Case Study Review of Cable Supported Roofs

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Abstract

Case study review of the design and construction planning of three recent long span projects: Georgia Dome, Marine Midland Arena, and Denver International Airport's Main Terminal Building. Emphasis is placed on the physical and computer modeling, and applications of structural optimization.

Introduction

Successful completion of large scale projects requires close teamwork and careful planning at an early stage between the Designers, Contractors, and Construction Manager. Furthermore, complex and highly technical projects usually require portions of the scope of work to be organized as design/build packages. This paper presents a review of three such projects:

- Georgia Dome
- Marine Midland Arena
- Denver International Airport's Main Terminal Building

Discussion is primarily limited to an introduction to the structural design scheme, the construction planning, and the physical and computer modeling that was used in the planning and value engineering of these systems. A funicular form finding method used for structural optimization will also be introduced.

Georgia Dome

Introduction

The Georgia Dome is the worlds largest enclosed cable supported roof. It has a clear span of 240m x 193m. The structural form of the system is commonly referred to as a "cable dome", or more specifically termed by its designer, Matthys Levy, a "Hypar Tensegrity Dome".[3] The system is a 3-dimensional pre-stressed cable truss system that achieves high efficiency through the maximization of tensile members and the minimization of compression and bending elements.

More simply, the roof is essentially comprised of a series of "cable hoops" suspended from the perimeter. A set of posts projecting upward rests on the hoops, from which in turn another interior hoop is suspended. The system continues upward and inward in this fashion until it closes at the center.

Laying out the geometry of the system in this manner produces tensile elements in all but the vertical posts and, of course, the perimeter "ring". It becomes analogous to a large 3-dimensional truss system that has been pre-stressed sufficiently to remove compression from the top flange. In place of the normal bottom (tension) chords spanning the system, there are the highly tensioned "hoops" running circumferentially around the roof.

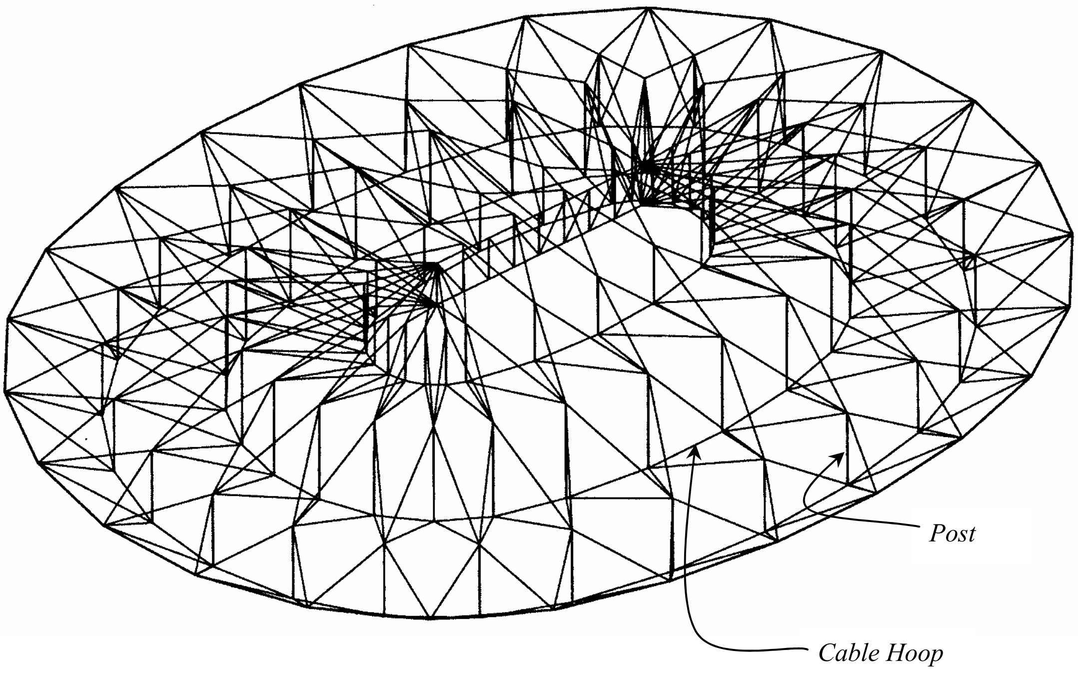

Figure 1. Hyper Tensegrity Dome

Construction Planning

The construction planning for this project had two very different phases:

Initial Planning: The initial planning occurred very early on in the design. Close teamwork and input by the Designer, the Roof Contractor, and the Construction Manager were required. The goal was to maximize the construction efficiency of the overall stadium and thereby achieve low cost for the entire project. We could not let the installation of the roof system dramatically interfere with other parts of the building construction. One of the main tools used during this phase was a "working" physical model of the roof system. We worked with the physical model, assembling, testing, etc., in order to develop the basic installation sequence.

Final Planning: After the general installation plan had been established, we turned to the computer to quantify each step of the construction. Twenty different steps in all were analyzed using large deflection finite element method (FEM) software. From start to finish, 80m of movement, as well as the pre-stressing at each stage, were modeled. Following are diagrams of a few of the installation steps analyzed.

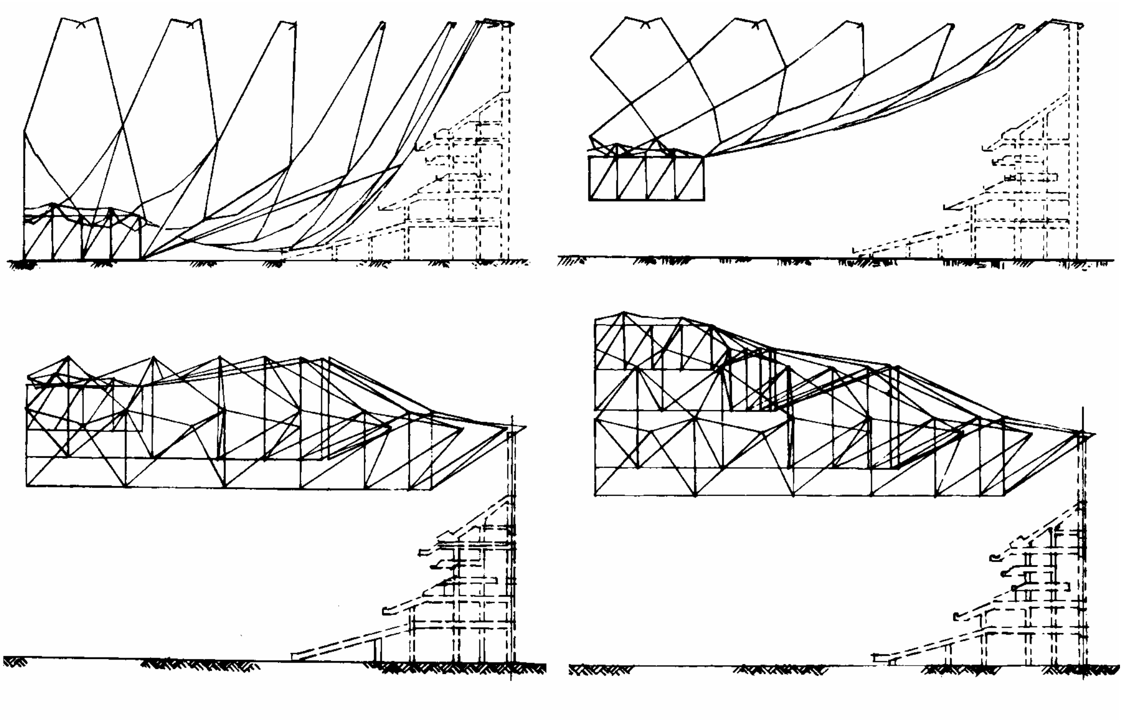

Figure 2. Computer models of some of the intallation steps.

