the remaining portions of the solar spectrum, 15% is re-radiated as infrared heat while the remaining 9% is transmitted through the roof and into the Great Hall as daylight, or the visible portion of the spectrum.

This abundance of natural light is described in the amount of footcandles of daylighting transmitted through the Terminal roof. With about 10,000 footcandles of light above Denver on a sunny June day, more than 9,000 footcandles are transmitted through the roof. Conversely, on an overcast December day, the roof lets in about 200 footcandles of light, which is up to four times the illumination levels typically found in office buildings. With additional daylight streaming in through the conventionally-glazed areas, there is no need for daytime artificial lighting.

Besides the valuable aspects of its daylighting qualities, one of the greatest benefits of the terminal's tensile membrane roof is its energy efficiency. The roof's PTFE fiberglass membrane drastically reduces the energy consumption in powering artificial lighting as well as cooling the Great Hall's interior from heat generated by the lights. It was projected that the interior would need to be heated about three to four weeks per year, despite the region's cold temperatures. The remainder of the time, heating needs would be met by solar energy transmitted through the tensile membrane roof and conventionally-glazed areas, as well as from heat produced by the traveling public and airport staff, baggage and passenger conveyance systems, computers, nighttime artificial lighting, signage systems, and food courts. Lastly, energy needed for winter heating is reduced through waste heat recovery in the baggage area make-up ventilation system.

The Jeppesen Terminal was designed in accordance with the Owner's Airport Complex Energy Design and Daylighting Energy Design Standard and exceeded the standards in effect at the time – ASHRAE 90.1-1989. This ASHRAE standard has three paths for demonstrating compliance to the energy design requirements: Prescriptive Criteria Method, System Performance Criteria Method, and Building Energy Cost Budget Method. Because of the unique nature of the building design and complexity of the systems in the design, the Building Energy Cost Budget Method was chosen to assess energy design standard compliance. The projected annual design energy cost was approximately $0.20 per square foot less than the required annual energy cost budget. In 1991 dollars, this resulted in projected savings of more than $270,000 per year compared to a terminal building designed to prescriptive requirements.

THE MEMBRANE

The material making up the Jeppesen Terminal's roof is Teflon® PTFE-coated fiberglass, used architecturally since 1973 when the pioneering tensile membrane roof structure of the University of LaVerne's Student Center was constructed. The original membrane at LaVerne remains in place 32 years later. PTFE fiberglass is noted for its durability, noncombustibility, translucency, high reflectivity, and self-cleaning properties. Pound for pound, the fabric is stronger than steel, yet weighs less than five ounces per square foot. While most conventional roofing systems typically are generally replaced every 20 to 25 years, the demonstrated service life of a PTFE fiberglass roof is in excess of 30 years.

The membrane's substrate consists of woven glass fiber yarns made up of Beta® glass filaments. Contributing a high degree of flexibility, these extremely fine filaments are crucial to withstanding the punishing twisting and bending actions resulting from sustained live loads imposed on the tensile membrane roof. The substrate is the component providing the membrane's mechanical strength and noncombustibility.

Coating the substrate is polytetrafluoroethylene (PTFE), a UV-resistant fluoropolymer that provides long-term weather protection. Durable PTFE coatings remain stable at temperatures as high as 450°F and flexible at temperatures down to -150°F. The unique combination of chemical inertness, thermal stability, and high surface hydrophobicity make PTFE ideal for roof membranes requiring such performance characteristics as superior weatherability, fire resistance, and low maintenance.

LaVerne is a landmark for two reasons. First, it has proved PTFE fiberglass is sturdy enough to be used in permanent tensile structures. Second, as the oldest constructed example with 30+ years of continuous service in a particularly challenging environment as that of Southern California, LaVerne has demonstrated the durability and weatherability of PTFE fiberglass membranes.

However, this high-performance fabric was not developed for architectural applications. It was originally engineered and manufactured in the late 1960s for America's space program. Following the devastating Apollo I fire in January 1967 and intending to improve the safety of its astronaut crews, NASA solicited proposals from the industrial fabrics industry for a new spacesuit fabric. Their performance requirements called for a fabric that had to be noncombustible yet flexible, lightweight, and durable. A woven fiberglass fabric coated with a PTFE fluoropolymer was subsequently chosen by NASA for the Apollo spacesuits. Interestingly, this fabric – reinforced with high-strength, antiballistic fibers like Kevlar® – is still in use today with NASA's shuttle program.

