Structural Form in Architecture

Part 3 - From Tents to Tensile Architecture

By Horst Berger

The history of structural engineering can be said to be the history of the human pursuit of ever lighter structures. That's a good step into the direction of a more sustainable built environment. Tensile structures are the lightest of them all. A good example is the Haj Terminal at the Jeddah International Airport (*Figure 1*), the world's largest roof structure. The author refers to it as a forest in the desert, because it provides relief from the heat without mechanical energy.

Two previous articles looked at the nature and evolution of structural forms, such as arches, domes, shells, grid shells and air supported fabric structures. All of these are structural systems shaped to carry loads predominantly in direct force flow (normal forces rather than bending moments). All of them are edge supported. Except for one, all carry loads under compression. The exception is an air-supported structure which – by introducing internal air pressure – reverses the force system. Here, all the members are in tension. This makes a huge difference: tensile components are very light, easy to shape and easy to transport. The reason is the basic difference in the nature of tension members and compression members. Let's have a look.

Part 1 of this series of articles ran in the November 2007 issue of STRUCTURE® magazine; Part 2 in January, 2008. Visit **www.STRUCTUREmag.org** for online copies.

Figure 1: Giant fabric tensile roof at the Jeddah Airport.

Tension and Compression

Figure 2a shows a vertical member in direct tension. Under this load, the member spanning between the two end points lengthens elastically. It stays straight under the tensile force or becomes straight if it was slack. Its load capacity is determined by $P = A f'$, where f' is the tension strength of the material. The compression member of *Figure 2b*, in contrast, has two ways of getting shorter: elastically along its axis and by bending sideways. This latter action can lead to buckling. The capacity of thin members to support loads is determined by their buckling capacity which, in its simplest form, is determined by the Euler formula:

$$P = \pi^2 E\, I / L^2$$

This is one of the most beautifully transparent laws in structural engineering. The force increases with the stiffness of the material and the rigidity of the cross section, and it decreases with the square of the length of the member. Strength plays no direct role. The shape and thickness (expressed in I, the moment of inertia) are important. (A tubular shape is more efficient than a solid one). The buckling length is dominant, since it appears as the square in the denominator.

Therefore, a compression member must have rigidity. It must be given a shape from which it can deviate only slightly under load by way of elastic deformation. By contrast, the load capacity of a tension member depends on its strength only. Length plays no role. The higher the strength of the material, the smaller its cross section and the lighter the structure. Therefore, a tension member is flexible. It can be folded or rolled for transportation. It also can adjust its shape to changing loads. So live loads are absorbed by change of shape as much as by change in stress, making tensile structures highly non-linear.

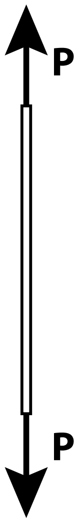

Figure 2a.

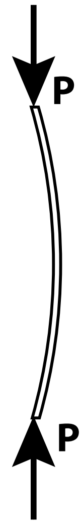

Figure 2b.

The Evolution of Tensile Structures

In the development of human structures, tensile solutions came relatively late mainly because they did not make spaces work easily without internal supports, their end supports had to be restrained against the inherent tensile forces, and their tensile materials had to be manufactured. Bamboo ropes were probably amongst the oldest tensile members. Single ropes were used in locations, such as the Himalayas, to ride across deep canyons. The Chinese built marvelous bamboo rope bridges. They lasted for centuries because portions of the multiple bamboo ropes were replaced every year. The Chinese also had the first wrought iron chain bridges, having invented wrought iron as early as the second century AD. *Figure 3* shows one of them.

These bridges, because of their flexibility, were often damaged in strong wind gusts. Modern suspension bridges avoid this by stiffening the roadway. A better way to stiffen a suspension bridge would be to provide a hold down cable which, being curved in the opposite direction, would hold the bridge down, as shown in *Figure 4*. This configuration is often used in long span pipe bridges. The addition of such a hold down cable would have prevented the famous collapse of the Tacoma Bridge.

