

Innovative Approaches to the Erection of Tension Roof Structures

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WITH TODAY'S increasing use and acceptance of tension systems for roof structures, and the advanced analytical techniques utilized in conjunction with the computer, new and innovative types of tension structures have been inspired. These range from single- and double-layer cable systems to multi-directional grid networks to free-form structures having unique cable configurations. In order to construct these new types of roof structures in a practical manner, innovative approaches for erection are often generated.

Unlike framed, rigid structures, most tensile structures are quite flexible and thus exhibit large movements, especially during erection. As a result, special care must be taken in the development and implementation of the erection of the structure.

Another factor that must be considered is that the tensile structure usually requires a pretension of some magnitude to make it function as conceived. This is particularly true due to the relatively low stiffness which most tensile elements possess compared to framed flexural systems present in the same structural assembly. This need for pretensioning adds another dimension to the erection, i.e., jacking of one type or another.

Pretensioning is usually also required in a tensile structure in order to insure that during the service life of the structure the tensile elements, which are usually slender members with very little compressive capacity, will remain in a state of tension. Therefore, in the development of the design, the full range of variation in tensile forces must be considered relative to the initial tensile force at the erection stage.

In many cases, a method of erection is developed solely for one specific project. Presented herein is an account of the erection techniques utilized in the construction of several tension roof structures, for which the authors' firm has had the responsibility of designing and/or supervising erection.

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GRANDSTAND ROOF, SUFFOLK MEADOWS QUARTERHORSE RACE TRACK, YAPHANK, N.Y.

This recently completed cable-supported roof, which measures approximately 146 ft by 500 ft in plan, includes a portion that cantilevers 76 ft out over the stands (Fig. 1). This cantilevered portion consists of steel girders supported by a system of cables tied back to the remainder of the building (see Fig. 2). There are three cables located along each girder line: an outer cable which is placed over a mast and spans 70 ft in each direction from the mast; and two inner cables, one on each side of the mast, each spanning 35 ft from the mast. The roof is comprised of 24 such girder lines, and thus has a total of 72 cables. The outer cable is a $3\frac{3}{4}$ -in.-dia. bridge strand, and the inner cables are $1\frac{3}{4}$ -in., 2-in. or $2\frac{3}{8}$ -in.-dia. bridge strand, depending upon the location.

A conventional method of erecting the $3\frac{3}{4}$ -in.-diam. outer cable would have been to connect one end of the cable, place the cable over the saddle at the top of the mast, and then, using a block-and-tackle arrangement, pull the other end into its connection and install the bearing nut. An alternate method of erection was devised

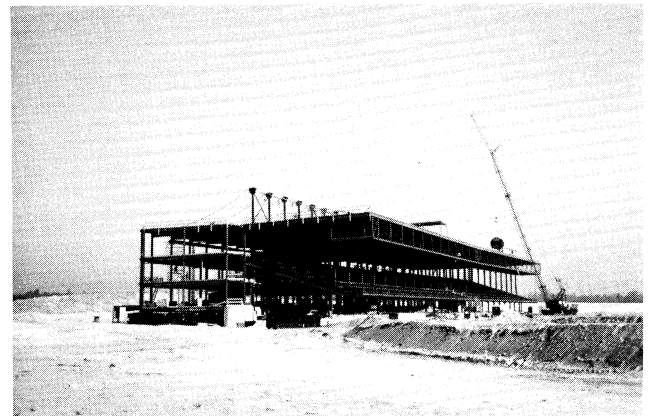


Fig. 1. Suffolk Meadows Quarterhorse Race Track, Yaphank, N. Y.