Since LaVerne marked the first architectural application for PTFE fiberglass, more than 60 million square feet of this fabric has been installed as roofing over airport terminals, bus stations, stadiums and arenas, exhibition and convention centers, shopping centers, and performing arts facilities in the some of the world's most rugged climates.

Characteristics representative of the PTFE fiberglass membranes in use for DIA's Terminal roof and exterior curbside canopies are shown in the adjacent table.

Sheerfill® Architectural Membranes are available in a range of strengths and light transmission

Physical Characteristics	Roof Outer: Sheerfill® IIA	Roof Liner: Fabrasorb® II	Exterior Canopies: Sheerfill® IIA
Fabric Composition	PTFE fiberglass	PTFE fiberglass	PTFE fiberglass
Coated Fabric Weight	38 oz./sq. yd.	8.5 oz./sq. yd.	38 oz./sq. yd.
Thickness of Coated Fabric	28 mils	9 mils	28 mils
Breaking Strength, After Creasing (lbs./in.)	475 warp, 380 fill	210 warp, 180 fill	475 warp, 380 fill
Trapezoidal Tear Strength (lbs./in.)	60 warp, 70 fill	17 warp, 180 fill	60 warp, 70 fill
Solar Transmission	16%	27%	16%
Solar Reflectance	72.5%	65%	72.5%
Flame Spread (ASTM E84)	5 max	5 max	5 max
Smoke Generation (ASTM E84)	20 max	15 max	20 max
Burning Brand (ASTM E108)	Class A	N/A	Class A
Incumbustibility of Substrates (ASTM E136)	Pass	Pass	Pass
Flame Resistance (NFPA 701)	Pass	Pass	Pass
Sound Absorption, 250-4000 Hz (ASTM C136)	N/A	0.55 sabins/sq. ft.	N/A
Greige Goods Roll Width	150 inches	150 inches	150 inches
Total Surface Area in Project	380,000 sq. ft.	280,000 sq. ft.	97,000 sq. ft.

levels to cover virtually any size of permanent structure. All Sheerfill membranes conform to rigid fire and building codes for permanent buildings. Fabrasorb® Acoustical Membranes are acoustically-absorptive fabrics used as liners in tandem with Sheerfill membrane systems. Fabrasorb serves not only to attenuate sound but also to enhance the thermal characteristics of fabric roof assemblies.

(Teflon® and Kevlar® are registered trademarks of DuPont. Sheerfill® and Fabrasorb® are registered trademarks of Saint-Gobain Performance Plastics Corp.)

DESIGN OF TENSILE MEMBRANE STRUCTURES

The process of creating a tensile membrane structure begins with understanding the basic physical principles governing its shape. In order to produce a stable structure, the membrane surface must have double curvature, such that the radii of curvature in two principal directions must originate on opposite sides of the surface. This is known as anticlastic curvature, and the basic shape is defined mathematically as a hyperbolic-paraboloid. This basic shape can be combined with cables and other elements to create an infinite number of actual possibilities.

A prestressed tensile membrane structure will thus typically have two principal directions of curvature: one convex and one concave. The membrane is generally oriented so that the yarn fibers are parallel to these principal directions. The internal prestress corresponding to these directions yields opposing forces that hold the system in static equilibrium. When an external load is applied to the membrane, deflection will occur, slightly changing the shape and radius of curvature. The stress in one principal direction will resist the load, while the stress in the perpendicular direction will help the system maintain stability. In this manner, the membrane acts biaxially to resist applied loads.

The design process required for tensile membrane structures differs significantly from the process used for conventional structures, in that the structural analysis must be completely integrated into the architectural design. The geometry of a tensile structure is not arbitrary and cannot be precisely defined before analysis. The geometry is established through a shape generation or formfinding technique to ensure static equilibrium of the tensile system.