In a three-dimensional cable net, the same effect can be achieved by running a set of hold down cables at right angles to the set of main cables. This leads to a saddle shape. It was first used by engineer Fred Severud for the roof of the Raleigh Arena in 1953. *Figure 5* is a schematic view of this cable net. Such a cable net requires the introduction of internal pre-stress forces in all cables, to prevent the surface from going slack under various live load conditions. In this structure, the resulting horizontal forces are resisted by the edge arches.

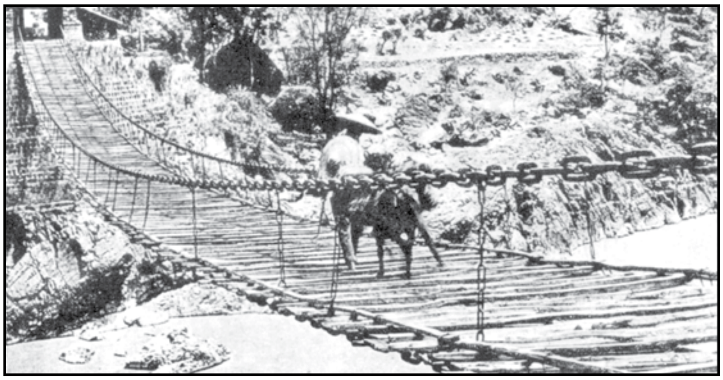

Figure 3: Chinese Chain Bridge.

Any interior node point is typical for the principal configuration of a cable net or a membrane. In the 1950s, Severud had no way of computing the correct surface shape. He had to use approximations and tune the system by adjusting the forces in the cable ends during the erection and prestress process.

It was left to the pioneers of fabric structures to develop answers because, for membranes, approximations were not good enough. The problem for cable nets and fabric membranes was to find ways to develop the exact surface geometry so that all components would be under the design stress when erected and stressed. Answers could only be found with the help of the power of the emerging computer. The first solutions were invented in the early 1970s. They became known as formfinding programs. Geiger/Berger, the firm where the author was then a partner, were among these pioneers. They developed computer programs with the help of leaders in non-linear analysis, especially William Spillers. They were the first to apply these programs to the design and construction of very large permanent tensile structures, including the Jeddah Haj Terminal which, more than 25 years later, is still the world's largest roof cover. (*Figure 1*)

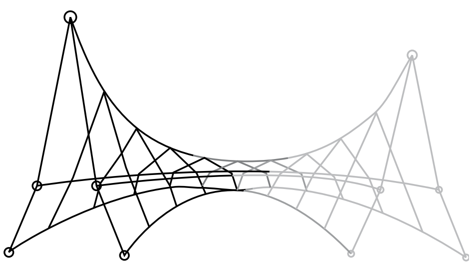

Figure 4: Stabilized Suspension.

Using the Internal Equilibrium of Surface Structures

It is essential for engineers to understand the origins of the design tools they are using and visualize the behavior of their structures. To illustrate the process of formfinding, the author uses his own iterative approach, because it is most transparent. And for simplicity, the illustration describes an isometric solution for a pole supported tensile structure.

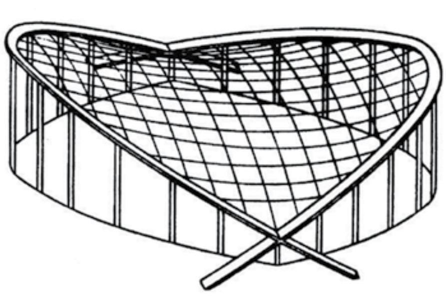

Figure 5: Cable Net of Raleigh Arena.

In this isometric solution, the plan is given by its outline with a mesh representing a cable net or fabric strips. Also, the elevations of support points are given. The formfinding program will develop the final surface configuration (*Figure 6a*). Initially, the elevation of all other node points ($z_{i,k}$) is unknown. A typical node point ($z_{i,k}$) is shown in *Figure 6b*. The two intersecting lines in *Figure 6b* represent two cables (or center lines representing fabric strips) intersecting at node i,k. Assume the four edge nodes are fixed. The horizontal components of the cable forces, Hx and Hy, are the prestress forces given by the designer. The vertical components can then be determined by the equation:

$V = H (z_{i,k} - ze) / (x_{i,k} - xe)$, with the index e indicating edge nodes. By looking at the diagram of *Figure 6b*, it is obvious that these vertical components of the tensile forces increase when the node i,k moves up, or decrease when node i,k moves down (see dashed lines). If the structure has no weight, the sum of the four V forces has to be 0. If a force P is to be considered (for instance a uniform surface load p, such as the dead load, has to be multiplied by the plan area: $P = p\Delta x \, \Delta y$), the sum of the V forces has to equal P.

