THE GEORGIA DOME, ATLANTA

HYPAR-TENSEGRITY STRUCTURE

Author: Matthys P Levy - Principal, Weidlinger Associates, New York

Presented by: Chris P Michelmore - Director, Connell Wagner (SA) Pty Ltd

MSAA/LSAA Conf Proceedings

Introduction

Spanning an incredible 240m (784 ft), the Georgia Dome roof breaks new ground in the development lightweight structures. Starting with a concept springing from the inventive mind of Buckminster Fuller, the Hypar-Tensegrity Dome solves the practical problems and opens the door to a wide variety of options for covering large spaces. This paper describes the process from concept to solution, showing how the interrelation of many aspects of the structure, geometry, buildability, material constraints, and economy all converge to create a solution replete with innovative and elegant details. For the future, variants are proposed to cover anything from an arena to a recreational facility.

Historical Background

The Osaka World Fair of 1970 opened the door to the popularization of fabric structures. The fairgrounds were resplendent with numerous examples of balloon type constructions, but it was the low profile United States pavilion with its translucent air supported fabric roof that sparked the imagination of all who saw it. Here was a radical departure from what we think of as a roof. Gone was the hard opaque structure in steel, wood, or concrete, replaced by a paper thin membrane, upsetting our sense of what a shelter should be. Permanence was redefined from hard to soft, from dark to light, from heavy to airy. This roof, designed by David Geiger, was the first of many lightweight structures used to cover long span spaces, primarily sport facilities, built in the last two decades.

For all its advantages - and there are many - the air supported roof had one failing; it requires a mechanical device, a blower, to maintain its erect shape. Although it is still undoubtedly the lowest cost long span roof structure, a number of deflations at the Silverdome in Pontiac and Metrodome in Minneapolis, usually accidental and caused by improper operation, underscored the weakness of having to rely on a mechanical device for structural stability. This led to the reinterpretation of an idea first expounded by Buckminster Fuller in 1954.

Fuller patented a roof system he called an "aspension" or tensegrity dome, describing it as a structure in which islands of compression resided in a sea of tension. The dome consisted of a radial series of discontinuous trusses in which the bottom chord instead of being in the plane of the truss exists as a series of hoops tying together all of the radial trusses. This idea was brought to life by Geiger in his design of the circular roof structures for the Olympics in Seoul of 1988. Rather than using the triangulated geometry proposed by Fuller, Geiger used radial planar trusses in his circular domes. It had the effect of simplifying the geometry while removing a degree of lateral stability of the top radial chords of the dome, which now relied on the fabric for stiffness.

MSAA/LSAA Conf Proceedings

Sports Stadia - Geometry and Function

Most football stadiums have oval plans; in fact, most sports halls are non-circular in plan. The need to develop a roof adaptable to a variety of non-circular configurations, led Weidlinger Associates to reexamine the cable dome concept. It appeared that a triangular geometry is significantly more adaptable to non-circular configurations and has the advantage of greater redundancy and greater adaptability to nonsymmetrical loading conditions.

On the negative side of the ledger, the use of triangular geometry increases the degree of complication, particularly at nodes at which as many as 6 cables and one post meet, all converging to a point The task of designing a node to accomplish this goal in an economic manner proved to be one of the key elements in developing the hypar-tensegrity dome. (Fig. 1)