This technique is first used to establish the structure's natural equilibrium shape, which is the geometric configuration that is in static equilibrium with its own internal prestress forces. After arriving at a stable configuration, the structure is analyzed under various load cases using large deflection finite element analysis software. This permits the inclusion of such elements as the membrane, cable, and mast components in a three-dimensional computer model resulting in rapid, accurate member analysis and sizing. Upon completion of this analysis, reaction forces are summarized in a tabular format for use by the consulting structural engineer to complete the design and analysis of the surrounding structure and foundations.

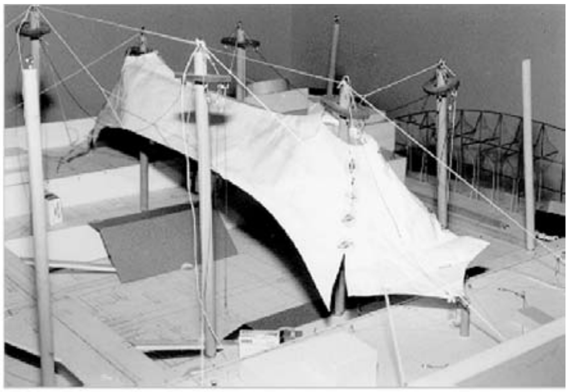
INITIAL ROOF CONSTRUCTION PLANNING

In August 1991, Birdair was contracted by PCL/Harbert to provide design-build services for the Jeppesen Terminal's immense roof and curbside canopies. Prior to this, Birdair had provided consultative services to Fentress Bradburn Architects, Severud Associates, and the rest of the design team in the way of tensile engineering and analysis, cost forecasting, scheduling, and construction feasibility. The scope of work as contracted by Birdair consisted of the roof's double-layer membrane system; structural steel and cables; mast-top treatments, including skylights; structural framing for perimeter east and west clerestories and north and south curtainwalls; and a clerestory expansion joint/closure system between the outer membrane and clerestory framing.

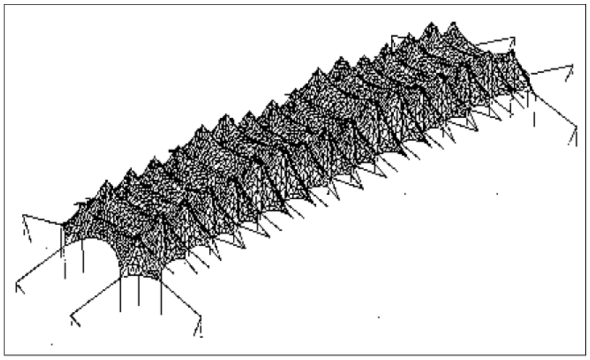
One of many challenges to overcome in successfully constructing a tensile membrane roof the size and complexity of the Jeppesen Terminal's was determining a safe method to accomplish installation of large fabric panels and rigging. Each bay of the Terminal's roof consists of more than 20,000 square feet of PTFE fiberglass membrane. If not erected properly, the risk of wind damage during fabric lifting was extremely high, as the roof is vulnerable during periods when the fabric is partially installed. During these times, the membrane has only partial prestress loading and therefore has less inherent stability. It would be subjected to loading conditions completely different from the design conditions of the completed structure. To overcome these hazards, extensive planning and analysis requiring both physical and computer modeling techniques were used in conjunction with structural engineer Severud Associates.

The first planning step was to build a physical model which was used to qualitatively study installation and formulate a preliminary plan. The 1/8-inch scale model consisting of one half the structure represented all major structural components of the roof system and the Terminal's primary surroundings that would be present during construction.

Working with scale replicas of the fabric assemblies, Birdair tested different methods and sequences of fabric packaging, handling, rigging, and lifting. The physical model was worked until Birdair had schemes it believed were physically possible to achieve and could be accomplished safely in the field. The same physical model was later sent to the field where it was used on site to help refine procedures and instruct Birdair's installation crews.



A working physical model helped develop and test installation procedures.



A "coarse mesh" System Model was used to quantify overall behavior.

