STRUCTURAL FORM IN ARCHITECTURE

Domes, Arches and Shells

By Horst Berger

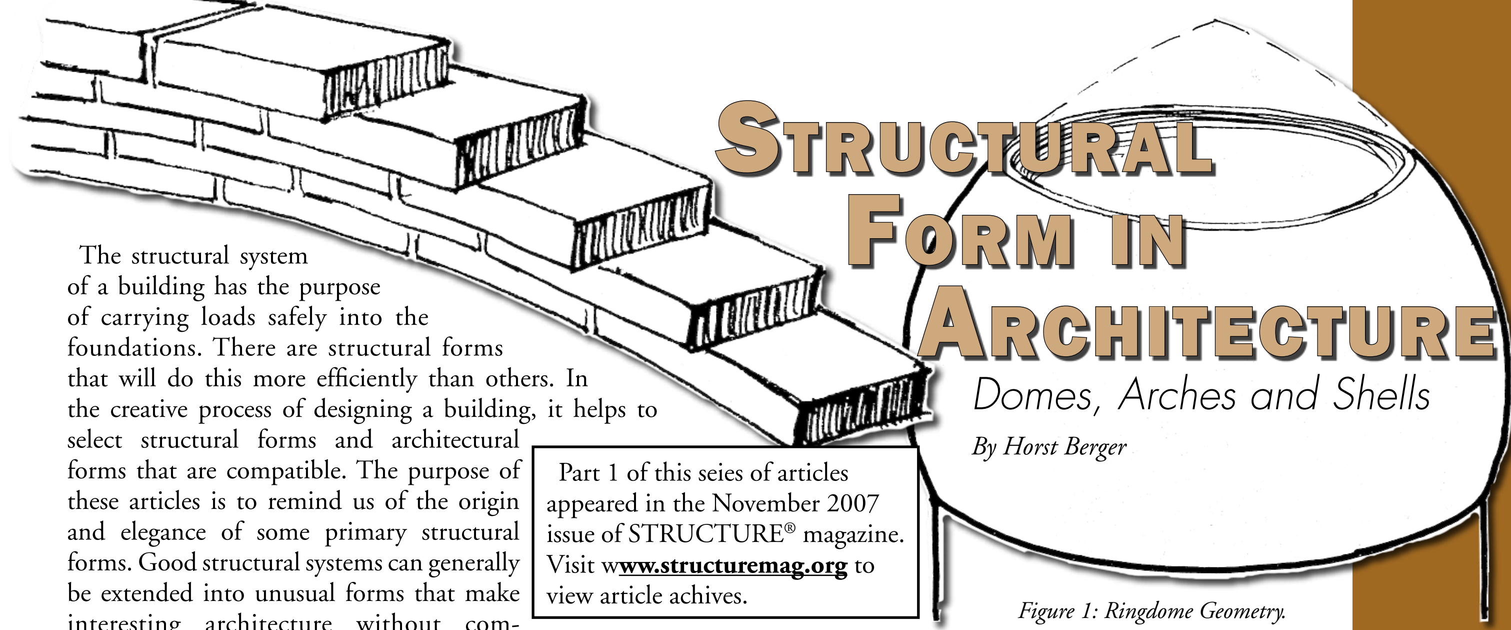

Figure 1: Ringdome Geometry.

The structural system of a building has the purpose of carrying loads safely into the foundations. There are structural forms that will do this more efficiently than others. In the creative process of designing a building, it helps to select structural forms and architectural forms that are compatible. The purpose of these articles is to remind us of the origin and elegance of some primary structural forms. Good structural systems can generally be extended into unusual forms that make interesting architecture without compromising function, reliability and economy.

Part 1 of this seies of articles appeared in the November 2007 issue of STRUCTURE® magazine. Visit w**www.structuremag.org** to view article achives.

The first article started with the oldest of all structural systems, prehistoric stick-domes, and it pointed out their relationship to the most recent grid-shell structures. Here we will begin with another dome form: adobe ringdomes.

