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Denver International Airport Tensile Roof Case Study

Toiture en tension de l'aéroport international de Denver

Fallstudie der Abdachung des internationalen Flughafens Denver

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SUMMARY

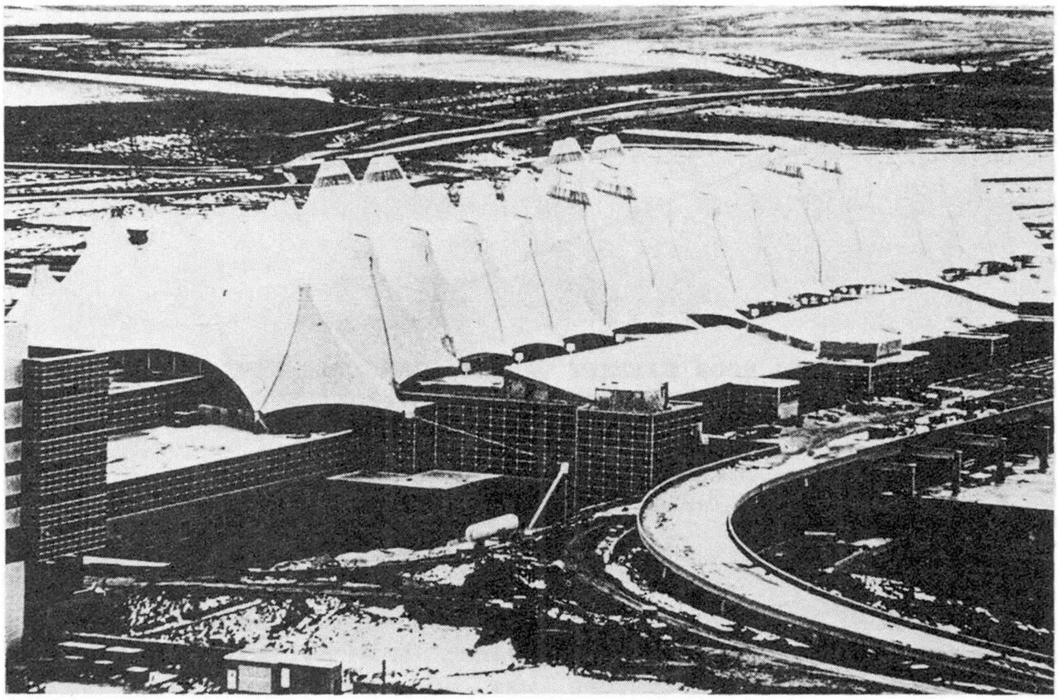
This paper presents the planning, fabrication and construction phases of the tensioned fabric roof system at the new Denver International Airport. It presents the physical modelling and computer modelling required, the fabrication, the installation of the system and some of the associated problems.

RÉSUMÉ

Ce rapport présente les phases de concept, fabrication et construction du système de la toiture en tension de l'aéroport international de Denver. Les modèles physique et informatique, la fabrication, l'installation du système ainsi que d'autres problèmes sont présentés.

ZUSAMMENFASSUNG

Der Bericht enthält die Projektierungs-, Fabrikations- und Errichtungsphasen der Abdachung des internationalen Flughafens Denver. Eingeschlossen sind die notwendigen physikalischen und Rechner unterstützten Modelle, die Herstellung und Installation des Systems sowie andere damit verbundene Probleme.



Aerial View of the Roof

Introduction

The tensile membrane fabric roof structure enclosing the Great Hall area of the New Denver International Airport is truly a milestone project for the tensile structure industry. It unites structural engineering with architecture to produce a magnificent and expansive interior space.

The fabric roof measures approximately 300 by 1000 feet in plan. It is supported by 34 masts of approximately 100 feet in length, has a surface area of about 380,000 square feet, and uses literally miles of structural steel cable. The dramatic peaks and valleys give it a unique shape emulating the Rocky Mountains that are synonymous with Denver and provide a striking backdrop to the new airport's western view.

This paper will provide a case study of the fabrication and construction phases of the project. The topics discussed in detail are the initial planning, the computer modeling, the fabrication, and the installation of the tensile roof system.