Construction

The construction planning and analysis produced the following sequence of events:

1. Layout and assemble ridge net on the ground with all connections and weldments.
2. Raise the ridge net system by means of hydraulics placed on the perimeter ring beam, and pin the ridge net to the perimeter beams.
3. Layout outer hoop cable system on the ground and assemble with connection weldments.
4. Lift the outer hoop and suspend from the permanent outer diagonal cables.
5. Lift and set the outer posts between the outer hoop (below) and the ridge net (above).
6. Inner hoop and post jacking: For each successive set of interior hoops and posts a different procedure was used.
    - Lift and hang posts from the ridge net.
    - Assemble hoops on ground, then lift and attach to post bottom.
    - Install temporary jacking cables between the top of the outer posts and the bottom of the next corresponding inner post.
    - Simultaneously jack all 26 diagonal cables, raising the hoop and posts simultaneously until the permanent diagonal cables can be attached.
7. Install the clamping hardware and prefabricated PTFE/glass fabric over the top of the cable net.

Figure 3. Georgia Dome during fabric installation

Marine Midland Arena

Introduction

The Marine Midland Arena, located in Buffalo NY, was built as a new home for the National Hockey League's, Buffalo Sabres. The arena seats about 20,000. The overall roof plan measures 140m x 104m. The structural system of the roof commonly called the "Braced Tensegrity Dome" is patented under the title, "Tension Braced Dome Structure." The design team of Ellerbe Becket Architects and Engineers, and Birdair as the Roof Design-Build specialty contractor was formed early in the development of the project.

