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Research

Leonardo's Successors

Abstract. Ideas similar to Leonardo's for lattice structures can found many later practical applications (Buckminster Fuller's domes, the Zome geometry of Steve Baer from the Whole Earth days, the Tensegrity structures based on the sculpture of Kenneth Snelson, as well as the Catalan vaulting traditions of Gaudi and the Guastavinos.

Introduction

Leonardo's domed wooden roofs are a product of the intense energy with which Leonardo examined the world around him and looked for ways to exploit basic principles for mechanical advantage. He was very conscious of the examples of the past, but even more excited by stimuli from natural organisms. The system he developed for the domes is at the same time a critique of past efforts to create roofed spaces without columns, and a precursor of systems it would take centuries for later inventors to rediscover. The essence of these drawings is the attempt to span relatively large open spaces with simple repeatable elements that do not require much labor to make or to assemble. What makes his system elegant and "modern" is that the idea derives from the construction sequence and the underlying geometry, and does not depend on sophisticated construction techniques or expensive materials.

Leonardo in Florence was inescapably aware of Filippo Brunelleschi's achievement in creating the dome of the Duomo. It was the wonder of the age and the emblem of the new thinking we now call the Renaissance. Brunelleschi's machinery for building the dome had as much influence on Leonardo's thinking as the achievement of the dome itself did. For an ambitious designer in Florence there would be no more such vast commissions, but the role of all-around problem solver was one the Florentines respected and one for which Leonardo was well suited, with his wide-ranging interests and uncommon ability to make connections between the working principles of organic and inorganic systems. Rivers, humans, birds, bridges, buildings, were all subjected to his analytical eye and his irresistible urge to tinker. If in many cases these analyses never went beyond the sketchbooks of the codices, the mental habits displayed there were in play everywhere he was asked to go.

The genius of Brunelleschi's dome was that it had solved the problem of keeping a large masonry dome from collapsing by a completely new method. As they are being built, domes want to fall inwards, and when they are complete they want to explode out at the base. The new system used stone and timber tension chains buried in the rings of the dome to resist the outward bursting pressure, and the successive layers of the dome were built as horizontal circular arches which resisted the tendency of the masonry to fall inward while the structure was incomplete. It was a dramatic balancing act.

The Romans had thrown mass at the problem, using formwork and fill to support concrete and brick shells. Hadrian's engineers made the dome of the Pantheon thinner as it went higher, had used square coffers to stiffen the shell, and even used hollow jars at the

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top to lighten the load. Even so, the perimeter at the base started to show signs of cracking, so the engineers added the outer rings that give the Pantheon its characteristic profile, in order to overload the base and literally overpower the outward thrust. It was a solution appropriate to the mindset of empire. It used the abundance of cheap labor produced by the imperial system to compensate for an incomplete understanding of how structures work.

The architects of the Gothic cathedrals had developed a more sophisticated idea of how to counterbalance loads with other loads, and how to use ribs to support thin shells of stone blocks. The ribs allowed the formwork to be much lighter, but the system required that the ribs be locked in place by the central bosses before the scaffolding could be removed. The machinery for hoisting the stones to the height of the work area was not much more advanced than that of the Romans, so the size of the blocks tended to be small, and the whole construction depended on balanced compression carried from boss to base. Irwin Panofsky's brilliant essay *Gothic Architecture and Scholasticism* details how the articulation of Gothic structure is analogous to the scholastic subdivision of syllogistic explication of the universe as a creation and emanation of the mind of God [Panofsky 1957: 34-35, 58-60].

The challenge of the Florentine dome was that it did not have a way to brace the exterior against the outward-pushing bursting pressure the huge vault would place on the drum, which had already been built. Further, the drum was so high and so wide that filling it with scaffolding or earth as the Romans would have, or with a timber frame supported on the drum as was Gothic practice, were both beyond the resources and the technical ability of the builders. Scaffolding would collapse under its own weight, fill would burst the walls, and timbers to span the space couldn't be set in place (fig. 1).