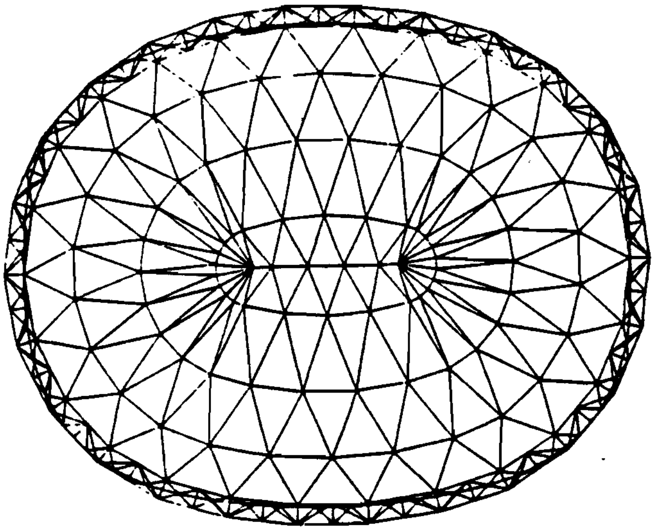

FIGURE 1

The optimum seating arrangement determines the shape of any stadium and for the Georgia Dome, for instance, it is an oval derived in each quadrant from three circular segments. The pure geometry of a cable dome starts with a circle of equally spaced nodes along a compression ring and like spaced segments along ever smaller circumferential rings (each offset from the next to develop the triangular geometry). An elliptical configuration follows from the circle in exactly the same manner except that the angles of the cables converging to a node in the case of the circle are all the same and those of the ellipse are all different. This has the practical consequence of requiring nodes that are all different along a meridian, creating a difficult fabrication problem, and consequently an uneconomic structure.

To get around this problem, Weidlinger Associates proposed a roof geometry based on one or two circular elements thus reducing the number of different nodes and increasing repetition. This was the second key decision in developing the hypar-tensegrity dome. With this arrangement, it is possible to approximate the perimeter of any sports facility while keeping the perimeter of the dome within the horizontal dimension of the required compression ring.

MSAA/LSAA Conf Proceedings

Practical Constraints - Cables and Node Elements

Previous cable domes used nodes made out of castings and, at first, Weidlinger Associates considered following the same path, giving particular consideration to the complications resulting from the triangular geometry. After studying both upper and lower nodes, the designers concluded that a rational arrangement of welded plates could be developed as substitutes for castings. The benefit of this simplification was a lower node cost. Before reaching this result, another complication had to be overcome. The cables coming together at an upper node lie in two plates angled on either side of a radial line bisecting the node. Since multiple cables are required and since the centre of gravity of each group of these cables must intersect at the geometric centre of the node, all the cables arriving at a node must be arranged to satisfy this condition.

This was accomplished by placing cables on either side of the radial boundary in what amounts to saddles lying in each of the two planes, resulting in two highly stressed plates joined to each other along the radial line. These were originally designed to be welded together, but a more economical solution was developed using a single bent plate which was facilitated by redesigning the saddles, originally machined out of a single thick plate, as bars welded to the bent plate. The node resulting from this creative design process is the third and critical element in the development of the **hypar-tensegrity dome.** (Fig. 2)

FIGURE 2

Once the key decisions in the initial development of the structure had been made, there remained a number of secondary considerations which impacted on the economy and efficiency of the dome structure:

What is the optimum number and spacing of hoops?
What is the optimal height of the posts?
How is the fabric tension maintained?
What is the ideal spacing of sectors around the perimeter of the roof?
What is the structure of the compression ring and how does it relate to the structure of the stands below?

Each of the answers was derived from practical considerations as well as from technical constraints, and it turns out that many of the requirements are interrelated.

MSAA/LSAA Conf Proceedings

Loading Conditions

In order to examine the development of the dome, it is necessary to first define the loads that have to be resisted, including gravity, wind and seismic loads, prestress forces and forces due to temperature changes. Of these, seismic effects are essentially negligible due to the small self weight of the roof structure. The only component of the roof that may have to be examined for seismic effects is the compression ring, especially if it is made out of concrete.

Prestress in the cables is necessary because first, under gravity loads, the top chord of the dome structure will tend to go slack near the centre of the dome and second, the fabric needs an initial tension to prevent flutter. Since the profile of the dome is extremely shallow (less than 1:8), wind tends to cause negative forces (suction) on the roof. A wind tunnel test is needed to establish the distribution of these forces across the roof.

Often neglected is consideration of the network of catwalks, needed at the level of the hoops to permit servicing lights, speakers and rigging for special events, which impose loads on the structure of the same order as the weight of the fabric (15 N/m^2, 0.3psf). The total dead load of the roof is an incredibly low 0.4 kN/m^2 (8psf), even exceeded by the wind suction of about 0.6kN/m^2 (12 psf). Most building codes also require a minimum live load to be supported by the surface of the dome of 0.96 kN/m^2 (20 psf), which can be reduced to 0.6 kN/m^2 (12 psf) for the cable design and 0.8 kN/m^2 (16 psf) for the fabric design.