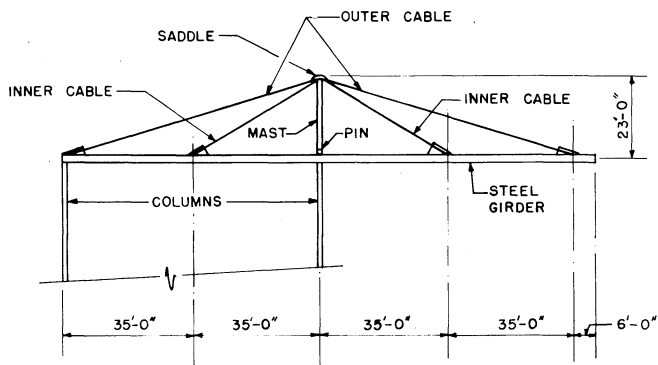


Fig. 2. Typical transverse section of grandstand roof



Fig. 4. Placing the outer cable atop the mast using the lifting saddle

in order to: (1) minimize the sliding of the cable over the mast saddle, which might have resulted in damage to the galvanized coating of the strand, (2) eliminate the possibility of inducing local bends into the cable in attaching and operating the block-and-tackle system as a primary erection device, and (3) accommodate the accessibility of the crane, which was limited due to the physical constraints imposed by adjacent portions of the structure. The alternate method of erection consisted of first making the connections at both ends of the $3\frac{3}{4}$ -in.-dia. outer cable while it was still lying on the roof slab. After these connections were made, the cable was raised at its mid-point, using a special lifting saddle (see Fig. 3), and was placed into the fixed saddle atop the mast (see Fig. 4). The lifting saddle was designed specifically for this project. It provided a means of lifting the cable without introducing a bend that had a radius less than the minimum recommended value. It also provided the required geometry and structural capacity to pass around the fixed mast saddle, lift the cable above it, and lower the cable into the saddle groove.

Cable lengths are usually calculated such that the final tensioned position of the adjustable end of the cable lies approximately at the center of the take-up range. However, in order to minimize the force required to lift the cable up over the fixed mast saddle during erection, this conventional approach was modified and the final tensioned position of the cable set as close as possible to the maximum take-up position. This was done to allow the maximum extension of the cable during erection, which provided the greatest amount of slack and thus minimized the lifting force. This was not only a convenient measure to reduce the weight and cost of the lifting saddle, but necessary in order to provide a lifting force within the limited capacity of the crane, which had to reach from a location more than 100 ft from the hoisting point.

Two jacks were used to tension each cable (see Fig. 5). The $3\frac{3}{4}$ -in.-dia. outer cable was tensioned using a pair of 150-ton double-acting pull jacks having 12-in. strokes. Each inner cable was tensioned using a pair of

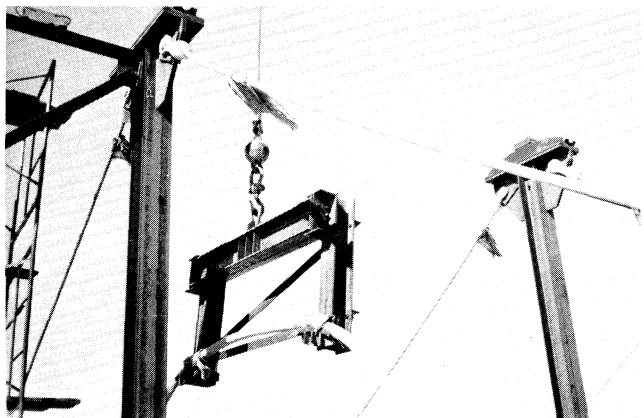


Fig. 3. Raising the $3\frac{3}{4}$ -in-diameter outer cable using the lifting saddle



Fig. 5. Typical tensioning apparatus

100-ton double-acting pull jacks also having 12-in. strokes. These jacks were selected for several reasons, including: (1) adaptability to the type of socket connection detail, (2) relatively small lead time requirements for fabrication, which accommodated the tight construction schedule, and (3) flexibility for other future uses, which resulted in a lower leasing cost. Threaded high-strength steel jacking rods connect to the jacks at one end, pass through the jacking plates, and connect to the girder connection plate at the other end (see Fig. 6). The tensioning of the cable is achieved by having the jacks pull themselves toward the girder connection plate via the jacking rods. The jacks bear directly on the jacking plates; these in turn bear on the jacking nut, which is attached to the threaded stud. The stud in turn is screwed into the cable socket. As the jacks draw the jacking plate assembly toward the girder connection plate, the bearing nut moves off the adapter fitting. As an added safety precaution, the bearing nut is continuously advanced manually to be in near contact with the adapter fitting at all times. When the required force is attained in the cable, the bearing nut is tightened against the adapter fitting, and the jacking apparatus is removed.

In order to determine the number of cables to be tensioned simultaneously, a study was made to obtain the most economical solution. In order to achieve the required load distribution in the cables at any one girder line, the three cables in that line had to be tensioned

simultaneously. If only one girder line at a time was tensioned, the cost of the jacks and hydraulic apparatus would be relatively low, since only three pairs of jacks would be required; however, the labor costs and the time involved in moving the jacks 24 times outweighed the low equipment cost. In addition, due to the relatively small distance between girder lines, it was determined that the tensioning of one line would influence the load distribution and deflection of the adjacent line, and that a minimum of two lines (six cables) should be tensioned simultaneously. If all 24 girder lines (72 cables) were tensioned at the same time, the labor costs and time would be a minimum; however, the high equipment cost negated this possibility. After studying the various alternatives, it was determined that jacking six girder lines (18 cables) at a time was the most efficient in terms of time, equipment, and labor costs (see Fig. 7).