Initial Planning

One of the challenges that must be overcome to successfully construct a fabric roof of this magnitude, is determining a safe method to accomplish the installation, in particular, the fabric panels and rigging. Each bay of the structure is comprised of over 20,000 square feet of fabric. The risk of wind damage during fabric lifting is extremely high, if not performed properly. The roof is also vulnerable during the time period when the fabric is partially installed. During this period, the fabric has only partial pre-stress and therefore less inherent stability. It will be subjected to loading conditions that are 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 are used.

The first step of the installation planning was to construct a working physical model. The physical model is used to qualitatively study the installation and formulate a preliminary plan. In the case of the Great Hall roof, we constructed a 1/8" scale model of half of the structure. The model represented all the major structural components of the fabric roof system and the primary surroundings that would be present during construction.

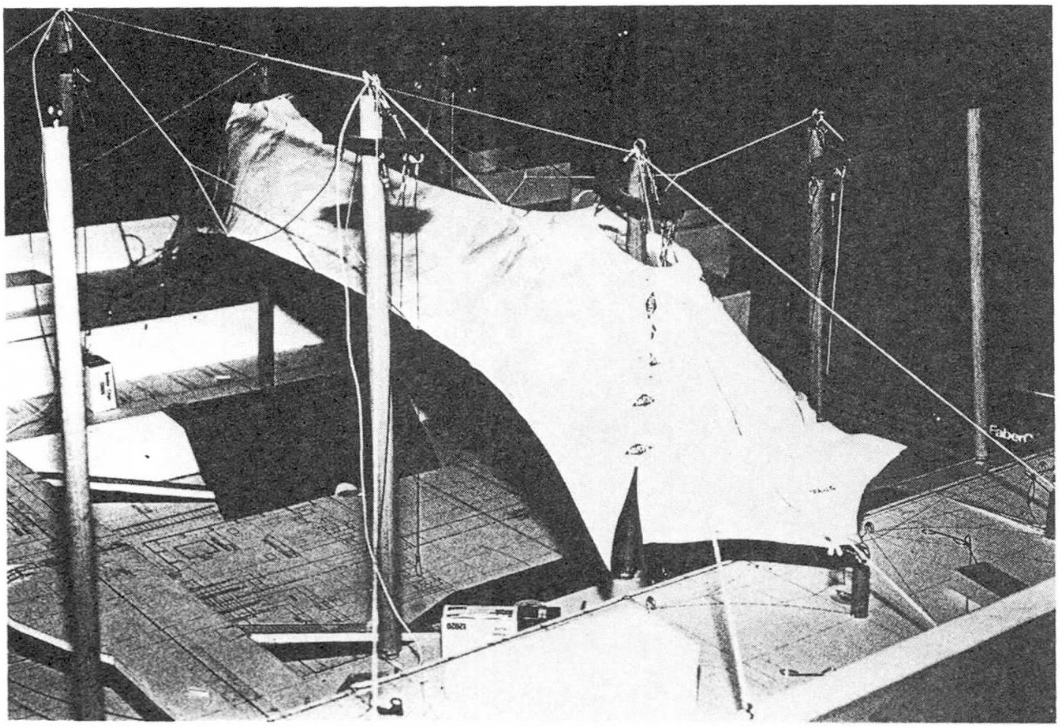


Figure 1: Physical Model. A working physical model is used to develop and test the installation procedure.

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

Computer Modeling

After the qualitative work was completed with the physical model, and a general plan had been established, computer models were built to perform the quantitative structural analysis. Large deflection finite element method analysis software is used for this work. The computer models are required for both the construction planning and the fabrication detailing. Three general types of models are required; overall system models, installation models, and fabric pattern models.

The overall system models are used to represent as much of the entire system as possible, in order to get an understanding of the overall behavior and structural interaction of the system as a whole. In the Great Hall fabric roof, the behavior and equilibrium of the various components are all inter-related. The system model is used to determine the geometrical configuration and pre-stress forces that will work in equilibrium together to produce the desired architectural and structural performance.