Ringdomes

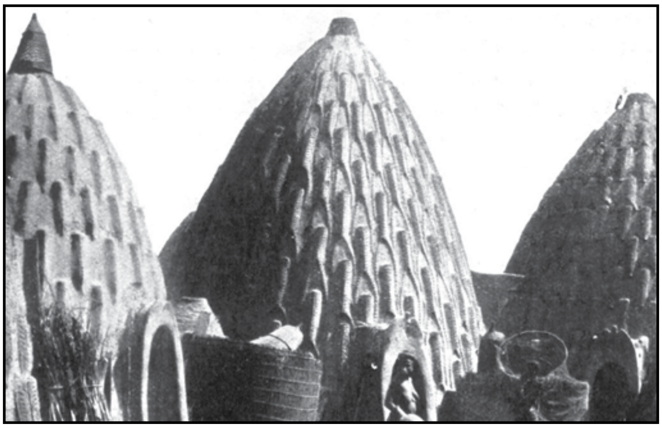

Figure 2: Adobe Ringdome Houses in Cameroon.

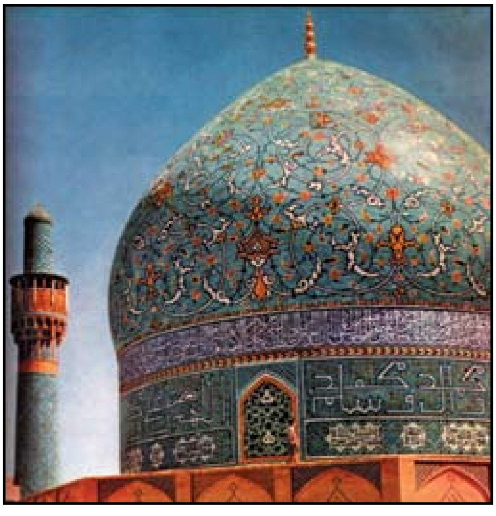

Figure 3: Tile covered brick ring dome of Royal Mosque in Isfahan, Iran.

The invention of adobe as a building material most likely derived quite naturally. In order to add a firm skin to a dome structure made of sticks or reeds, sometimes the surface was covered with clay; and, the clay was reinforced with pieces of straw so that it would restrain cracks and hold the skin together. Many structures of this type were built in Africa. The sun would dry and harden the "adobe" skin, as we now call it. Since all of the materials are natural and simply return to the earth, we have no evidence to tell us when these first occurred. It is likely that they greatly pre-date what we consider "history", which for all practical purposes started no more than about 10,000 years ago with the beginning of agriculture and the first cities.

Some early genius invented the sunburned brick. The right mix of clay and water, with cut straw segments added, was prepared in a pit, then cast in forms and hardened in the sun. Someone else had the idea of building walls by staggering consecutive layers by half a brick to create a bond. And again someone else – capable of imagining things in three dimensions – built the first adobe dome by forming a ring of adobe bricks and adding successive rings of slightly smaller diameters on top of each other (*Figure 1*). The result is the pointed dome, which we all know from Middle Eastern mosques.

The huts of *Figure 2* are beautiful examples of adobe brick domes. They demonstrate a natural integration of form, function and structure. Similar to the stick-dome – undoubtedly the guiding formal image in the mind of the inventors of adobe dome structures – the overall sculptural form approaches a *minimal surface*, creating the most usable space with the least amount of surface material. By creating step-like elements that protrude from the rings in an alternating arrangement, access is provided for builders during the dome's construction and for maintenance during its lifespan. With this resulting pattern as a start and a purpose of making the steps more useful, the design of the structure was developed into a delicate piece of sculptural art, engaging the play of light and shadow.

Later in history, adobe bricks were replaced by kiln-burned bricks, and the surfaces were finished with brilliantly colored tiles to form the gorgeous mosques of the Middle East. *Figure 3* shows one of the best, the Royal Mosque in Isfahan, Iran.

A ring-dome made of stone is shown in *Figure 4 (page 34)*. I found it in Jerusalem. It was probably built in the days of the Roman occupation. Note that no skin is needed to cover the masonry dome. With all members in compression, the surface, with carefully mortared joints, becomes waterproof.

