Structural Form in Architecture

From Pre-historic Stickdomes to State-of-the-art Gridshells

By Horst Berger

Roof of the Jeddah Haj Terminal in Saudi Arabia.

We live in a time of rapid change. Technology has just taken a giant leap forward. Something is changing almost every day. For today's practicing engineer, it is hard to understand that only fifty years ago a leading structural engineer in his opening remarks to a conference in Chicago on "Wind on High Rise Buildings" summed up the state of the art in this way: "The profession of structural engineering has been characterized as the art of molding materials we do not really understand into shapes we cannot really analyze, so as to withstand forces we cannot really assess in such a way that the public does not really suspect." Today computer assisted design allows us to visualize building structures that could not be imagined before, and allows us to analyze the structural behavior of the most complex structures imaginable. We can evaluate wind forces and snow loads and investigate the dynamic impact of earthquakes on buildings.

Furthermore, since advanced construction technology can carry out whatever we design, everything seems to be possible. The availability of tools of almost unlimited power makes it difficult to decide what should be designed and built, and what should not. So there is no easy measure of what is a "good" design and what is not, or even what is a "good" structure and what is not. This applies especially in a world where sensationalism is often a value in itself and therefore seems to justify the excessive cost that often goes with structurally unreasonable designs.

Also, structural engineers no longer seem to be able to intuitively understand the behavior of complex structural systems, because they don't have to. They feed into the computer what they have and see whether it works. And they are often challenged by the architect of an extreme design concept: "So, you can't do it?!" This leads to the question posed recently by a prominent structural engineering organization…What should govern: statics or aesthetics?

This is clearly the wrong question because for a building to stand up the structure has to function. For the building to be economical, the structure has to be buildable. Beyond that, the building form should persuasively and elegantly express its purpose and meaning, and express its integral relationship with the natural environment. The design of each and every building needs to be a process of creating such a result. And there are many more aspects to be considered and integrated into this process. Like all art, each undertaking is an attempt at a perfect result. In architecture, the artwork is undertaken by a team, much like the members of a chamber music group or a jazz band. To make good music, they all need to listen to each other. If they are out of tune, none of their separate efforts are of much use because the dissonance will hurt the ears and make noise rather than art.

Structural form and architectural form need to be in tune for a building to be considered "good." To be "good" requires that the building serves its function, is a solid structure, is an impressive piece of art, and obeys the demands of a sustainable natural environment – a requirement of which we have newly become aware. To explore these relationships in some depth, it is important to investigate the role of structural form in architecture in the past and the future. Let's start at the very beginning.

Pre-historic Stick Domes

Building is one of the oldest occupations of the human race. The earliest evidence of a dwelling structure dates back approximately 400,000 years. In 1966, traces of some twenty dwellings were found in a beach cove near Nice in southern France. The construction of these dwellings – in a camp now called *Terra Amata* – was similar to that of stickdomes still found in use by colonizing westerners in parts of Africa, Asia, and America. Tree branches or saplings were stuck into the ground, close together, to form an oval floor plan. Then a ridge beam along the center, carried by sturdy posts, was erected. The saplings were bent inward to touch the ridge beam, and were laced to each other to form arches across

Figure 1: Stickdome Frame in Nigeria, about 1910.

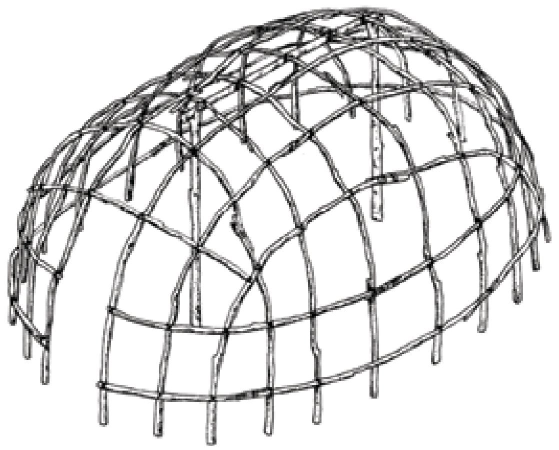


Figure 2: Othogonal Stickdome: Wigwam.

the width of the house. Most likely, horizontal ring members were added to tie the arches to each other. These gave the structure integrity and strength and helped complete the support frame for the thatch, which formed the enclosure surface. Boulders were placed around the periphery to firm up the ground around the anchorage.