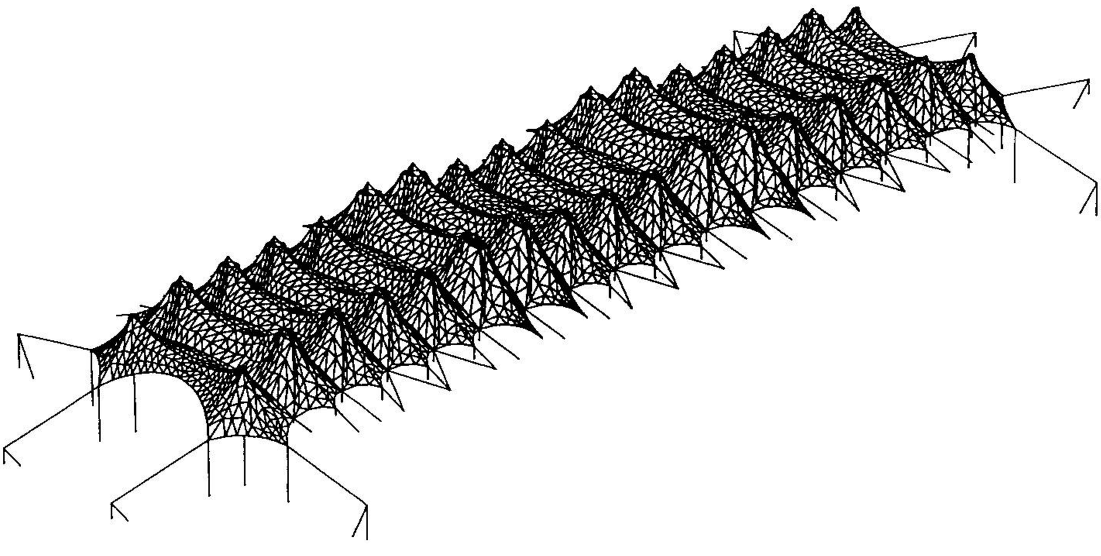


Figure 2: System Model. A "coarse mesh" system computer model is used to quantify overall behavior.

To make the installation models, a portion of the system model appropriate to represent a particular stage of construction is used. The installation rigging and temporary guying systems that will be present are added to the model. The pre-stress forces and geometry are modified to better represent the real conditions. The installation models are used to design the installation rigging and check the permanent roof components during the different construction phases. It is not unusual to uncover problems that were not possible to determine during the design phase when the final installation sequence was not known.

The pattern models are used to produce a very precise representation of the final geometry of the membrane and cables. These models will be used to produce the fabric cutting patterns and final cable fabrication lengths. A different pattern model was built for each bay of the Denver Airport. The pre-stress forces and boundary geometry established through work with the system models are used in the input data to these models. A much "finer mesh" is used to better represent the actual geometry. The software used to generate the pre-stressed equilibrium shape of the membrane also pulls the node lines (later to become seam lines) onto geodesic curves (ie. shortest path curves) along the membrane surface. This insures optimal seam locations both from a fabrication and aesthetic perspective.

Fabrication

The patterns are produced on the computer by laying sections of the model down into 2-D. The pattern data is then transferred to the fabrication shop electronically where a wide-area plotter plots the templates full-scale on paper. A typical template is 12-feet wide