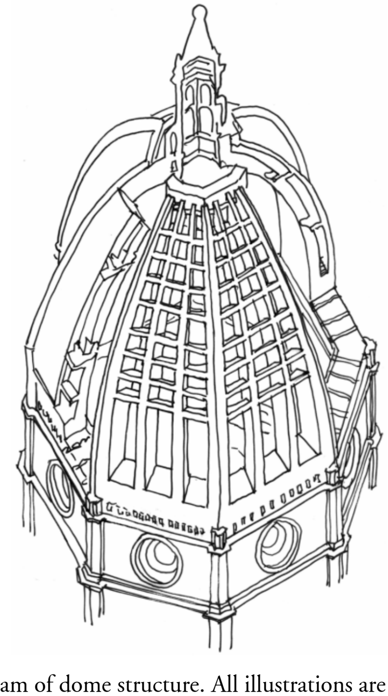


Fig. 1. Diagram of dome structure. All illustrations are by the author

Brunelleschi solved the problem with horizontal rings that could be built sequentially and support themselves. He also devised machines that could continuously raise not only the bricks and mortar but the long stones he needed to lock together to create tension "chains" around the compression rings. His design brought together a new understanding of curved structures, derived from study of the Ptolemy atlas of the spherical world, and the ability to invent mechanisms to solve problems of transmitting mechanical force which came from his experience as a metalworker. Both what to build and how to build it were his ideas and they changed the world.[1]

The problem is that all this ingenuity still took a lifetime and large amounts of material and capital. It was not suitable for daily use in marketplaces and workshops. Leonardo's idea, on the other hand, would work immediately, simply, and even demountably. Though the model he proposed wasn't as big as the Duomo (27 meters as opposed to the Duomo's 43.7 meters and the Pantheon's 43.3 meters), the system did not produce bursting stresses and could presumably have been made as large as needed.

Unfortunately, it didn't catch on. There are references to a portable bridge for military use that he designed using a similar construction technique, and there is also another intriguing sketch that shows a structure composed of straight elements held in position by some kind of cable, whether as an arched bridge or a curved roof is hard to tell (fig. 2). This is especially suggestive for later tensegrity structures, because it appears to have the cables in tension supporting beams in compression, but it's hard to tell exactly what is going on in these figures. It's another Leonardo mystery.

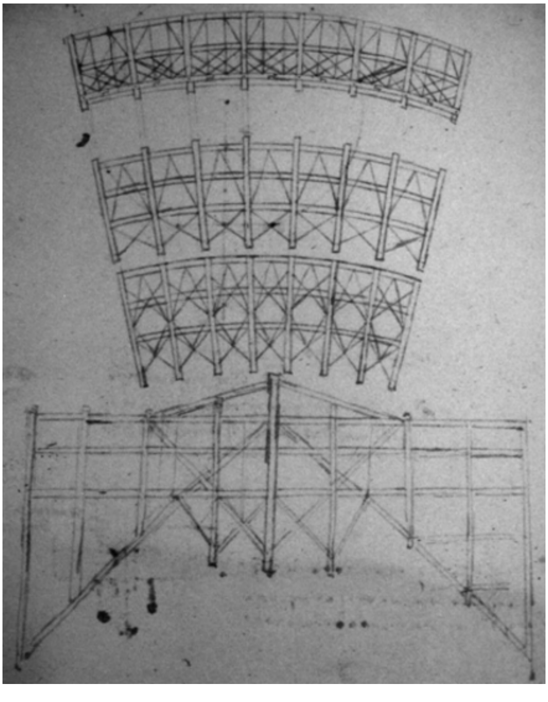


Fig. 2. Leonardo da Vinci, Ms. B of the Insitut de France, f. 29 v

As far as any related experiments with this kind of reciprocal structure, in which beams appear to support each other, there isn't much. A sketch on fol. 23r of Villard de Honnecourt's invaluable notebooks shows a roof structure which uses the "seed" of Leonardo's right-angled pattern as a way of using beams to support each other around the open well of a courtyard (fig. 3).