A comprehensive step-by-step erection procedure was developed specifically for this project, in order to insure the proper sequence of tensioning of the cables. After tensioning the group of six girder lines, the procedure required that the jacks at only three of the six lines be advanced, thus leaving three lines with jacks from the previous group. This was done in order to monitor the effect of the new tensioning on that which had already been completed, with adjustments being made as required. Since the erection procedure required the jacks be moved from one cable location to another, the jacking plates were designed to be removeable. Therefore, after completing the tensioning at a girder line, the hydraulic lines were disconnected and the jacking plates and jacks were unbolted and moved to the next girder line. The actual tensioning was broken down into a series of increments in order to provide a gradual application of load. Using this erection procedure, the tensioning of all 72 cables was performed safely and efficiently, and was completed over a 2½-week period.

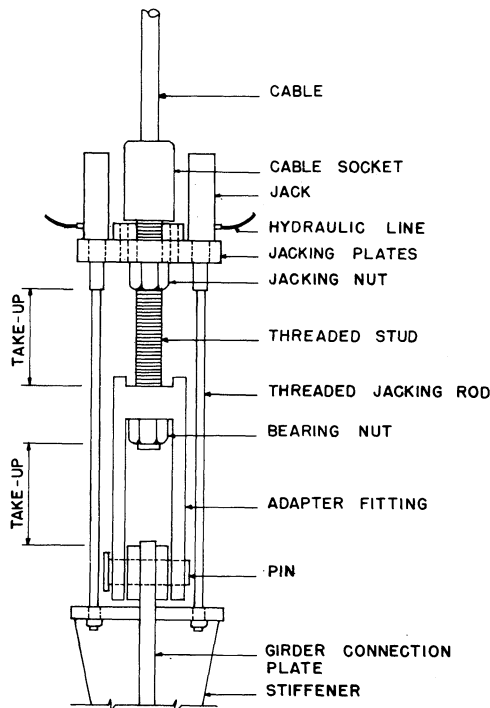


Fig. 6. Details of the cable jacking assembly

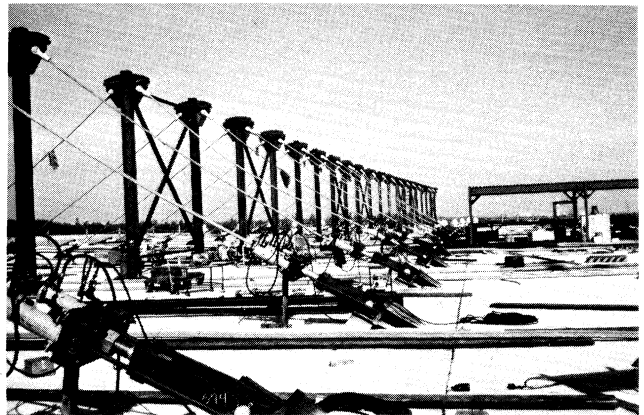


Fig. 7. Jacks set up to tension six girder lines simultaneously

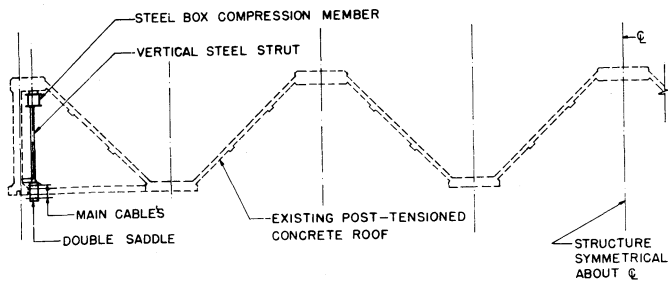


Fig. 8. Transverse section showing the remedial cable system within the envelope of the existing roof

REMEDIAL MEASURES FOR THE ROOF OF AN AIRCRAFT MAINTENANCE HANGAR

Although the authors' firm was not the original designer of the project to be subsequently discussed, it was engaged as consultant to design remedial measures for the post-tensioned concrete folded-plate roof of an aircraft maintenance hangar. The roof measures approximately 150 ft by 255 ft in plan, and is supported at each of the four corners by a concrete column. Subsequent to the completion of construction, the as-built roof evidenced excessive cracking and continuously increasing deflections, which adversely affected large sliding doors beneath one edge of the roof, and a glass wall beneath the opposite edge.