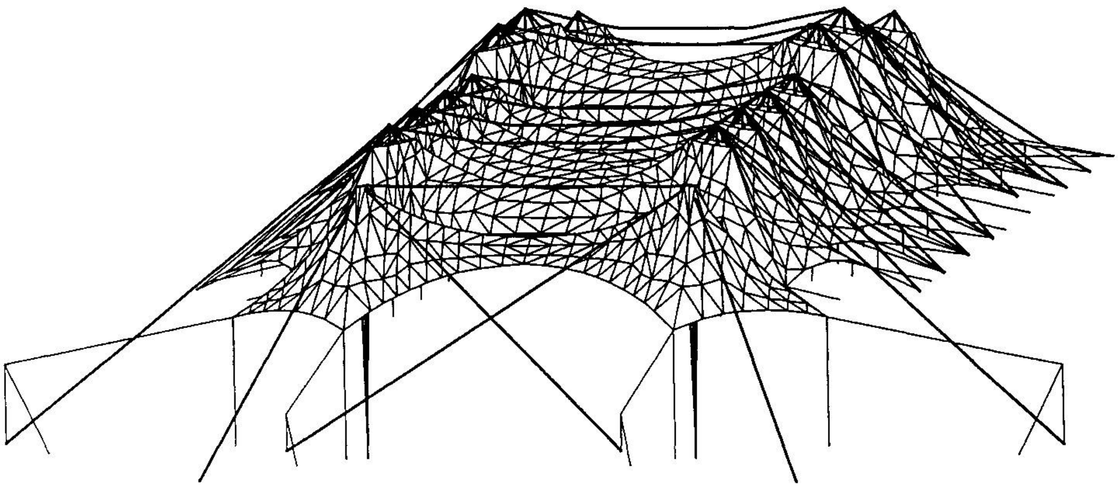


Figure 3: Installation Model. An installation computer model is used to analyze and design the temporary rigging and partially installed roof.

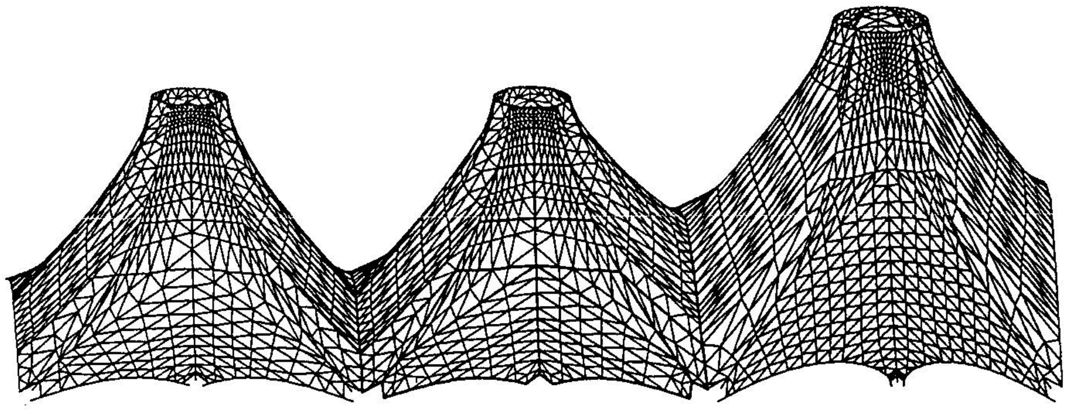


Figure 4: Pattern Model. "Fine mesh" computer models are used to generate the precise shape for patterning the fabric. The mesh lines (later to become seams) are established along geodesic curves on the surface. An example of these is shown with heavy lines in the center bay.

to match the fabric roll width, and up to 100-feet long. Fabric panels are cut from the templates and heat-welded together in the shop to form "assemblies". Each bay of the Great Hall roof consisted of 4 fabric assemblies. Each fabric assembly was individually rolled or folded and then packaged for shipment to the site.

Installation

At the time installation of the roof systems began, the concrete structure of the Great Hall building was complete up to the 5th level. Level 5 is the floor level for the primary Great Hall space. It was used during installation as a staging area and work surface for both men and equipment. Designed for live loads as much as 250 PSF, it was able to support up to 40-ton cranes, provided load-distributing mats were used.

The 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 of the building. In the completed structure, the masts are stabilized by the fabric roof system and associated cables that are located within the shape of the membrane surface. They have no external guy cables and therefore must be allowed to pivot on spherical bearings at their bases. Temporary guy cables were required to stabilize the system during installation. As there was no place to position guy cables that would not interfere with fabric installation later, temporary mast top extensions were bolted to the masts to provide a place 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 would not be able to carry. The problem was analyzed and solved using the installation computer models discussed earlier. The solution used was to add temporary stay cables to work in conjunction with the truss rings (similar to the stay cables on a boat mast) and remove the bending movement in the masts.