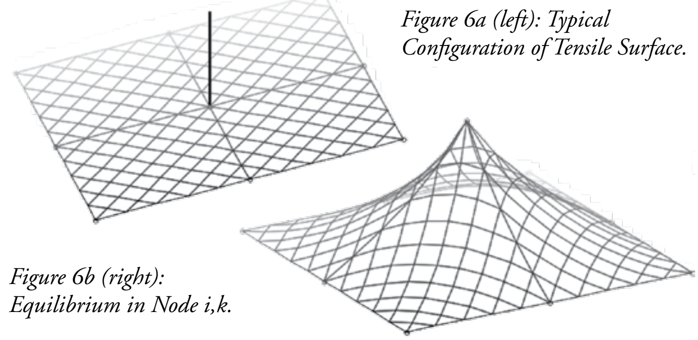

Figure 6a (left): Typical Configuration of Tensile Surface.

Figure 6b (right): Equilibrium in Node i,k.

From these equations, the value of $z_{i,k}$ can then be computed, following the equation: $P = \sum V$

The general answer is a complex equation. However, for the most common case, where the values of the horizontal forces Hx = Hy, and the node spacings $\Delta x = \Delta y$, the amazingly simple answer is:

$z_{i,k} = \frac{1}{4} (z_{i-1} + z_{i+1} + z_{k-1} + z_{k+1} + \Delta x \, P/H)$. In other words, the new node elevation is the average of the four adjacent node elevations, plus a contribution from the curvature factor, $\Delta x \, P/H$. With this new node elevation established, the iterative process moves on to the next point. The system converges rapidly. By selecting the proper loads p, a tensile structure's shape can be accommodated for the dead load of the membrane and an air supported structure can be shaped for the internal pressure. By reversing the force directions, a shell or grid shell can be shaped for its own weight. Now the dead load acts as a downward load and all component forces become compression forces.

By replacing the orthogonal coordinate system with a coordinate system normal to each node (orthogonal to a plane parallel to the four respective edge nodes), the shape can be generalized, creating a geodesic surface with uniform tensile forces throughout. As an example, *Figure 7* shows the formfinding net for the Denver structure. It was generated (after the design of the structure) by Ed DePaolo of Severud Associates, who adapted my method to work within an AutoCad program.

Today, there are many formfinding programs available. They usually are part of a package of programs which include non-linear analysis and patterning. For the purpose of developing a first design shape for a structure, you can find a free and fast program at **www.horstberger.com**.

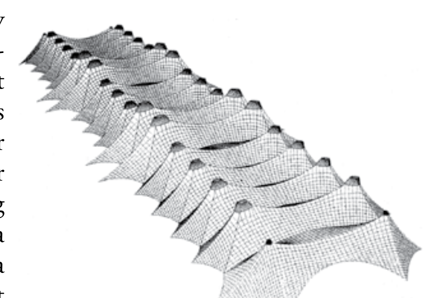

Figure 7: Geodesic Shape of the Denver Structure.

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Using the example of the Denver structure, we return to our consideration of the basic ways of establishing stability in cable net or membrane surface systems. *Figure 8* shows the outer fabric membrane, which forms the roof skin and the primary support structure. Here, the ridge cables carry the down loads (snow) and the valley cables carry the up loads (wind uplift). The two are connected by the stressed fabric skin, and – for redundancy and safety – by the surface cables, similar to the structure of *Figure 4 (page 39)*. This configuration demonstrates features of a form that is very common for tensile architecture. In this non-linear system, much of the load is carried by change of shape rather than change of stress. For instance, under snow loads, non-linear analyses show that the fabric hangs almost free between ridge cables, thereby taking on an optimal shape for carrying these loads in pure tension. In Denver, this system has worked very well. The roof has been through twelve winters and has survived a record storm without harm.