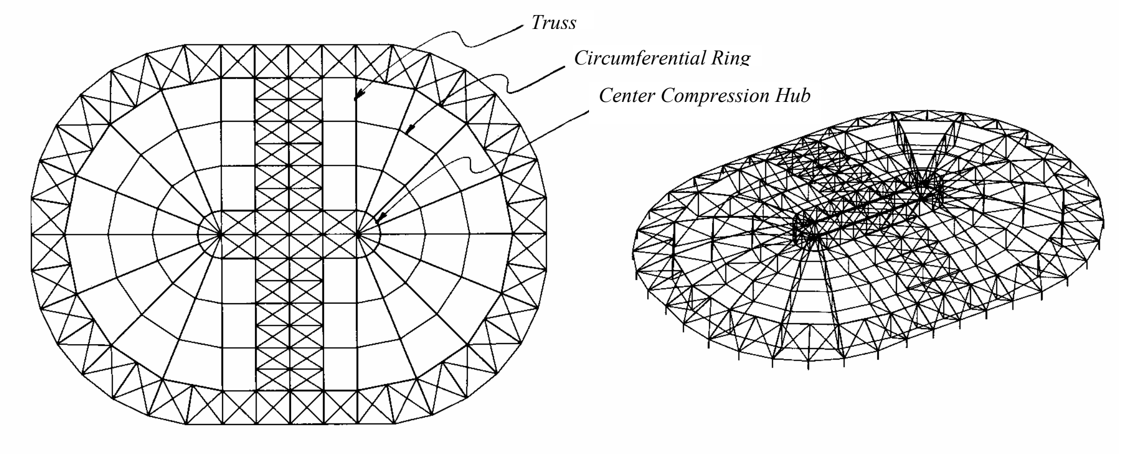

Figure 4: Braced Tensegrity Dome Framing

Design

The design is derived from a combination of a tensegrity cable dome, (as in the Georgia Dome), and a single layer rigid dome. The concept was developed by Wesley Terry[2] using modeling techniques, including the effects of pre-stress and large deflection normally used for tensile membrane and cable net analysis. In essence, the system is designed and carries load as a "pre-stressed cable dome," where the tension only top chords (i.e. ridge net) are replaced by standard mill shape steel tension/compression members. The result yields a structural system that has the lightweight clear span advantages of the cable dome, gaining efficiency through the maximum use of tensile elements. The system is however, simpler than a cable dome and eliminates the need for the large compression ring around the perimeter. It has better strength and buckling stability than a more conventional thin rigid dome system. The primary load paths are compression in the center hub, compression and flexure in the "trusses" at the straight sides and primarily dome type compression in the radial trusses at the ends. The circumferential rings at the bottom chord are always in tension. At the top chord, the inner ring is in compression and the outer ring is in tension, much like a dome. The circumferential rings at the top and bottom chord levels and the perimeter-braced ring resist the thrust forces normally resisted by a single, large perimeter ring beam.[2]

From an idealized point of view, the system works as a thin rigid dome that is reinforced and supported from below by a cable dome system. Combining these systems allows the dome to have a shallow rise, yet maintain high stiffness, strength and cost efficiency. Confusing in its behavior maybe, but the system works very well. The weight of the completed system including catwalks, rigging grid, roof joists, and connections were less than 0.8kPa., compared to 1.0 to 1.3kPa. for simple span roof systems of comparable size and loading.

Construction Planning

The construction planning began early in the design process to insure that the final design and installation plans would be compatible. Connections, as an example, were developed jointly during the design stage between Ellerbe Becket and Birdair. The goal was to create compact, simple, economical connections that would be fast to install and require no field welding. Single pin connections were used where possible. In depth computer modeling was performed to both assist in the development of the plan, and then to quantify and check loads and member sizes in the key steps of the installation sequence. It was concluded that two shoring towers would be used to hold the roof in its "weightless configuration," i.e. in its theoretical shape prior to dead load deflection. In this configuration member forces were very low and erection could take place without any significant pre-stressing.

Figure 5: Marine Midland Arena Roof Construction. Shoring towers were used to hold the roof in its "weightless configuration."

The installation was performed using the following steps:

1. Shoring towers were placed beneath the future location of the central truss hubs.
2. The central truss hubs were then assembled on the ground and lifted onto the towers.
3. Straight sections of the center truss followed in a similar manner.
4. The radial "trusses" were assembled on the ground, the lifted and installed as one way trusses.
5. The circumferential rings were then installed.
6. Finally the shoring towers were removed, effectively "pre-stressing" the system. At this point, the circumferential "hoops," (which normally would simply brace the members in a more conventional system), now pick up substantial force and become primary load carrying elements.

The three-dimensional computer modeling predicted 120mm of deflection upon removal of the shoring towers. The actual field measured deflection was 130mm.

Denver International Airport

Introduction

The tensile membrane fabric roof structure enclosing the main terminal 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 90m by 300m in plan. It is supported by 34 masts of approximately 30m in length, has a surface area of about 35,000 square meters. The dramatic peaks and valleys give it a unique shape emulating the Rocky Mountains that are synonymous with Denver and provide a striking backdrop for the new airport.

Construction Planning

Initial Planning: The first step of the installation planning was to construct a working physical model. The physical model was used to qualitatively study the installation and formulate a preliminary plan. In the case of the tensile roof, we constructed a 1:100 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. Working with scale replicas of the fabric assemblies, we tested out the different methods and sequences of the 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.