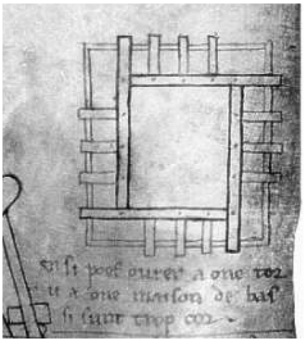


Fig. 3. Villard de Honnecourt, fol. 23r (detail)

This pattern, I am told, also appears in the music room of the Palazzo Piccolmini in Pienza, built by Bernardo Rossellini, probably between 1458 and 1464.[2] In both these cases, though, it is merely the seed. Leonardo's invention was to discover that the basic four-beam structure could be replicated by mirroring and offsetting to create a structure of essentially unlimited extension. But apart from the sketch, there is no evidence that Leonardo ever built one of his structures, and certainly his idea was not adopted by others.

Wren's workarounds

So what other solutions were there? Primarily there were timber trusses, a more polished version of traditional timber framing in which diagonal braces were combined with complex joint details to created frames that would span space. These were dependent on good quality wooden beams, and trees were grown especially for timber frameworks.

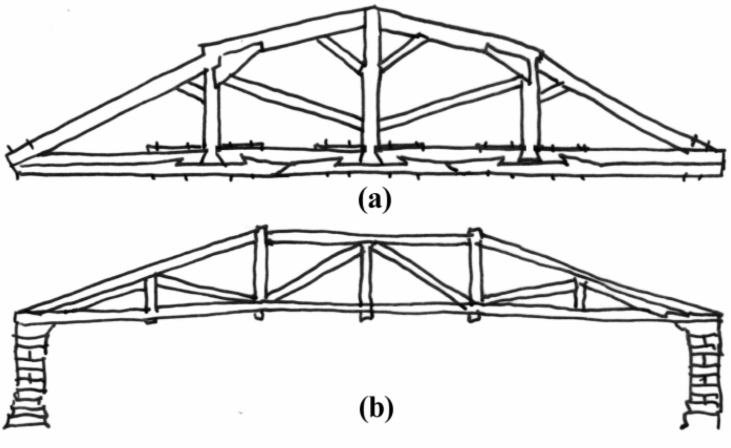


Fig. 4. a) Diagram of truss by Wren; b) Diagram of truss by Palladio

In 1669 the young Christopher Wren adapted a system developed by John Wallis for a "geometrical flat floor" to create the truss for the 21.3 meter clear span of the Sheldonian Theater at Oxford. According to his contemporary, Robert Plot [1677], it was "perhaps not to be parallel'd in the World" [Tinniswood 2001: 104] and considered a technological marvel of the same kind as the Florence dome (fig. 4a). In fact, the technological innovation was simply the splicing together of shorter beams using variations on "scarf" and dovetail joints, together with iron bolts to hold the joints together. This system may have been new to England, but Leonardo had sketched something similar in the *Codex Atlanticus* (344 verso a), and scarf joints had been used in the ceiling of the Doge's Palace in Venice at least by 1424 [Mehn 2003].

The roof itself was braced rather than genuinely triangulated, as was for example the bridge truss in Andrea Palladio's books. Palladio drew the bridge of Cismone [Palladio 1738, Bk. III, ch. VII, pl. III] (fig. 4b), though he stops short of claiming it as his own design, and accurately described the action of the truss members as working reciprocally ("… those are also supported by the arms that go from one colonello to the others, whereby all the parts are supported the one by the other; and their nature is such, that the greater the weight upon the bridge, so much the more they bind together, and increase the strength of the work…." [Palladio 1965: 65]). Wren's upper framing, however, was not a true truss because it did not use the diagonal rafters as part of the structural bracing.[3]