The study of surviving ancient communities shows that variations of this type of stick-framed dome structure were used in many parts of the world and followed traditions developed over many generations. In one tradition, the arches followed a radial arrangement that met at a central peak, like the spokes of a wheel (*Figure 1, page 37*). In another tradition, they intersected each other at right angles to form an orthogonal grid (*Figure 2*). Thatching for the enclosure was made from readily available natural materials, such as tree leaves, grass, straw, or reed. This gave the enclosure its capacity to protect the space against sun, rain, snow, and wind. It kept the inside cool in the summer, warm in the winter, avoided condensation, and allowed ventilation through its porous skin.

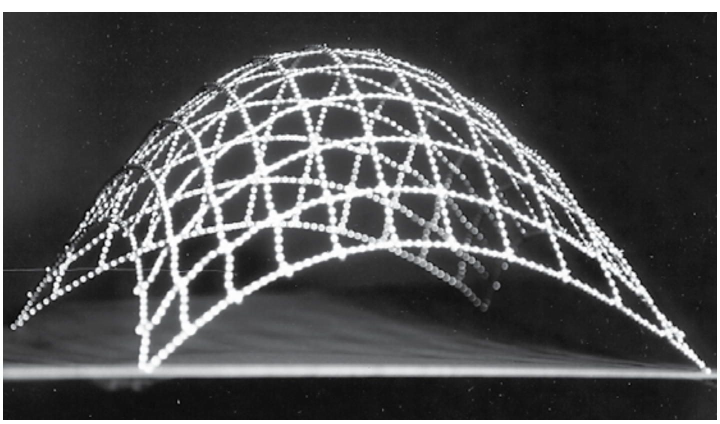


Figure 3: Reversed hanging cable grid.

The form of these stick-framed dome houses derived from the process of construction and the handling of naturally available materials. Yet its geometry of intersecting arches and hoops resulted in an ingenious structural system of great efficiency, because it carried the forces from its own weight and from wind and weather down to the ground in the most direct way. If we measure structural efficiency by the ratio of the weight of the structure to the external load (enclosure, wind or snow) that it can carry, the stick-framed domes of the ancient communities were among the most efficient structures ever built. When covered with thatch, these domes could not possibly have weighed more than one pound for each square foot of surface area (5 kg/sq. m). Yet they were capable of carrying loads many times their own weight. In fact, it is unlikely that they ever failed due to the impact of the forces to which they were subjected. Their life span was limited by other factors, such as the durability of the materials and the changes which the traditions and of the community demanded.

As we know, structures with deep, properly shaped curvatures, such as arches or suspended cables, are vastly more efficient in transmitting loads than shallow flexural members such as beams and even trusses. The most efficient shape is a funicular shape that is in balance with the loads it carries. It is the shape which a structure takes on when it has no stiffness at all, acting as if every point of it was hinged like a chain. The problem with such a flexible structure is that its shape changes when the loads change. Linking a number of chains into a two-way net creates a more stable structural network. They can carry changing loads without drastic changes of shape, because there are many different paths that the internal forces can take in the process of bringing the external loads to the support points. Replacing the chains with solid sticks and turning the entire system upside down produces one of the basic grid dome configurations (*Figure 3*), which has a remarkable resemblance to the principal geometric shape of the early stick-framed domes of pre-historic house construction.