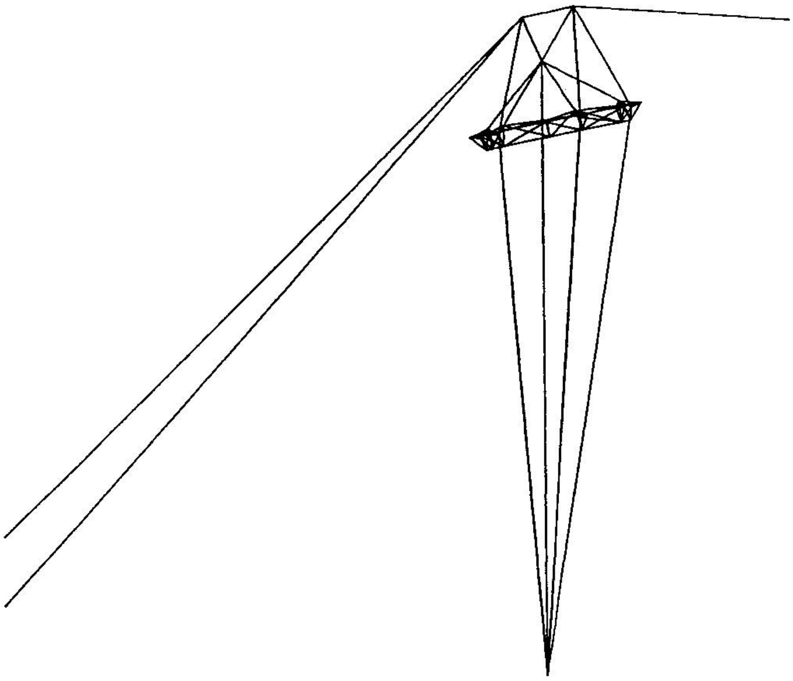


Figure 5: Stay Cable Rigging. A computer model is used to design the temporary stay cable rigging and mast extensions.

The truss rings were delivered to the site in two pieces, set around the mast bases (at the Level 6 elevation), and then welded together. The mast top units, skylights, and mechanical equipment were then assembled on the rings. Hoisting of all the rings (two at a time) was accomplished with a large drum hoist secured in one location on Level 5. The drum hoist cables traveled through a series of sheave blocks and fairleads up to Level 6, 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 rings together with their mast top units were sequentially hoisted in pairs.

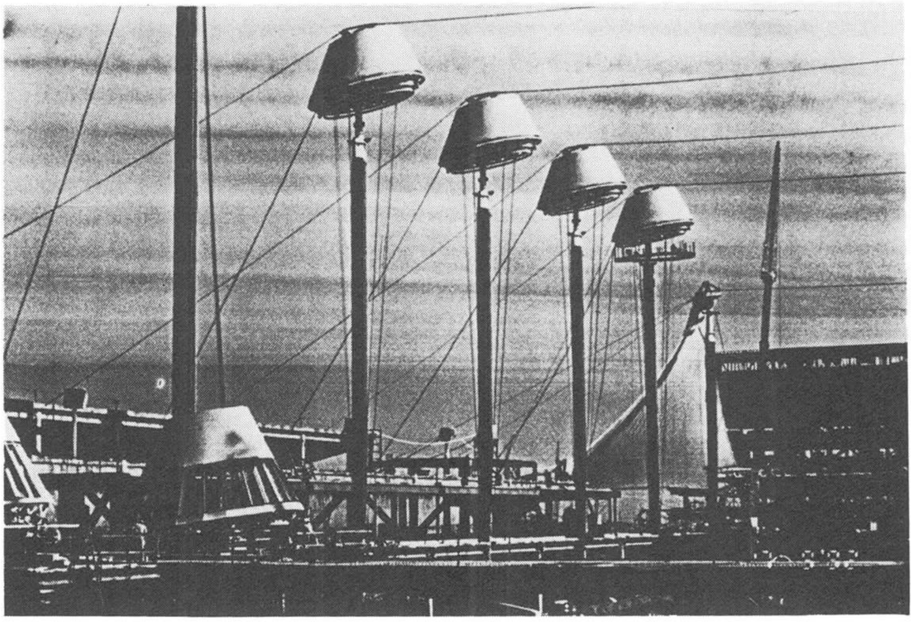


Figure 6: Mast and Truss Ring Installation. The masts are guyed with external temporary cables. The truss rings are assembled around the mast bottoms and then winched up into position.