After investigating several alternate schemes for incorporating the corrective work, it was determined that the most economical solution, which also accommodated the functional requirements of the hangar, was to erect two remedial cable systems within the envelope of the existing folded-plate roof (see Fig. 8). The upper portion of each remedial system consists of a built-up steel box compression member, nominally 22 x 24-in., made from 1½-in.-thick plates. Four 3¼-in.-dia. bridge strands, placed in two layers, form the primary components of each system. Vertical steel wide-flange struts are spaced at 36-ft centers and are connected to

the box compression member using pins. At the lower end of each vertical strut there is a double-saddle arrangement which supports the four main cables. A system of adjustable secondary bracing cables was added in order to facilitate the plumbing of the vertical struts during erection, and to provide additional stability during the tensioning of the main cables (see Fig. 9).

The remedial cable system was designed to achieve the following objectives:

- (1) Lift the excessively deflected portions of the roof to a position that would be safe for the sliding doors and the glass wall
- (2) Control subsequent deflections in order to prevent any future cracking or other related problems from occurring
- (3) Provide the proper strength and stiffness to adequately sustain the forces developed as a result of lifting the concrete roof, as well as the forces developed in conjunction with the concrete structure in resisting superimposed snow loads

The lifting of each end of the roof was accomplished by the simultaneous tensioning of the four main cables. It was not possible to locate the jacking apparatus at the exact center line of the span, due to the presence of a horizontal concrete strut at this point (see Fig. 9). Nor could the remaining portions of the center bay on either side of the concrete strut be utilized, since the jacks and fittings for the lower cables would encroach into the envelope of the door opening below. Raising all four cables above the concrete strut would have significantly reduced the effective depth of the remedial system, and would have been accompanied by a substantial increase in the magnitudes of the forces and the sizes of the members. Therefore, the jacks for the two upper cables were located in the bay adjacent to one of the end bays, while the jacks for the two lower cables were located in the corresponding bay at the other end of the roof. This resulted in a symmetrical jacking arrangement for the remedial system as a whole, and eliminated the overall unsym-

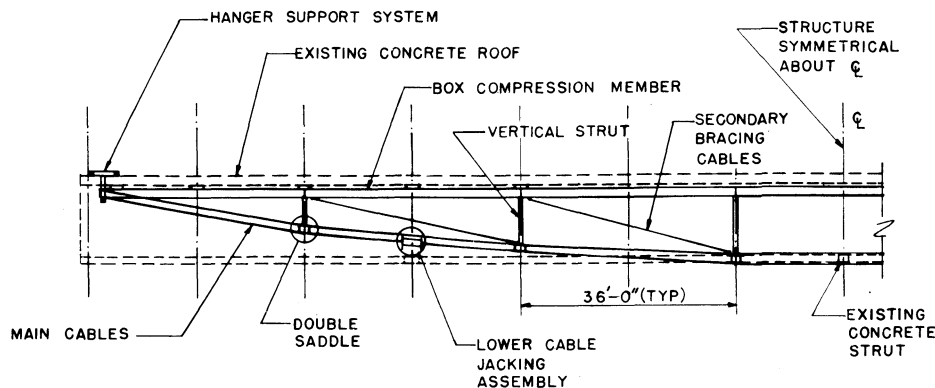


Fig. 9. Elevation of the remedial cable system

metrical effects of the friction forces developed at the saddles during the tensioning operation. In order to further minimize the effects of friction in general, each of the saddle grooves is provided with a teflon lining.

At the point where each cable is tensioned, the cable is made discontinuous. The two ends of the cable are attached to standard bridge bowl fittings (see Fig. 10). The fittings are connected together by two high-strength steel threaded rods which pass through, and extend out from, one of the fittings. A 156-ton center-hole jack fits over and connects to each rod extension and bears on the bridge bowl fitting via a machined part that provides clearance with the bearing nut. During the tensioning, the jacks draw the rods through the bridge bowls, bringing the two fittings closer together, while the bearing nuts are continuously advanced manually. All tensioning was safely controlled from the floor of the hangar, approximately 100 ft below the roof, and was performed as a series of increments over a two-week period in order to achieve a gradual application of load.