The ancient dwellers followed no such theories. They found their dome forms intuitively, using their hands. Depending on the way they connected the two halves to each other at the center, a continuous arch (*Figure 4a*) or pointed arch (*Figure 4b*) was created, representing structural forms we identify with the Romanesque or Gothic styles of medieval cathedrals. The two basic forms of the pre-historic stick-framed domes – radial structures with the arches all coming to one central hub, following a polar coordinate system, and orthogonal structures with two sets of parallel arches intersecting each other at right angles, following a Cartesian geometry – are still the two primary geometric configurations for long span domes in modern engineering.

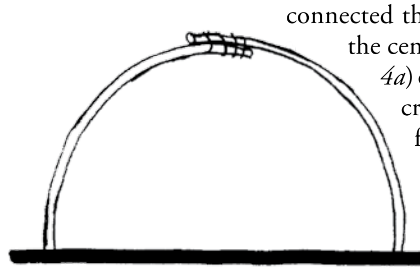


Figure 4a: Arch form origins.

The success of these ground-supported domes was based not only on their structural efficiency and the simplicity of their construction process, but also on the shape of the envelope. The envelope, integrating wall and roof into one continuous surface shape, resulted in a "minimal surface" as today's structural engineers would call it. The envelope enclosed a maximum of usable space with a minimum of surface area, reducing the amount of material needed and the time to assemble and maintain it. It also conserved the energy needed, such as firewood to keep it comfortable in the winter nights.

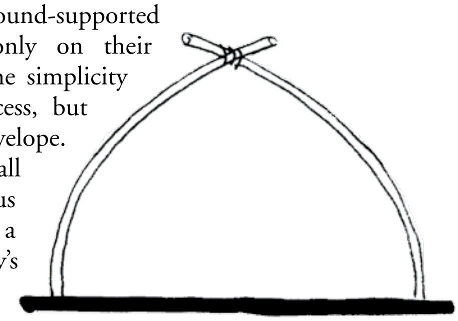


Figure 4b: Arch form origins.

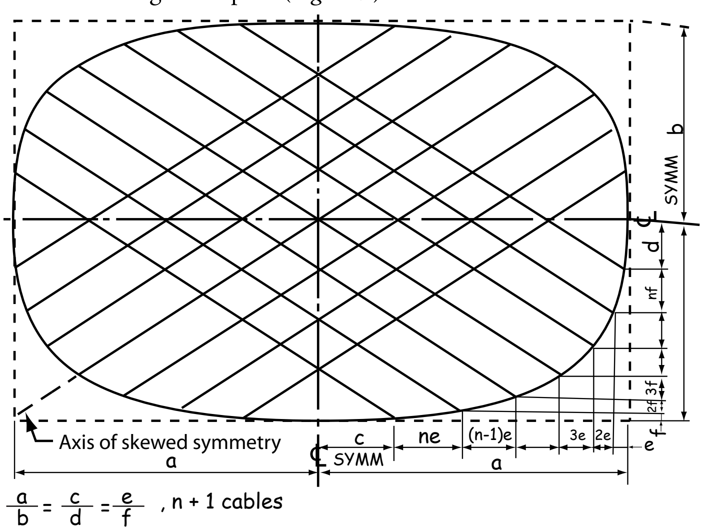
Air-Supported Domes

It is fascinating that these very oldest structural forms are directly related to some of the very newest grid domes and grid shells, including – surprisingly – air supported structures. This air-supported structural system, which in the 1970s replaced rigid dome structures for full size stadium covers, is based on a geometry of intersecting structural lines. Giving the surface a low profile curvature and reinforcing the fabric with a grid of high strength steel cables to create a cable net, large

continued on page 40

Figure 5: Unidome air-supported roof.

and super-large spans could be achieved at a fraction of the cost and construction time required for conventional structural systems. The internal air pressure, bowing the structure upward, gives the cable net the form of an arch grid. The geometric configuration developed by the late David Geiger, then the author's partner in the consulting firm of Geiger Berger Associates, has an uncanny kinship with the ancient orthogonal stick-framed dome shapes with their sets of parallel arches and their oval ground plan (*Figure 5*).