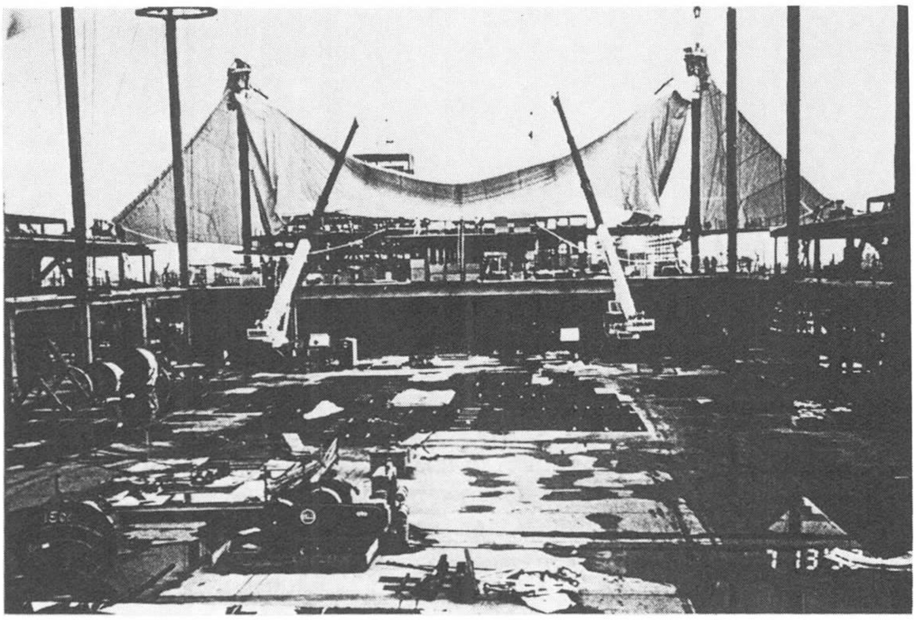


Figure 7: Fabric Hoisting. The fabric was lifted with a drum hoist secured on the level 5 slab (seen in the foreground). Two hydraulic cranes were used to assist.

As the ring assembly and hoisting proceeded, the outer fabric installation began. The fabric assemblies were unrolled on the Level 5 slab, and installed one bay at a time. The perimeter clamping hardware and cables (ridge, valley, etc.) were attached to the fabric while down on the slab. The fabric was positioned such that the two halves of a bay rested together, one on the top of the other prior to hoisting. The primary hoisting was performed using the same winch that was used to hoist the truss rings. The hoist cables were attached to each end of the bay's ridge cable which were lifted towards the rings. Two hydraulic cranes (positioned on the Level 5 slab) were also used to assist. As the ridge cable was lifted, the fabric bay went with it. Once the ridge cable was pinned, the fabric bay was spread open and attached at the valleys to the neighboring bays.