The same technique was used to form longitudinal, vaulted structures to cover spaces like bazaars. Using partial rings oriented vertically, and adding one to the next, again arranging the bricks in staggered, bonded courses, vaults of any length could be produced without falsework after giving form to the first arch. Entire communities were built in this manner. In the late 1950s, I saw two workers in Teheran, Iran use this technique to form shallow vaults between steel beams, framing in a large floor area at a speed competitive with modern concrete construction. As discussed later in this article, masons of the medieval cathedrals also used this type of vaulting.

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Figure 4: Stone Ringdome in Jerusalem.

Arches

Surprisingly, the linear arch came much later than the dome, simply because it could not be built without false-work, and there had to be an understanding of the inherent structural force flow. An arch does not stand up until the keystone is placed, meaning the stones forming the arch first have to be supported by a form (generally made of wood), and that form has to be removed by a difficult process called de-centering. In that process, the vertical forces, caused by the weight of the stones, are converted into a curved thrust line resisted by horizontal restraints at the spring points. Simultaneously the form has to be unstressed before it can be removed. The Romans – most likely their Arab slaves – were the first to understand this, so they were the first to build arches.

The Roman arch shown in *Figure 5* is one that I found in Pumakkale, Turkey some 20 years ago. It was built approximately 2,000 years ago. The arch is circular, as were all the Roman arches. The two-span arch of *Figure 6* is a particularly gracious example, combining function, structure, and form into a superb total design that has lasted more than 1,700 years.

Figure 5: Roman Arch in Pumakkala, Turkey.

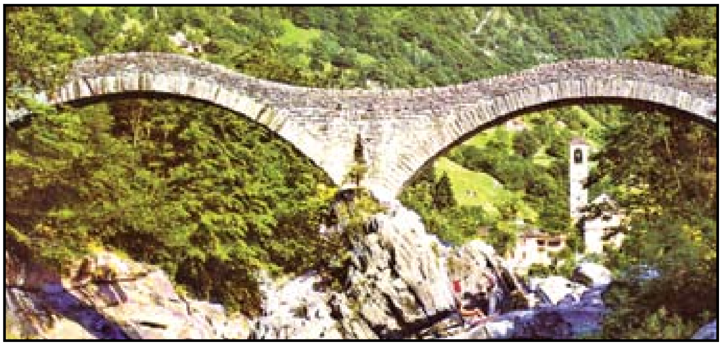

Figure 6: Roman Bridge in Spain.

Figure 7: Cologne Concrete Bridge Span.

Figure 8: Cologne Concrete Bridge Cantilever.

Various arch forms were tried in the Middle Ages and especially in the Baroque period. The idea of the *funicular* form was part of the new scientific understanding of structures, which began with Galileo in the 17th century. Suspension bridges inevitably provided the visual idea. Their totally flexible suspension chains or cables could only carry load in a funicular shape. For compression members, which always require a certain amount of stiffness to prevent buckling, the case for the funicular shape was not so obvious. It was Emil Moersch in Germany and Robert Maillart in Switzerland who made the funicular shape the basis for their concrete arch bridges, leaving behind the formalistic geometries of circles, greatly reducing their mass and creating structures of amazing elegance. *Figure 7* shows an example of an arch bridge built in 1957. It was my fortune, educated in tradition of Moersch and working in the firm he once headed, to be the project engineer for this structure.

Spanning 90 meters (295 feet), the footbridge at the Muehlheimer Hafen near Cologne, Germany, is now 50 years old. The dense, high-strength concrete that was used to build it makes it look like new even today, as the photo shows. Only the steel railings have been replaced. The funicular form is quite visible, with the sharper curvatures right under the support points of the approach beams. *Figure 8* shows the approach ramp – a curved, cantilevered, post-tensioned box girder section.

Roman Concrete Structures

Concrete was also an invention of the Romans, and like many things the Romans did, it was forgotten throughout the Middle Ages. The architecture of the Roman Empire, especially of the city of Rome, is not imaginable without the use of concrete. They built the most fascinating walls that consisted of a concrete core with tied triangular bricks that formed the finished faces. They built floors framed by