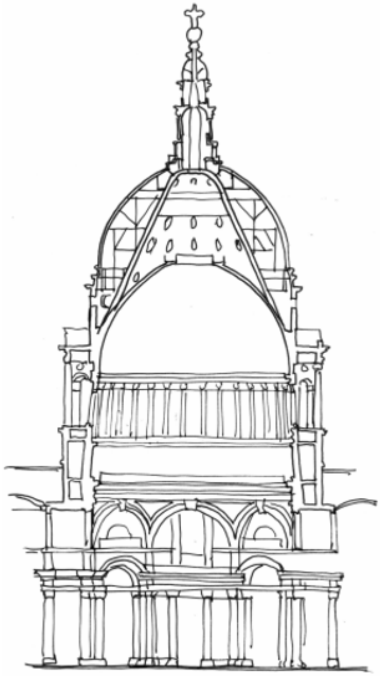


Fig. 5. St. Paul's Cathedral, London

When it came Wren's time to design a dome on the scale of the Cathedral of Florence, he used what we would call a "workaround" to address the problem of bursting. Instead of building a circular dome, he set a brick cone on a base chain (fig. 5). The stresses in a cone are transmitted directly along the length of the cone to the base, so it did not have to be tied as it went up. A shallow masonry shell formed the interior dome, and a copper skin over a timber framework formed the outer dome. So Wren's structures, while innovative and clever, evaded the question of how to span large areas simply.

Cast iron

The real breakthrough to a system with the elegance of Leonardo's simple beams came in the village of Coalbrookdale, where in 1759 Abraham Darby, John Wilson, and T. F. Pritchard used repeated cast iron components to span more than 30 meters (fig. 6). The new material and the idea of prefabricating replaceable elements led to an explosion of new structural ideas for glasshouses and exhibition halls.

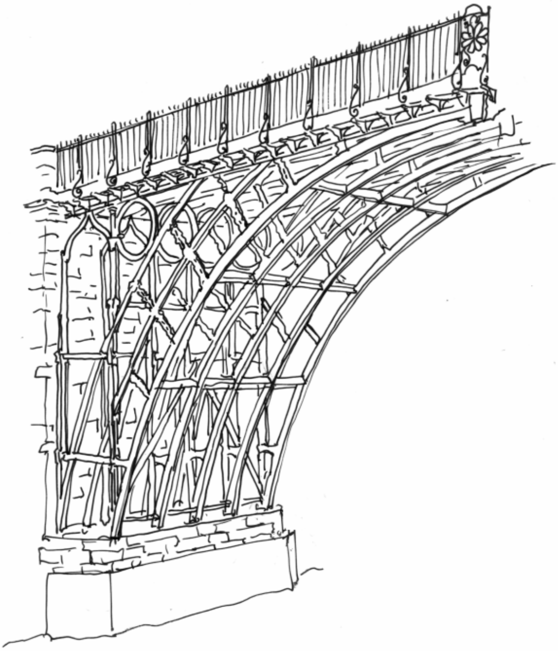
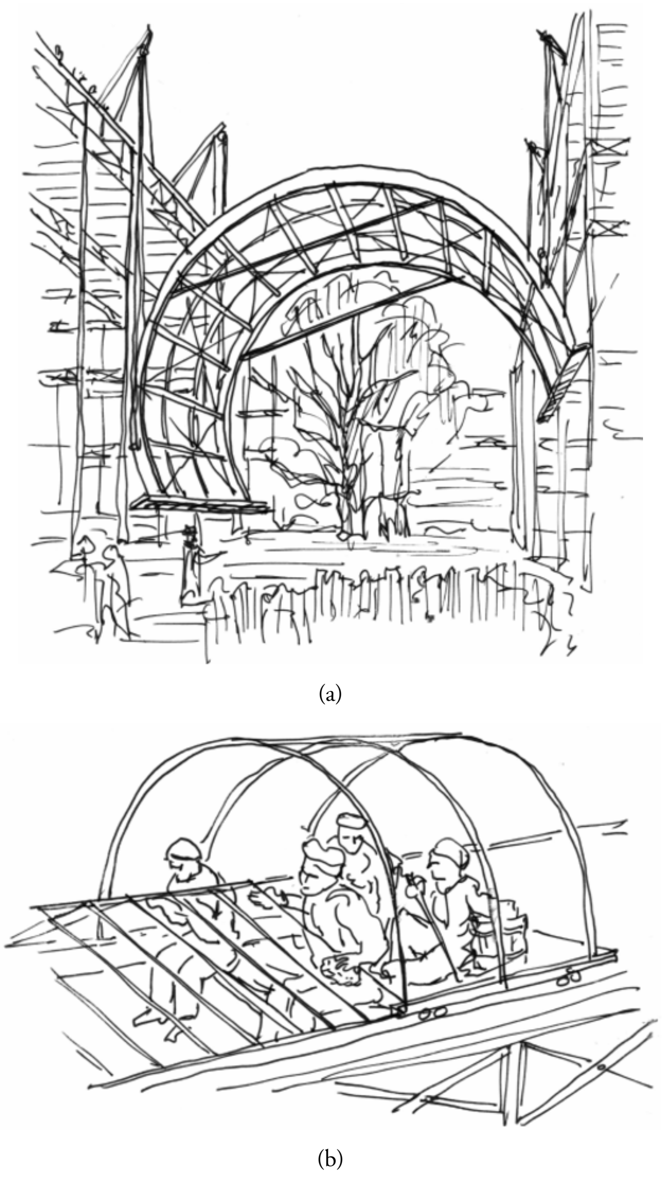