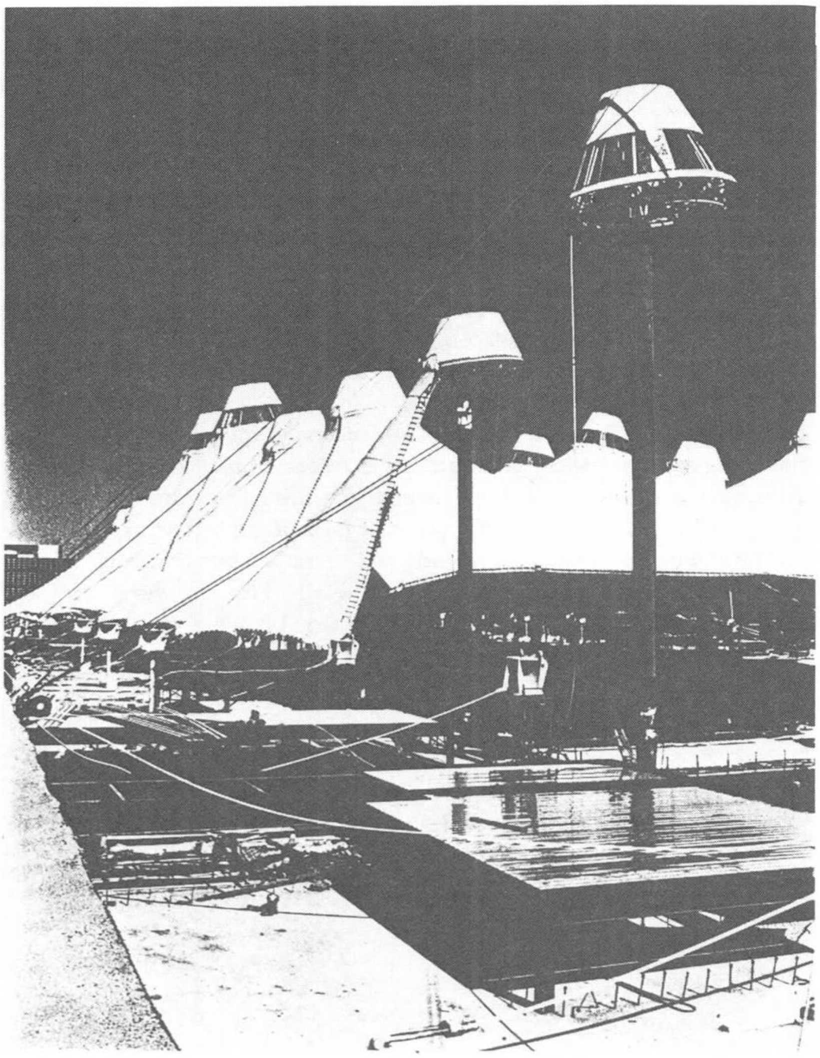


Figure 8: Partially Installed Roof

Following completion of the outer fabric the clerestory framing was installed. This work was erected from the inside of the building using hydraulic cranes situated on the Level 5 slab. An air-inflated expansion joint was installed to close the space between the outer fabric and the rigid clerestory framing.

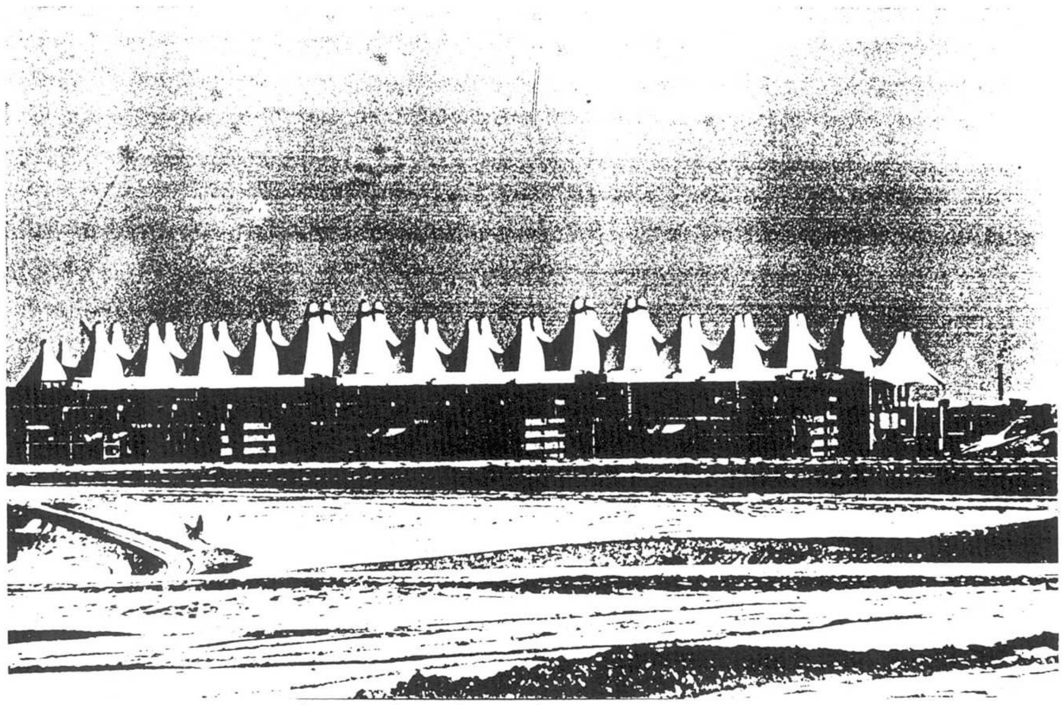


Figure 9: Elevation of the Installed Roof

The liner was installed after the clerestory glazing was complete, and an interior space was protected from the weather. It was erected sequentially in much the same manner as the outer fabric. 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.

The fabrication and construction of the roof system took the efforts of more than 300 people, over a time period of approximately three years. The fabric roof will become a landmark to the City and County of Denver, recognized worldwide for its unique architecture and the magnificent space it creates.