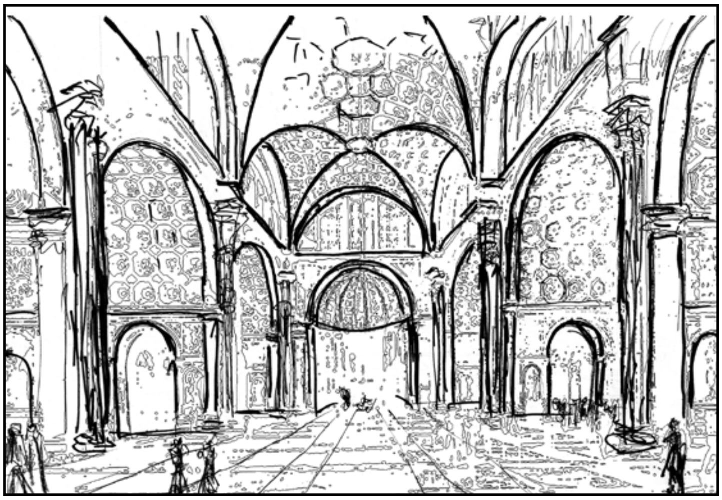

Figure 9: Basilica of Maxentius, Roman concrete shell of 312 AD.

setting thin ceramic tiles on formwork, shaped in the form of shallow shells, and backing them with a thin layer of concrete. That's how apartment buildings, up to six stories in height, were built in Rome.

Warehouses were covered with semi-circular cylindrical shells, and some large cisterns were covered with shells reminiscent of contemporary reinforced concrete shell construction. The best known Roman concrete shell, of course, is the 1,900-year-old Pantheon with its 43-meter (145-foot) circular coffered concrete dome. To me, the most fascinating Roman concrete structure is the Basilica of Maxentius due to its interesting shell configuration. Completed in 312 AD, it was the last and largest basilica in the Formum Romanum. It lasted approximately 500 years, until it was knocked down by an earthquake. It also became the architectural model for many of the medieval cathedrals; however, they would be built of stone or brick. *Figure 9* shows a sketch of its configuration, the last and largest of its kind and a symbol of the end of the West Roman Empire.

Medieval Cathedral Construction

The cathedral builders of the Middle Ages based their designs not on scientific knowledge, as the Romans had done at least in part, but on the experience of their craftsmanship. Therefore, the basic structural components were small in number, but there was an unending variety of actual structural forms used. The cathedral master, himself a mason by schooling and training, made no detailed drawings. He transmitted only the principal concepts of his design and relied on his fellow masons to fill in the actual details, thereby empowering them to rise to the level of artists themselves. It was this concert of artists – similar to a modern jazz performance – that created the lasting beauty of the medieval cathedrals.

Structurally, the vertical elements were walls, piers and columns. The horizontal elements were always arches. Horizontal flexural elements did not exist in these stone structures, since stone has a low tensile capacity. However, there is clear evidence that the master builders understood the flexural capacity of the vertical elements, and knew how to use it. In fact, in spite of their lack of explicit theoretical knowledge, they clearly had an amazing grasp of the structural behavior of their creations.

While they could not handle curves other than the circle, they liberated themselves from the straightjacket of circular geometry by introducing the pointed arch. It allowed them to vary the ratio of span to rise. By mixing orthogonal ribs with radial ribs, a rich variety of vault configurations became available. The vaults themselves, shaped by masons in a largely freehand approach, further enriched the astonishing wealth of sculptural forms used to create the ceilings of their great churches.

My personal understanding comes from the study of Ulm Minster in Germany. *Figure 10* shows a vault from above. The brick pattern suggests that – similar to the prehistoric brick vaults discussed earlier – curved arches were added, one to the next, slightly changing the curvature to create the three-dimensional shell shape, and staggering

Figure 10: Brick Vault at Ulm Minster from above.

the bricks to create the bond. *Figure 11* shows the same vault from below. Being hand-made, repetitive forms were never quite identical, giving the finished building the "natural" look that is the dream of today's architects.

Figure 11: Ceiling Vault over Nave of Ulm Minster.

Shells

Modern concrete shells seem to be the closest structural forms we have that create a similar sculptural expression. But there the similarity ends, except for some small-scale hand-made shell shapes, where intuitive shaping proved to be sufficient for structural capacity. Concrete was re-invented in the 19th century, and modern concrete shells were invented in the 1930s. *Figure 12* shows an early experimental concrete shell. A main obstacle to using concrete shells was always the difficulty of shaping the formwork. Felix Candela overcame this problem by designing so-called "hypar" shells. These are shells generated by two opposite sets of parabolas intersecting each other at right angles. Since they generate straight lines at a 45 degree angle to the main directions, formwork is easy to build. One of the most dramatic of Candela's structures is the Xochimilco Restaurant in Mexico, shown in *Figure 13*. Other hypar configurations can be and have been built in concrete, wood, and steel.