Fig. 6. Coalbrookdale Bridge

By the middle of the nineteenth century, the ideas generated by the Coalbrookdale bridge would culminate in Joseph Paxton's Crystal Palace of 1851. Paxton, a designer of glasshouses, is reported to have designed the hall in only ten days, using techniques he had already developed. Its modular construction covered 770,000 square feet of space and made use of shallow iron trusses. The diagonals of timber trusses, like those of Palladio's bridges, were added to horizontal and vertical members to create a very lightweight but strong web-like beam that stood in for the solid beams which casting techniques could not produce. Prefabricated sections could be bolted together in place, and a system of trolleys on rails enabled the roofers to install the glass panels with a minimum of effort (fig. 7). After the exhibition the palace was disassembled and re-erected at Sydenham Hill in South London, where it stood until destroyed by fire in 1936.



(a)

(b)

Fig. 7. Assembly of components of the Crystal Palace. a) Raising the arches; b) installation of the glazing

The Crystal Palace, in its simple elements easily assembled and disassembled, is the direct heir to Leonardo's timber grid. The system it embodied would become the standard for construction of large areas like railroad stations and exhibition halls well into the twentieth century, and its more humble variant of the open-web joist would be the material of choice for inexpensive market buildings and offices – just the kinds of buildings Leonardo had intended for his wooden domes.

The more general idea of interchangeable cast iron components would be adapted to more conventional buildings as well. In the 1850s in New York James Bogardus developed a system for commercial construction, using designs that appeared to be classical carved stone. In an engraving from 1856 he illustrated the strength and flexibility of the system by showing a façade with half its pieces missing, but which could still support itself.

After Bogardus, no longer would structural integrity depend on stacking masonry pieces and relying on the geometry of arches and lintels to hold them in place. Bolts could be used to suspend elements in tension, as well as to stabilize them in traditional compression structures. It would take a few years before the implications of the new freedom would begin to dawn on designers, but in the meanwhile cast iron became a means of cheaply imitating carved stone masonry, while providing strength and durability far beyond the capacity of masonry alone.

This idea of using a concealed or disguised iron structure to support buildings that appear to be traditional masonry buildings led to the early skyscrapers of Chicago and New York, but it was used even earlier in Thomas U. Walter's design for the enlarged dome of the U.S. Capitol, built during the Civil War. A section through Walter's dome shows that the system is a variation on Wren's St. Paul's (fig. 8). The structural skeleton is a nearly conical array of trusses, below which is an inner dome with coffers cast to resemble the stone coffers of the Pantheon, and above which are braces supporting an outer skin of cast iron resembling Wren's copper dome.