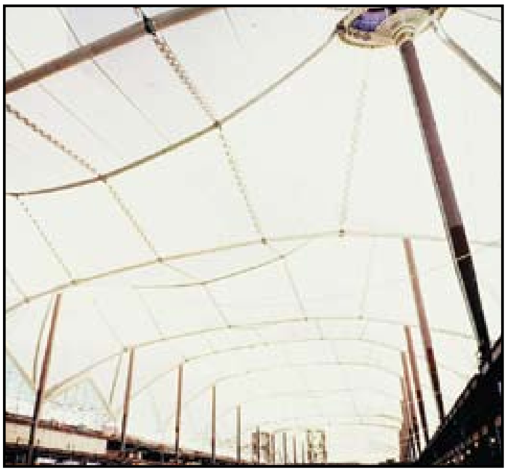

Figure 8: Denver Structural Membrane.

The Denver roof, consisting of two skins, has other properties which make it particularly desirable in a world that is now becoming conscious of the environment and sustainability. There is no doubt that the extreme light weight and flexibility of tensile materials cuts construction time and energy. Getting the space under the roof quickly also contributes to construction savings. Additionally, energy and maintenance during the lifetime of the building are also greatly reduced. The translucency of the fabric, combined with the clear-story windows (*Figure 9*), creates a level of natural light in the daytime that makes it practically unnecessary to have lights turned on in the great hall, thereby cutting electric usage. The same translucency radiates heat out in the night, so that in the morning, the space is cooler than the outdoors. In the daytime, the almost 75% reflectivity of the fabric cuts warming by the sun. Since much of the year a space such as this has excess heat, air-conditioning costs are reduced. The heavy concrete slab of the main hall and other building elements within this very large space, all tend to store heat, thereby averaging its temperature over time. The one negative factor of fabric roofs is the low insulation value of the double skin fabric that results in the need for heating during winter nights. A remedy here would be the use of radiant heat embedded in the slab, which would avoid unnecessary heating of the huge airspace, and multilayer liners made of inexpensive fabric materials that could increase the insulation value.

Figure 9: Finished Space at Denver.

Figure 10: Silicone Coated Fiberglass Roof at the Poughkeepsie Mall.

New Fabric Materials

Since the completion of the Denver structure, no fabric structure of the same architectural importance has been built in the US. However, there are signs that this is changing. Numerous stadium structures using fabric roofs are being built for the 2008 Olympics in China. More importantly, many fabricators of small fabric structures are spreading the use of fabric structures throughout this country. They are upgrading the quality of their products by professionalizing their design, fabrication and construction methods. The Denver Airport Terminal itself has changed people's views, i.e. many people have been in it and are impressed by the architectural quality of this great space. So, maybe even the critics will come around to accept it as architecture.

So far, the architectural community prefers glass. Part of the reason is that glass is considered "permanent" and fabric "temporary". These are not very useful terms by themselves. First cost, life span, maintenance, replacement cost, energy, and recyclability etc. are all aspects which are part of this discussion. Glass is much more expensive than fabric. It requires more structure to support it and is difficult to shape and to install. Because it tends to get dirty, it needs much more maintenance, and produces high levels of green house heating even when coated with a shading film. By contrast, fabric is part of the structure and is largely self-cleaning. The Teflon coated fiberglass of the Jeddah Haj Terminal is now over 25 years old and does not seem to need replacement yet. When it does need replacement, it should be replaced with a Silicone coated fiberglass fabric. This is an environmentally better material than Teflon coated fiberglass. Both components, the woven fiberglass base material and the silicone coating, are made from silica, an abundant mineral. Twenty-five years ago, the author worked with Dow Corning to bring this material into the world of permanent structures. Because the refractory index of both materials is similar,