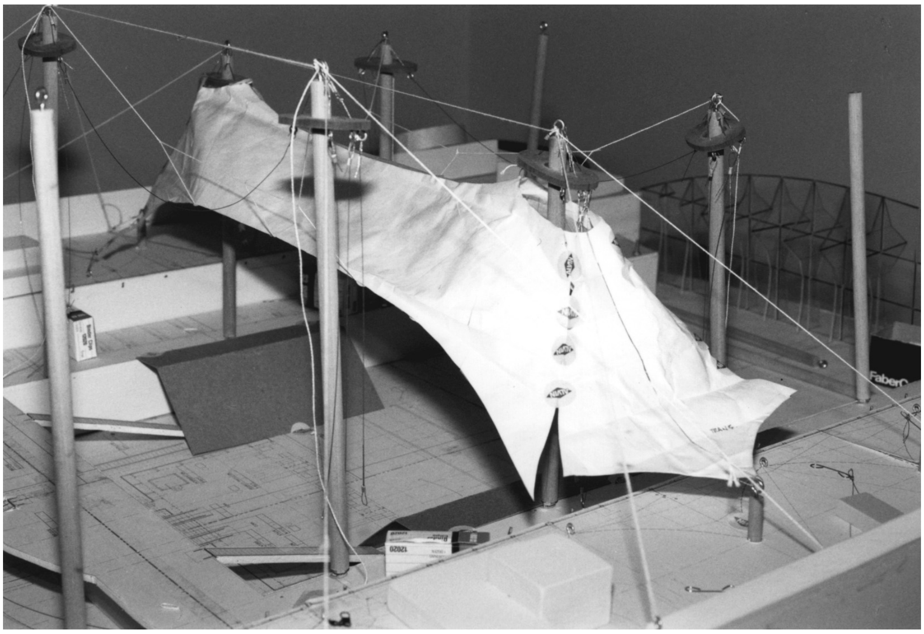

Figure 6: Physical Model. A Working physical model was used to develop and test the installation procedure

Final Planning: After the qualitative work was complete with the physical model, and a general plan had been established, computer models were built to perform the quantitative structural analysis using non-linear finite element method analysis software. A system model was built to represent the entire system. Installation models were built using parts of the system model appropriate to the particular stage of construction. Installation rigging and temporary guying systems were added to the models. The pre-stress forces and geometry were modified to better represent the real conditions that would exist during construction. These models were used to design the installation rigging and check the permanent roof components during the different construction phases.

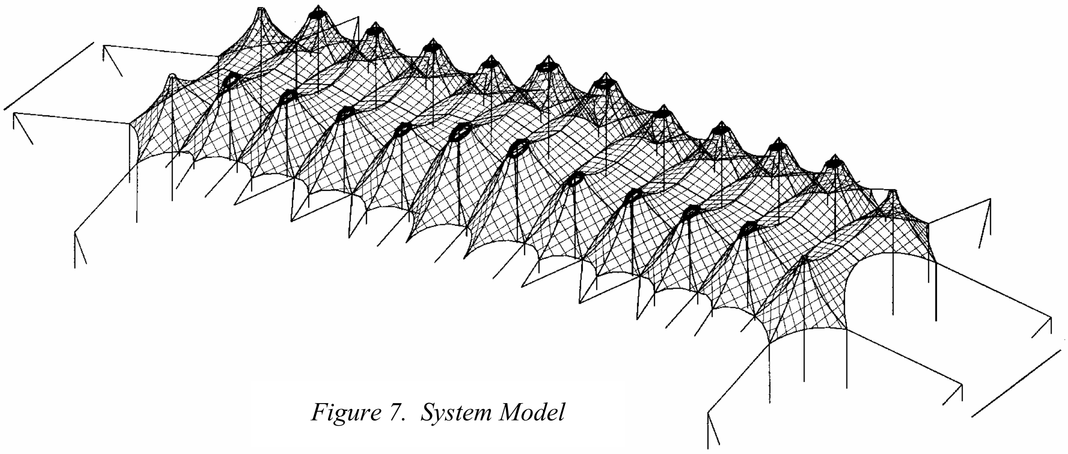

Figure 7. System Model

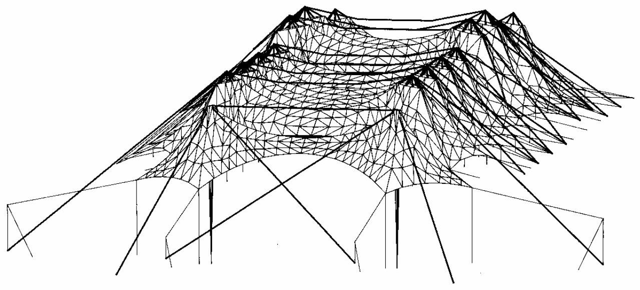

Figure 8. Installation Model. Installation computer models were used to analyze and design the temporary rigging and partially installed roof.