Finally, the remedial cable system maintains maximum flexibility in that any future requirement for additional jacking, or other adjustment of the roof, can be accommodated simply by reinstalling the jacks. It is possible to induce these additional jacking forces because a certain amount of reserve strength was designed into the remedial system in order to allow for such a contingency. As of this date, more than a year since the completion of erection of the remedial cable system, the system has achieved all the intended objectives, and there is no apparent necessity for future tensioning.

LOW COST, LONG SPAN ENCLOSURE

In order to provide a minimum cost enclosure for athletic facilities in the span range of 150 to 200 ft, the authors' firm has conceived and designed a braced-frame structure incorporating the advantages of industrialized construction in the United States and the economical savings of tensile structures. Figure 11 shows a cross section of the structure, and Fig. 12 shows a perspective view of the facility.

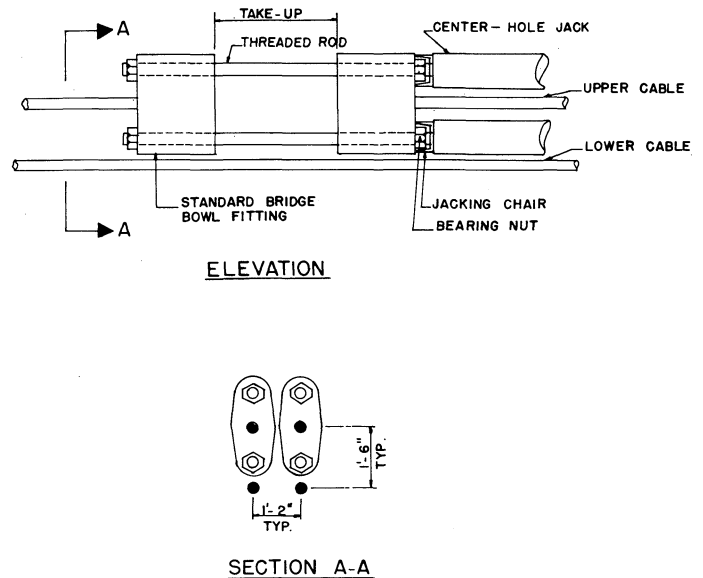


Fig. 10. Details of the cable jacking assembly

The structure consists of a rolled steel framework, having the basic shape of a gable frame, with the addition of outriggers which reduce the weight requirements for the structure while insuring the same performance. The tension rods which are incorporated provide an uplift force at about the third-point of the inclined roof member and, through the use of pretensioning, reduce the material requirements significantly.

The erection for this structure becomes critical to the design since, as mentioned above, the relative stiffness of the flexural frame members compared to the tension members is such that if the tension members were not pretensioned, they would just not provide the desired result. Therefore, after the frame is erected with a falsework tower at the middle, a jacking system is used to introduce force into the rods. In this case a force of approximately 70 kips is used. This type of structure is an example of the need for concise erection procedures for a tensile structure.