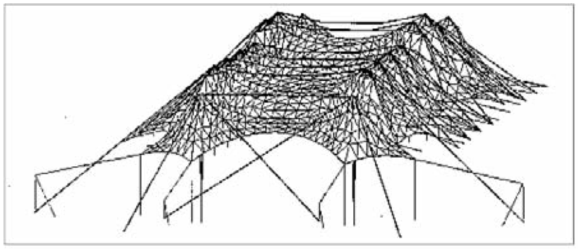
COMPUTER MODELING

After the qualitative work with the physical model was completed and a general plan established, computer models were built to perform the quantitative structural analysis. Large deflection finite element method analysis software is typically used for this work. Computer models are required for both construction planning and fabrication detailing. Three general types of computer models were required: Overall System Models, Installation Models, and Fabric Pattern Models.

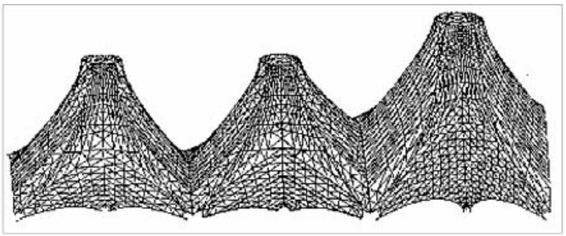
Overall System Models represent as much of the entire system as possible in order to understand the overall behavior and structural interaction of the roof. In the case of the Terminal's roof, the behavior and equilibrium of the various components are all inter-related. The System Model was used to determine the geometrical configuration and prestress forces that work in equilibrium together to produce the desired architectural and structural performance.

To make Installation Models, a portion of the System Model representing a particular stage of the Terminal's construction was used. Installation rigging and temporary guying systems that would be present were added to the model. Prestress forces and geometry were modified to better represent actual conditions.

Pattern Models were used to produce very precise representations of the final geometry of the membrane and cables, necessary for producing fabric cutting patterns and final fabricated cable lengths. A different Pattern Model was built for each bay of the terminal roof, and prestress forces and boundary geometry established from working with the System Models were used in the input data to these models. A much “finer mesh” was used to better represent the actual geometry. The software used to generate the membrane's prestressed equilibrium shape also pulls the node lines (later to become seam lines) onto geodesic curves (i.e., shortest path curves) along the membrane surface. This ensures optimal seam locations from a fabrication and aesthetic perspective.



An Installation Model was used to analyze and design the temporary rigging and partially installed roof.



A “fine mesh” Pattern Model helped generate the precise shape for patterning the membrane.

FABRICATION

Patterns were produced on the computer by laying sections of the final three-dimensional model down into a two-dimensional template. Patterning data was then electronically transferred to Birdair's fabrication shop, where a wide-area plotter plotted the templates full-scale on paper. A typical template was 12 feet wide (matching the roll width of Sheerfill PTFE fiberglass membranes) and up to 100 feet long. In the shop, membrane panels were cut from the templates and heat-welded together in three-inch-wide lap seams to form large “assemblies.” Each roof bay consisted of four fabric assemblies, which were individually rolled or folded and packaged for shipment to Denver.

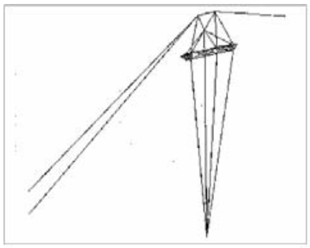
ROOF INSTALLATION

At the time erection of the roof began, the Terminal's concrete floor structure was complete up to the primary floor level. This floor was thus used during installation as a staging area and work surface for both men and equipment. Designed for live loads as much as 250 pounds per square foot, it was able to support up to 40-ton cranes, provided that load-distributing mats were used.

The steel masts were delivered to site in one piece. Top weldments, rigging, and miscellaneous hardware were attached while the masts were on the ground. The masts were then erected using conventional boom cranes located outside the terminal. In the completed structure, the masts were stabilized by the fabric roof system and the associated cables that are located within the shape of the membrane surface. The masts have no external permanent guy cables and therefore had to be allowed to pivot on spherical bearings at their bases. Temporary guy cables were required to stabilize the system during installation. However, as there was no place to position guy cables that would not interfere with fabric installation, temporary mast-top extensions were bolted to the masts to provide the means to attach the guying system.