Mathematically the shape of a super-ellipse is expressed by the equation $(x/a)^m + (y/b)^m = 1$. For an ellipse m = 2, for a rectangle m = ∞ With a=b=r it is a circle or a square, respectively. For a typical dome, m ~ 2.3.

Figure 6: Graphic construction of super-ellipse with mathematical construction shown below.

But here the resemblance ends. The oval shape of Geiger/Berger's air-supported domes had a precise mathematical definition. Its outline was a super-ellipse, belonging to a family of curves ranging between ellipse and rectangle (*Figure 6*). The elevations of the intersection points of the cable grid were computed by a form-finding process to generate internal equilibrium at all intersection points of the cable net and, at the same time, to load the peripheral compression ring so that it was funicular under air pressure and dead load. This meant that the ring would carry loads in the most direct, efficient way. The shapes of the ring and the cable net, as well as the patterns of the fabric pieces, were determined by computer, as was the prediction of the structure's non-linear behavior under wind, snow, and other external loads. These were among the earliest computer assisted design processes of non-linear systems in structural engineering.

What was intuitively conceived and hand made in the ancient stick-domes is now scientifically shaped and precisely constructed. The weight of the translucent air-supported dome – though capable of spanning 20 times as far, is almost exactly the same as these ancient stick-domes, one pound per square foot (5 kg/sq. m). Some of the eight major stadiums with air-supported roofs designed by Geiger/Berger are still in use worldwide. Though their dependence on mechanical devices has had its problems and has led to a number of deflations, the success of these air-supported domes has led to a greater acceptance of lightweight membrane structures, has opened the way to new, less controversial structural systems of similar efficiency, and has made the use of daylight a highly desirable and widely used feature of architecture.

Figure 7: Griddome in Mannheim, Germany.

Grid Domes

The German architect and pioneer of tensile architecture, Frei Otto, used an orthogonal grid dome geometry for his design of a grid-shell structure at the Garden Exhibition in Mannheim, Germany, in 1968. This ingenious design, in which Otto was assisted by the British engineer Ted Happold, used sets of thin, continuous wood struts covered by a translucent fabric. It demonstrated that spaces of great geometric variety can be created starting with simple square grids (*Figure 7*). The wood grid was assembled on the ground and was made of continuous wood members (similar to 2x4 studs) of overall lengths determined by a form-finding program, forming repetitive squares, except for the periphery. The foundations consisted of undulating grade beams. The result was a space of wonderfully fluid irregularity that was made of simple materials, put together and erected in a simple way. Covered with translucent and heat reflect-ing fabric, the structure was highly sustainable from an environmental point of view.

Figure 8: Main Railroad Station, Berlin, Germany.

A variety of very beautiful grid shell structures have been built in the last few years in Japan, England, and Germany. The German engineer Jörg Schlaich has developed an especially intelligent

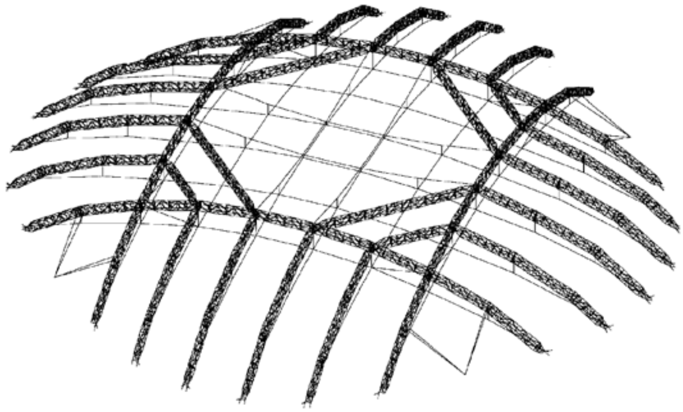


Figure 9: Unidome Roof System.

system by adding continuous diagonal prestressing tendons as diagonal members to a square grid made of simple steel bars (all interior bars of constant length with adjusted lengths for edge bars). This makes the grid a true shell in the form of a Schwedler Dome (*Figure 8*).