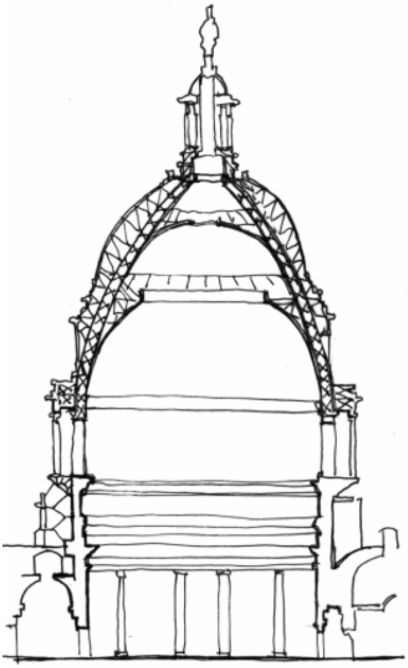


Fig. 8. Dome of the U.S. Capitol

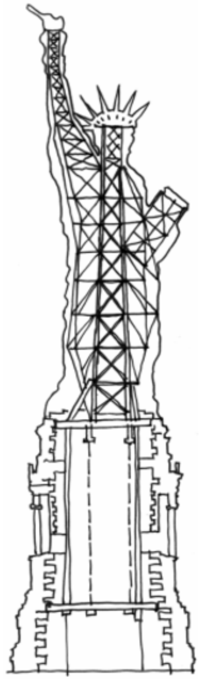


Fig. 9. The Statue of Liberty

Even Frederic Auguste Bartholdi's Statue of Liberty (conceived in the 1870s but not completed until 1886), which seems to be a huge version of a cast bronze figure, is a thin copper skin, attached with clever clips that prevent electrolysis between iron and copper to an iron frame designed by Gustave Eiffel (fig. 9). A large part of the fame of Eiffel's tower built in Paris in 1900 is a result of his letting the structure speak for itself rather than using his engineering skill to disguise an iron frame within a conventional envelope. Cast iron began to break free of its imitative role.

The most dramatic application of these techniques was the suspension bridge. Thomas Telford had pioneered the form, and John Roebling used it to build the Brooklyn Bridge, completed in 1883, and several others, establishing the type in America. Before emigrating to America, Roebling had studied with Friedrich Hegel; I have always seen his suspension bridges as the physical embodiment of Hegel's idea of the dialectic struggle in which a thesis is opposed by an antithesis, producing a new synthesis. In the suspension bridge the vertical tower in compression supports the cables in tension, which in turn support the bridge deck, which would be impossible without the other supporting elements. The towers are expressed as Gothic survivors of an earlier age, while the cables are unapologetically unadorned. Thus the structure spans the ages as well as the spectrum from extreme compression to extreme tension. This conceptual separation of tension and compression would be the key to a new understanding of structural form at the end of the next century.

Fuller's domes

Buckminster Fuller's geodesic domes are variations on the triangulated rigid metal framework. Though Fuller promoted himself as an innovator in the league of Leonardo and Brunelleschi, his system was fundamentally the application of the idea of triangulation to spherical structures. His domes take the geometry of the truncated icosahedron, a form familiar as the soccer ball, and subdivide the hexagons and pentagons into irregular triangles which can then be made more rigid by converting each triangle into a shallow tetrahedron. While the result appears novel, the principle of the frame made rigid by diagonal bracing has been the fundamental engineering principle of design since Palladio's bridge.

Before Fuller developed his tetrahedral system, telephone inventor Alexander Graham Bell had spent his later years investigating the possibilities of vast tetrahedral networks. Unfortunately for Bell, his vision was of using the structures as vast aerial kites for transporting cargo, an idea dependent on either prevailing winds or an as-yet undeveloped motor. The Wright Brothers' warped wings (fulfilling another idea prefigured in Leonardo's works) would spell the end of the tetrahedral kite. The tetrahedral grid would, however, prove to be one of the major structural innovations in the twentieth century.

Fuller's obsession with spherical domes became a profound limitation to the spread of his system to the world outside theme parks and world's fairs. A few circular halls, such as the 1957 Kaiser Dome in Honolulu, were built, but the major application of Fuller's system became enclosures of sewage treatment tanks and the proliferation of small dome houses among proponents of the counterculture of the 1960s and later.

One attempt to break out of the sphere was the use of the Zonohedral geometry by Steve Baer in New Mexico and Colorado in the 1960s [Kahn 1972: 102]. What he called "Zomes" are polyhedra with a complete circumferential zone of edges that are parallel to each other (fig. 10).