The guying system and partially-erected fabric subjected the masts to loading conditions and bending moments in the upper sections that the masts wouldn't be able to carry. The problem was analyzed and resolved using the Installation Models discussed earlier. The solution was to add temporary stay cables working in conjunction with the mast top truss rings (similar to stay cables in a boat mast) and remove the masts' bending movement.

The oval-shaped mast-top truss rings were delivered in two pieces, set around the mast bases, and welded together. The reinforced fiberglass mast top units, glass skylights, mechanical equipment, and lighting systems were then assembled on the truss rings. Hoisting the rings to the top of the masts (two at a time) was accomplished with a large drum



A computer model used to design the temporary stay cable rigging and mast extensions.

Steel masts were guyed with external temporary cables, and truss rings were assembled around mast bases and winched up into position.

hoist secured in one location. The drum hoist cables traveled through a series of sheave blocks and fairleads, over to the appropriate mast, up the mast, and into a block-and-tackle system to produce the required mechanical advantage. Using this system, the truss rings together with the mast top units were sequentially hoisted in pairs.

As the truss ring assembly and hoisting proceeded, installation of the outer Sheerfill membrane began. Membrane assemblies were unrolled on the Main Level 5 slab and installed one bay at a time, beginning from the terminal's north end. The aluminum perimeter clamping hardware and cables (ridge, valley, and catenary) were attached to the membrane while on the slab. The Sheerfill membrane was positioned such that two halves of a bay rested together, one on top of the other, prior to lifting. The primary lifting was performed using the same winch used to hoist the truss rings. Hoist cables were attached to each end of the bay's ridge cable, which were lifted towards the rings. As the ridge cable was lifted, the fabric bay went with it.

Fabric was lifted into place with a drum hoist (in foreground) secured on the terminal's Main Level 5. Two hydraulic cranes were also used to assist with the lifts.

Once the ridge cable was pinned, the fabric bay was spread open and clamped at the valley cables to the neighboring bays. Sectionalized clamping (much like a zipper) was used to seam together the prefabricated assemblies in the field. Once the sectionalizing clamping was installed, a weathertight seam cover of Sheerfill membrane was heat welded into place.

Following installation of the outer Sheerfill membrane, the triangular-shaped east and west clerestory framing were installed. This work was erected from the inside of the terminal using hydraulic cranes situated on the Level 5 slab. A large, circular, air-inflated expansion joint developed by Birdair was installed to provide a weathertight closure in the space between the outer fabric and the rigid clerestory framing. Using a combination of statistical evaluation of weather data over a 25-year period, physical model testing, and computer analyses, microclimate consultant Rowan Williams Davies Irwin had determined the roof would deflect as much as five feet under the most extreme snow and wind loading. As such, this flexible expansion joint was needed to accommodate this deflection so that the membrane would not crush the glass wall and clerestory systems.

The inner Fabrasorb liner membrane was installed after the clerestory glazing was complete and the Great Hall's interior was protected from the weather. It was erected sequentially in much the same manner as the outer Sheerfill membrane. However, being much lighter and protected against the wind, small electric winches were used instead of the large drum hoist. A temporary dust barrier was installed with the liner to minimize dust accumulation on the fabric that would be produced by the finishing trades to follow.

Partially-completed tensile membrane roof.

CONCLUSION

The design, engineering, fabrication, and construction of this pioneering building technology for Denver International Airport required the collaborative efforts of many talented architects, engineers, consultants, fabricators, and installers over a period of nearly five years. The result is a world-class example of integrated energy design, delivering exceptionally high levels of energy performance and comfort within a striking architectural expression. The tensile membrane roof has become a prominent landmark for Denver, recognized worldwide for its unique integration of architecture and engineering as well as for the magnificent interior space created for the Jeppesen Terminal's Great Hall.

> “Hopefully, the airport will become a new laboratory where architects can see this tensile technique and learn from it.”
>
> *– Curt Fentress, FAIA, Senior Principal, Fentress Bradburn Architects*

Aerial view of the Jeppesen Terminal's tensile membrane roof.

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