The Georgia Dome

The principles spelled out above have been applied to the design of the Georgia Dome, a 70,000 seat stadium currently under construction in Atlanta. The plan of the seating bowl has been optimised to provide the best seating arrangement for football, resulting in 52 bays around a 700m (2300 ft) perimeter, controlled primarily by the maximum available span of precast seating sections. The decision to approximate the oval perimeter described by the outside edge of the seating bowl by a curve constructed of two radii was followed by a trial-and-error procedure to find the best fit with the least deviation from the bowl perimeter.

The solution to this problem could not be finally determined without first deciding on the number of sections for the roof structure, keeping in mind that it had to be a fraction or multiple of 52 in order to maintain a sense of unity between the roof and seating column structures. Rather than using a sophisticated optimisation procedure, the decision to use 26 sections was arrived at by intuitive deduction by using panel widths of the same order of magnitude as used in prior fabric roof structures, fabric forces within those permitted for the teflon-coated fibreglass proposed to be used, and using a reasonable number of attachment points to the compression ring. (Fig 3)

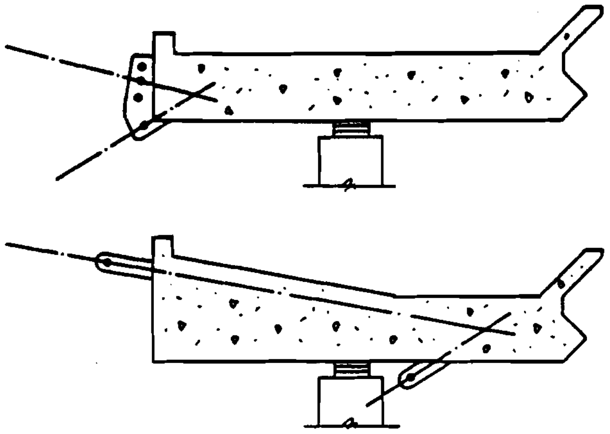

FIGURE 3

The next question to be answered concerned the continuity at the centre. As seen in plan, the roof consists of two circular segments on the ends separated by a butterfly section filling in the centre. Tying the two spokes of the circular segments is what appears to be a plane truss 184ft long. First conceived as a real truss with rigid members, it was later revised and detailed as a cable truss more in keeping with the overall spirit of this structure. Because the top and bottom chords of this truss are always in tension since the two circular segments are trying to pull it apart, they become cables just like the rest of the dome. The vertical posts which are in compression are steel pipes, and the tension diagonals are cables. (Fig 4)

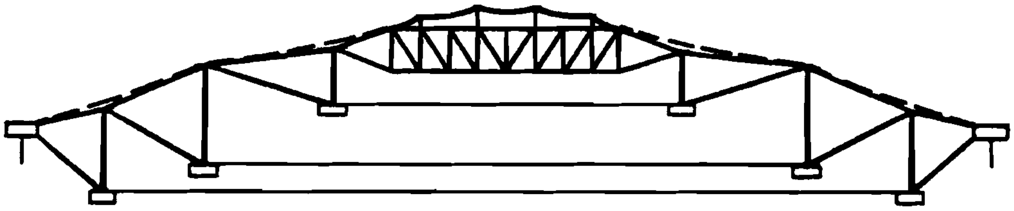

FIGURE 4

Consultation with fabricators established early on that the maximum viable cable size is 4 inches (100mm) based on the size of the largest transportable reel. The decision to use wire rope or strand in different parts of the structure depended upon whether or not a particular element was subject to future bending. The bottom chord tension rings, the diagonals, and the cables in the tension truss are likely candidates for strand which, although somewhat more economical than wire rope, is more difficult to handle in the field.

In order to develop a fabric surface with sufficient stiffness, the diamond shaped panels needed to be deformed into hyperbolic paraboloids by lifting two opposite corners and dropping the other two corners of the diamond. At the same time, the overall surface of the roof had to maintain a downward slope in order to ensure positive drainage of rainwater toward the edges. Finally, the overall height of the roof had to be minimised in order to achieve the least surface area - again, for economy. This resulted in the tent-like appearance of the hypar-tensegrity dome. (Fig. 5)