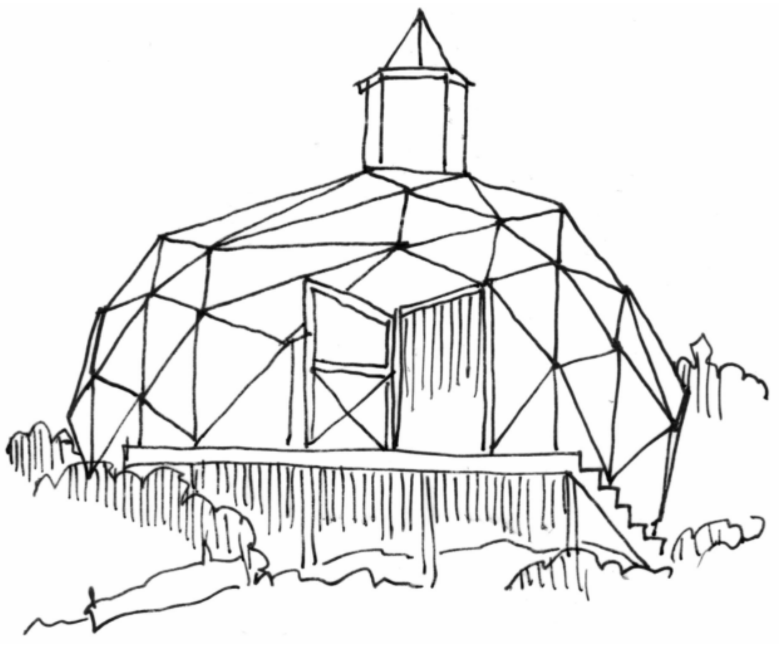


Fig. 10. Garnet Crystal Zome at Placitas, New Mexico

Baer realized that such domes could be stretched out of shape by elongating or shortening the parallel edges, and that domes could be joined into clusters using the parallel zones as links. The rhombic triacontahedron was the shape he found most suitable. While this generated some flexibility, it was not enough to make the dome a popular alternative to the rectangular box, either for homes or for convention halls. Remembering the name of the shape was almost as difficult as remembering the proportions of the struts.

The domes remain a vehicle for unconventional expression, outside the mainstream of construction technology. In many ways, Fuller's own writings and polemical stances helped to ensure they would remain there.

The octet truss

One system Fuller christened the "octet truss" did become a widely used structure, precisely because it was adaptable to rectangular and irregular spaces. As with the geodesic dome, the truss was a variant of the triangulated beam, with the diagonals spanning from beam to beam to create square-based pyramids that Fuller perceived as octahedrons cut in half (fig. 11).

Though Alexander Graham Bell had done something similar with tetrahedra, and Louis Kahn would use a tetrahedral concrete truss in his Yale Art Gallery, the octet form superseded the tetrahedron because its rectilinear geometry of staggered squares was more adaptable to the usual rectangles of modern floor plans. The octet would be refined by numerous manufacturers for use as roofing systems and display structures. Biosphere II is a good example of this kind of structure. It combines straight areas and curved sections, all based on the octahedral/tetrahedral geometry of the rigid truss.[4]