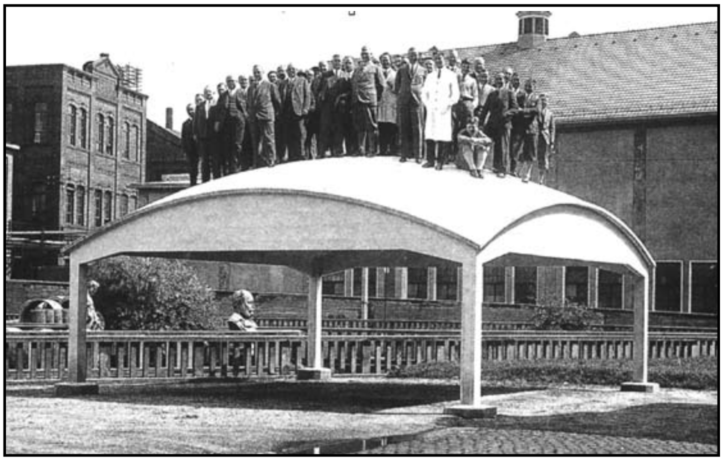

Figure 12: Early Shell at Dyckerhoff & Wittman.

Figure 13: Felix Candela's Xochimilco Restaurant.

Concrete shells were brought into the post-classical or digital era by Heinz Isler. He liberated shell design from the limitations of the classical geometry of circles and parabolas, by giving them the natural shape they want to take on to be in funicular equilibrium for their own weight and a given support condition. When I met Isler in 1978 in Madrid, I asked him: "Do you do what I do?" He said yes. By this he meant that he was using a digital formfinding method to develop his shell geometries, as I was doing for my fabric tensile structures. Initially, he found these shapes experimentally with the help of upside-down scale models. Stretched fabric spanning between wire catenaries was weighted with a uniform layer of slow-setting mortar. Once hardened, it was turned around to present the image of the shell. Later, he found that computer programs developed for the design of tensile structures could be used to generate load-balanced shell shapes.

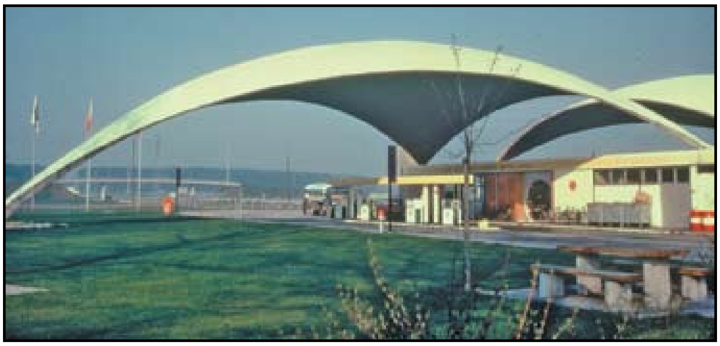

Figure 14: Heinz Isler Concrete Shell.

Figure 14 shows one of Heinz Isler's elegant shell designs. Isler overcame the forming problem by using and re-using laminated wood beams to carry plywood forms. For concrete shells, sound and insulation are generally problems. However, waterproofing is not, since concrete under compression develops no cracks, and un-cracked concrete is waterproof. Nevertheless, Isler does apply a silicon spray coating to the top surface. Edges and underground tie beams are post-tensioned to guard against buckling and to prevent foundation movement. There is little further reinforcement required for the 7-centimeter (2¾-inch) thick shells, and they have no measurable deflection. Beyond that, they are absolutely beautiful to look at.▪

Horst Berger is a structural engineer known for his innovative work in fabric tensile structures. His fifty year design carrier 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.***

A third article in the Structural Form in Architecture series will appear in a future issue of STRUCTURE®. The article will explore tensile structures, explain the basis of formfinding, and discuss issues of free-form design in the age of sustainability.