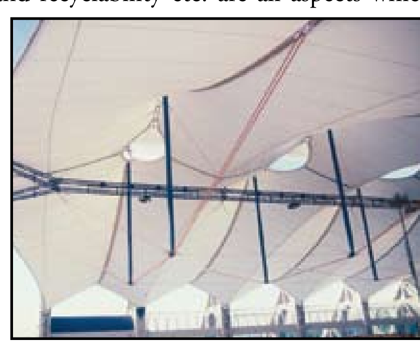

Figure 11: Flying Struts at San Diego Convention Center.

high translucencies can be achieved – up to 50% for regular structural materials, and up to 90% for lightweight liners. Even a transparent version is now in development. Their life spans are most likely over 50 years. The problem with the early material was dirt adhesion. However, this had no noticeable influence on the structure's translucency. *Figure 10* shows a structure which is now over 20 years old. It is in excellent shape, even if the roof appears dirty on the outside. There are now a number of silicone fabrics on the market which appear to have overcome this problem. They will take tensile fabric structures a good step forward. So will the very low cost new polyethylene fabrics with life spans of 15 to 20 years.

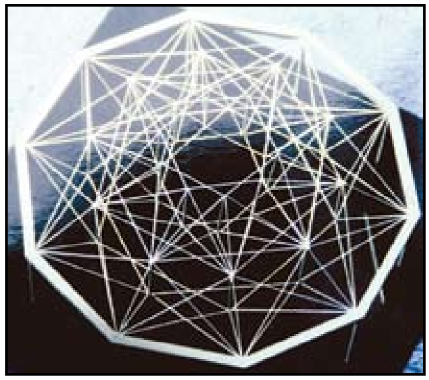

Figure 12: HB Cable Dome System.

Figure 13: Hybrid Arched Cable Dome.

Tensegrity Structures

There are two groups of structures which are particularly interesting for the future. The first group are arch supported tensile structures. There are two reasons. First, arches are end supported, creating architectural spaces which are high in the middle and low at the edges. They can be shaped in many ways, so even asymmetrical designs are possible. Second, the fabric spanning between arches has a downward curvature that dissipates sound thereby preventing the problem of disturbing sound reflections. It also makes great channels for rain runoff and is excellently shaped for snow loads.

The second group are tensegrity structures. The name comes from Buckminster Fuller, the structural visionary and pioneer of geodesic domes who used it to designate structures with discontinuous compression members and continuous tension components. There have been many sculptures but few structures which used this approach. The flying struts riding on suspension cables, which form a part of the support system of the San Diego convention center, are a primary example (*Figure 11*). For the original design of the roof for the Sun-Dome in St. Petersburg, Florida, the author developed the cable dome based upon this principle. To the authors knowledge, it was the first large span cable dome design for a real project. The configuration is shown in the study model of *Figure 12*. Each support cable carries two struts, and each strut is carried by two intersecting support cables. It was much more constructible than the system used by David Geiger, which was actually carried out, or any other cable dome system used to date. The first set of support cables, spanning parallel to the edge ring, are hung and connected to form a circular chain. The first ring of posts are placed and tied back. The next ring of posts are then added until the dome is completed. There is no interference with the structure below, and no difficult triangulations.

The author's favorite version of this system is one he developed later (*Figure 13*). It is a particularly powerful solution for very large spaces. It combines the tensegrity system with radial arches, avoiding the weaknesses of the tensegrity system (large deformations under gravity loads), and getting the best part of both worlds. Compression and tension are optimized. The arches are braced by cables that reduce their buckling length. No temporary support systems are needed for its erection since the arches are light and come in transportable sections. So for this light weight, constructible cable dome, the primary load bearing system returns to the structure which has proven to be most efficient since the beginning of the long evolution of building structures: the dome.

In Conclusion

This series of articles has attempted to show that there is an abundance of structural forms which are efficient and visually exciting. Their origins go back to early pre-history. Structural science and computer power open almost unlimited new possibilities. A rich built environment is possible without sacrificing efficiency and thereby endangering the environment. To achieve this, structural engineers must explore and offer creative solutions to design challenges and architects must be open to incorporate structural creativity into their design vision. In the process, they must listen to each other and adjust their approach so that the quality of their building gains. With the right effort, a sustainable world can be beautiful and affordable.▪

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****.*