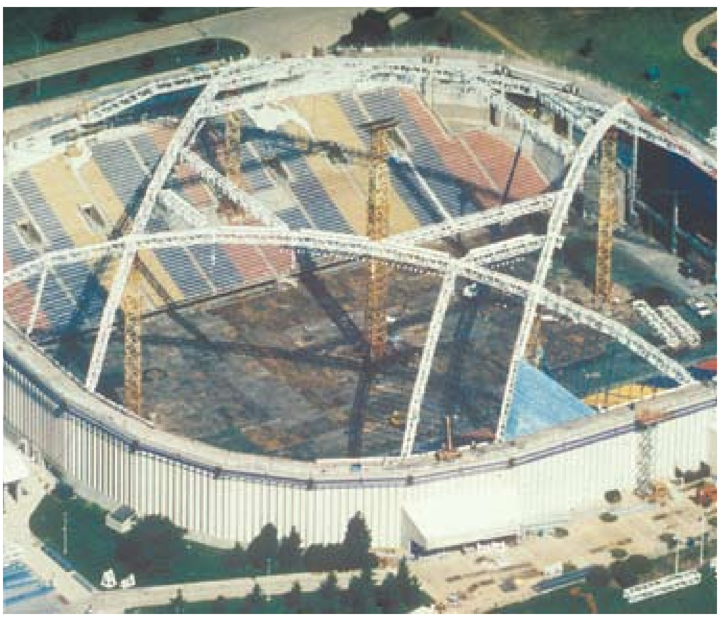


Figure 10: Unidome Construction Photo. Courtesy of DeNardis Associates.

For replacing the air-supported stadium roof at the University of Northern Iowa after a deflation in December 1994, a large span hybrid grid dome structure was developed by the author. Light segmental steel arches follow the plan geometry of the former cable grid, rising a distance above the present roof line, and connect to the re-installed cable net below. The arch grid and the cable net are restrained by the ring beam, and are stressed against each other. In the center, translucent fabric is draped over small arches and pulled down by segmental valley cables, providing ample daylight. Around the periphery, solid highly insulated roof panels span between the main arches. This creates optimal conditions for energy efficiency. The construction cost is indeed more than that of an air roof, but the life cycle cost, which takes energy and operational expenses into consideration, is lower. In addition, the fear of a deflation is gone (*Figures 9* and *10*).

The author will further explore "Structural Form in Architecture" in future issues of STRUCTURE® magazine.

Conclusion

Grid structures using continuous wood, aluminum, or maybe even composite tubular members of selected stiffness and strength for the grid members, covered with a multi-layer fabric cover, will offer solutions of amazing sculptural variety with great architectural spaces in buildings with optimal ecological conditions (*Figure 11 shows a sample conceptual image*).▪ .

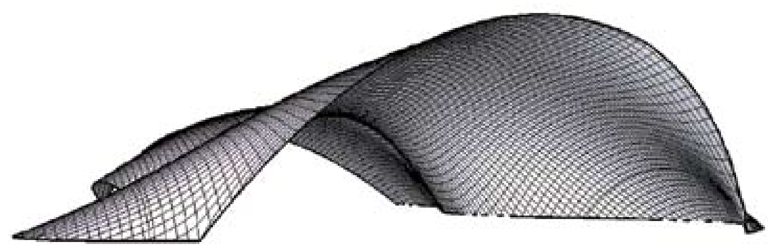


Figure 11: Griddome Image: Structural Form becomes Architectural Form.

Horst Berger is a structural engineer known for his innovative work in fabric tensile structures. His fifty year design career included partnerships in Geiger Berger Associates and Horst Berger Partners, both in New York City. For the last 17 years Horst Berger taught at CCNY's School of Architecture. CUNY appointed him a distinguished professor. His website is ***www.horstberger.com****. (See the Great Acheivements article in this issue; page 72.)*