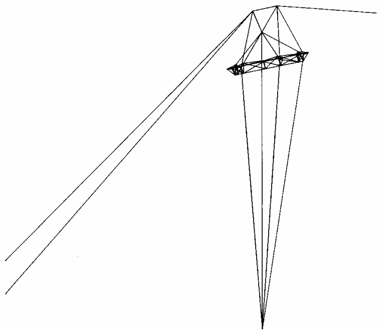

Figure 9. Stay Cable Rigging. Computer models were used to design the temporary stay cable rigging and mast extensions.

Modeling Software

Software that allows fast modeling and accurate analysis is a necessity for the successful execution of these types of projects. Our experience has shown that these tools, although obviously required for the basic design and fabrication, become invaluable to the construction planning and value engineering of structural systems.

One well known method that is used to minimize costs in a structural system is to maximize the use of "axial" elements (i.e. tension or compression), and minimize the use of bending elements (i.e. elements required to carry large bending moments). Concrete shells, suspension bridges, cable domes, and simple trusses are all examples of this principle. However, finding the geometrical configuration that will allow the design of such funicular elements in a complex 3D system is usually more easily said than done. To overcome the problem it is possible to reformulate algorithms in tensile form finding programs to allow beam/column elements to become a part of the form finding process. In other words, to solve for the geometrical configuration where bending moment is completely removed from bending/compression elements during the form finding process. The process takes some reformulation because compression elements that are allowed to substantially flex become inherently unstable. The following diagrams illustrate the technique. In this example the equilibrium shape of a pre-stressed cable net was generated simultaneously with the generation of the funicular shape (zero bending moment equilibrium configuration) of the supporting arch and perimeter ring.

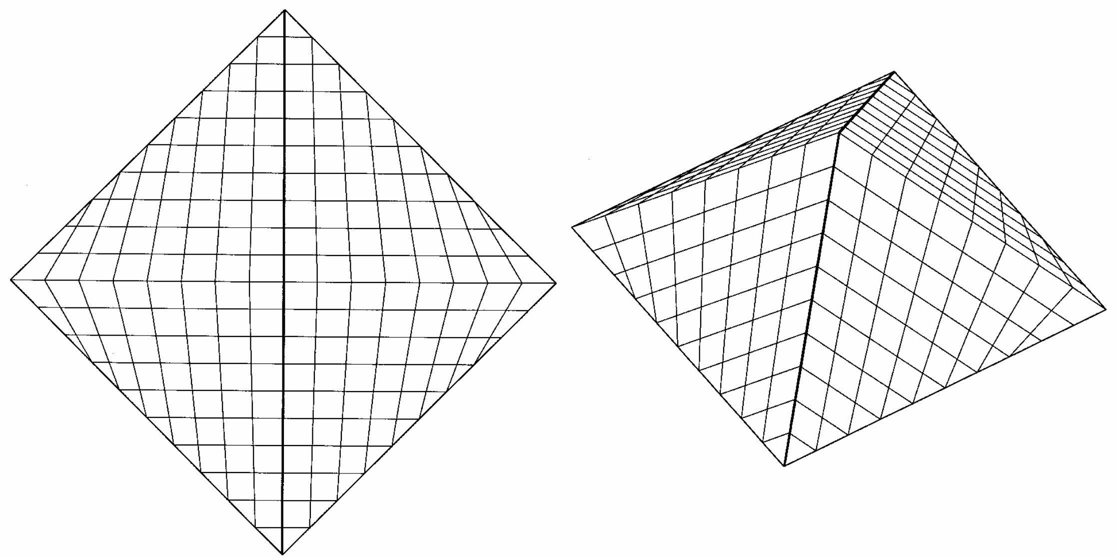

Figure 10: FEM model of the "starting geometry" of a cable net and beam system prior to Form Finding