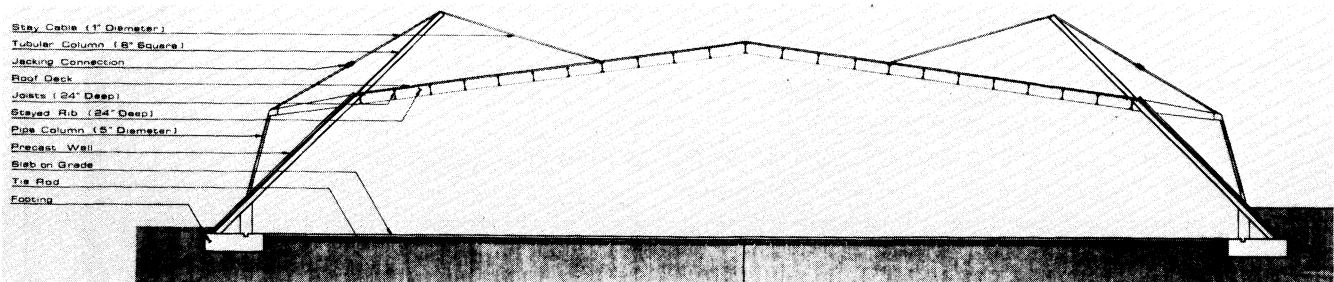


Fig. 11. Typical transverse section of athletic facility

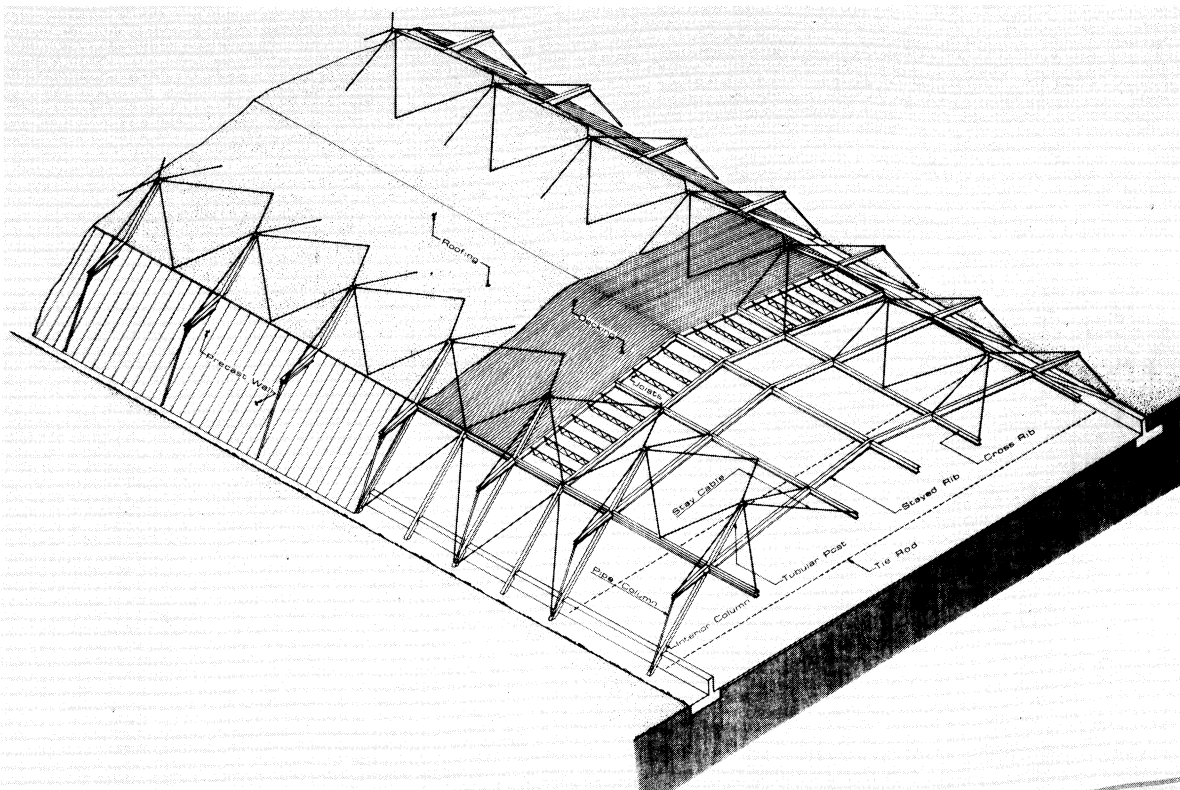


Fig. 12. Perspective view of athletic facility

TENSILE NETWORK COVERED BY AN AIR-INFLATED FABRIC

Recent trends towards fabric structures, either air-inflated or tensile in nature, have caused quite a bit of interest within the design professions. To use a fully inflated fabric structure usually entails the need for air locks and other devices in order to maintain air pressure and inflation. This causes an extreme cost penalty because of the usual requirement for large openings into the space. As a result, there is a great advantage in using a tensile network, i.e., an assemblage of cables prestressed in the form of a surface having negative Gaussian curvature and having an initial pretension adequate to maintain tension and thus eliminate dynamic instability.

A structure which is to be built in Cleveland, Ohio, utilizes a tensile network of cables covered by fabric. However, in order to maintain a thermal insulation value to the fabric cover and to ensure that all areas of the fabric are always tight and not flapping, pillows of air have been introduced between the two

layers of fabric. For a structure like this, the erection procedure does become quite complex. In this case, there are two sets of orthogonal cables: one set is comprised of load cables, and the other set is comprised of tie-down, or pretension, cables. After all the cables are strung, the pretensioning cables are jacked along the lower end near the ground. Once the cable network is fully tensioned, a secondary set of cables built into the fabric cover are then connected to the initial tension network, and the final structure takes its form. An air supply system along the perimeter of the structure provides air which, in turn, maintains the tensile tightness of the fabric.

SUMMARY AND CONCLUSIONS

In summary, this paper has attempted to give some insight into the problems and intricacies of designing and erecting tensile structures. Unlike the more rigid, flexural frame structures, the erection procedure and the initial stressing sequences for tensile structures are critical for the successful performance of the structure.