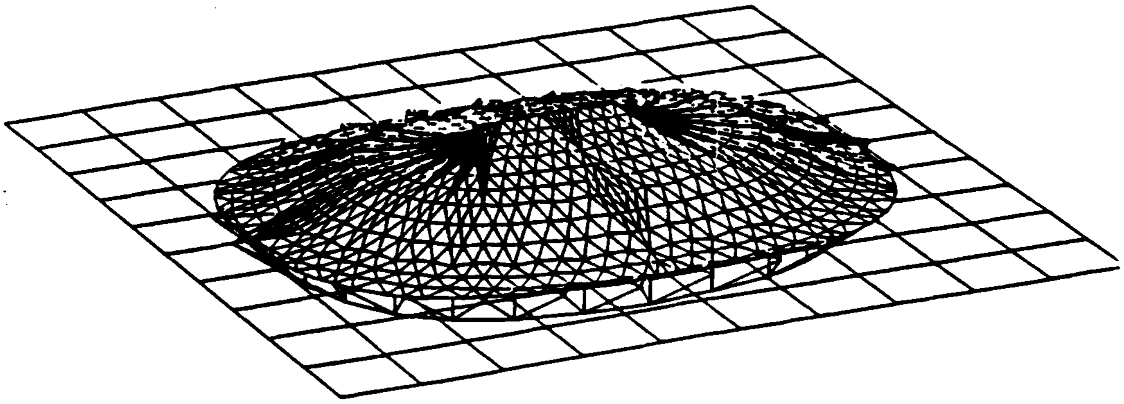

FIGURE 5

MSAA/LSAA Conf Proceedings

MSAA/LSAA Conf Proceedings

The slope of the first diagonal cable descending from the compression ring, together with the span to the first tension ring are strongly impacted by the need to maintain sightlines from the topmost seats. As the first tension ring drops lower, the spring line of the dome must be raised. On the other hand, making the slope shallower increases the forces in the diagonals and the compression ring. The balance between these conflicting requirements was studied to obtain an optimal slope range which for the first ring is close to 45°. Each subsequent ring, proceeding inward, can have a shallower slope since each carries less load and is not controlled by cable size limitations.

The number of tension rings cannot be independently determined since it is governed by the slope of each tension diagonal, the limitation on cable size, the size of segments, and fabric dimensional limitations. Rather than strictly optimising this, a number of alternate schemes were studied with 2,3 or 4 rings plus, of course, the centre tie. The choice of three rings appeared to provide the materials and ease of erection.

The compression ring design responds to requirements:

(1) the need to resist both compression and bending, because the ring is not funicular, and
(2) the need to mediate between the curve defined by the dome edge and that defined by the seating bowl causing torsion because the centrelines are not coincident. Two solutions were examined:

(1) a triangular steel truss with a horizontal top truss and inclined side trusses meeting at a base above the columns below (Fig 6), and
(2) a concrete box girder centred on the columns below.

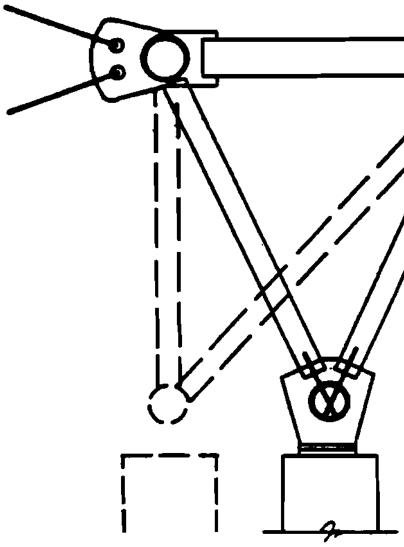

FIGURE 6

The concrete solution results in the attachment point for the roof being at different locations in the cross section of the girder (Fig. 3), meaning that the fabric roof is not geometrically "complete". The steel solution, on the other hand, modulates perfectly between the two geometries but unfortunately, in the case of the Georgia Dome, local economic factors decided in favour of the concrete solution.

A final problem relates to the need to isolate the roof structure from the seating bowl in order to permit it to respond to temperature changes as well as to the initial deformations from prestressing forces. At the same time, lateral forces from wind or seismic loads must be able to be transferred from the dome to the supporting structure which, in the case of the Georgia Dome with a concrete compression ring, can be resisted if a coefficient of friction of 4% exists between the ring and the column below. A pot bearing with teflon mating surfaces satisfies these requirements with a design that permits free movement radially and is laterally restrained with a 500mm (2 inch) movement before hitting a guide bar.

The final result of this design effort is a 37,200 sm (400,000 sf) free span roof celebrating the joy of the circus tent with the poles floating high in the air suspended by wires rather than planted in the ground obstructing the spectators' view.

MSAA/LSAA Conf Proceedings