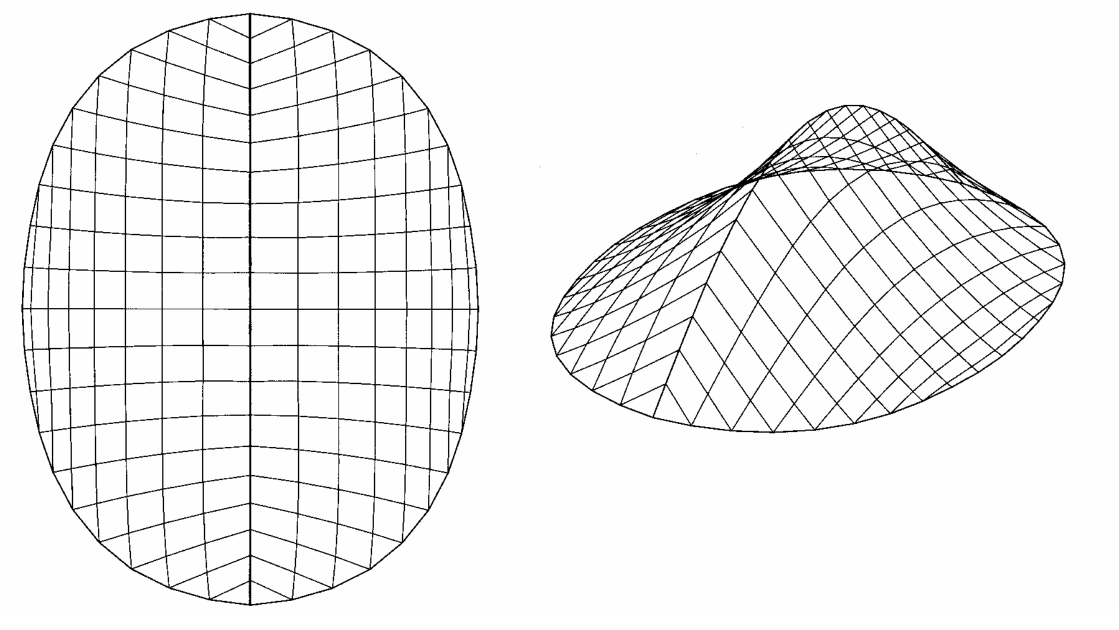

Figure 11: FEM model of the same system after Form Finding. The cable net is in equilibrium. The supporting arch and perimeter beams have translated into funicular shapes (i.e. zero bending moment).

References

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2. Hofmeister, Steven W., Houghton, Karen M., Storm, Gary A., and Terry, Wesley R. "Design and Construction of the Tension Braced Dome Roof Marine Midland Arena," ASCE Structures Congress, 1997

3. Levy, Matthys, Terry, Wesley R., and Jing, Tian Fang, " Hypar Tensegrity Dome Construction Methodology," Innovative Large Span Structures, vol. 1. Montreal: The Canadian Society for Civil Engineering, 1992

4. Terry, Wesley R., "Georgia Dome Cable Roof Construction Techniques," IASS-ASCE International Symposium, Atlanta: Spatial, Lattice and Tension Structures, 1994

Project Acknowledgements

Georgia Dome – Atlanta, Georgia

Architects:	Heery Architects & Engineers, Inc. Rosser Fabrap International Thompson, Ventulett, Stainback & Associates, Inc. Atlanta, GA
Engineer:	Weidlinger Associates New York, NY

Marine Midland Arena - Buffalo, New York

Architect:	Ellerbe Becket Kansas City, MO
Engineer:	Ellerbe Becket Kansas City, MO

The New Denver International Airport - Denver, Colorado

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Engineer:	Severud Associates Consulting Engineers P.C. New York, NY
Fabric Roof Consultant:	Horst Berger