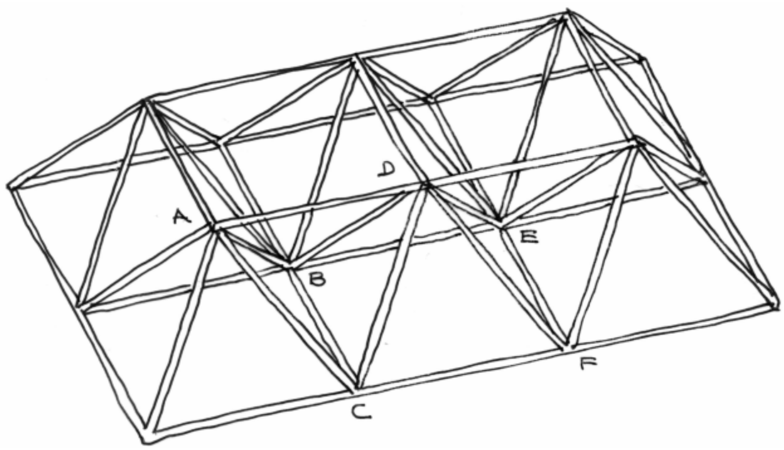


Fig. 11. Octet truss. ABCD = tetrahedron; BCDEF = half octahedron

One of the more flamboyant uses of the octet truss is Philip Johnson's Crystal Cathedral, built for evangelist Robert Schuller in Pasadena in 1980. The name is a clear reference to the Crystal Palace, and the space has the same quality of expansive transparency. It is emphatically not a dome, but a prismatic irregular structure of rectilinear elements, so it achieves the goals implicit in Leonardo's grid sketches: simplicity, flexibility, ease of construction, even, should it be necessary, ease of deconstruction.

One aspect of the Crystal Cathedral is that a whole section of wall had to be able to be opened to the parking lot, so people parked in their cars could see the pulpit. Johnson's office contacted NASA to find out how the Cape Canaveral Assembly building doors worked, and NASA engineers told them how to make the basic mechanism, but the doors themselves are sections of the same rigid octet truss.

Concrete

All of these systems were based on steel struts with various skins, usually glass or sheet metal. The other material of the twentieth century, reinforced concrete, was also used to span great distances, but the labor to build the formwork and to place the wet concrete made the material less attractive than metal.

One of the greatest concrete domes is also one of the earliest, Max Berg's Centenary Hall in Breslau of 1912-13 (fig. 12). Robert Hughes [1980] tells the story that when the formwork was to come off, the workers refused, fearing the dome's collapse, and Berg himself had to remove the first props before the workers would continue. The shell, with its ribs and concentric rings, is the skeleton of Brunelleschi's dome. Reinforced concrete uses embedded steel to resist the bursting and bending stress that masonry is so bad at handling. The concept of using concrete in compression and steel in tension marked a step on the way to thinking about those two forces in different ways, which would free engineering from rigid structural concepts. Brunelleschi had understood the function of the "chains" of stone that bound his dome, but had used hard stone with secretly conceived joints. Tie rods and iron chains had been used for centuries, but the innovation of embedding the thin rods in the concrete freed the engineer to create what were in effect long "stone" beams and shells.

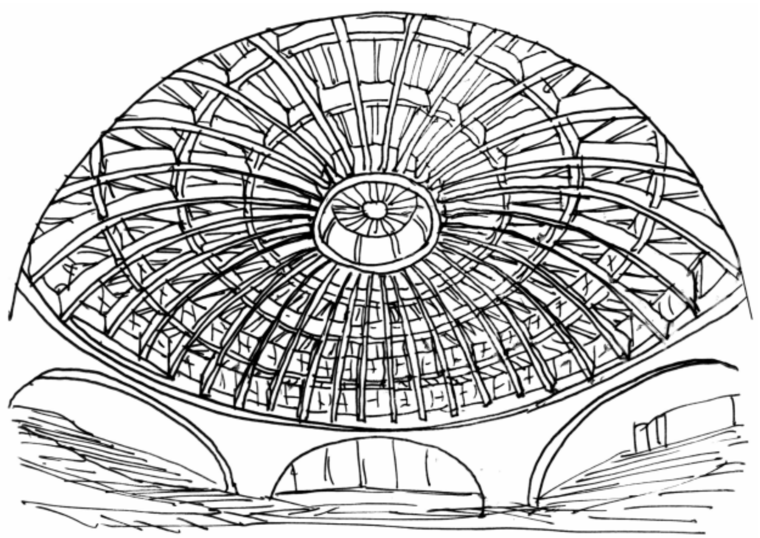


Fig. 12. Centenary Hall, Breslau

The poet of concrete was of course Pier Luigi Nervi, whose graceful structures allowed the mass of concrete to float almost effortlessly over vast spaces, and he pioneered the use of precast elements which made construction less difficult. Nervi's structural ideas were often based on the lamella structure of interlaced continuous beams. While not specifically a triangulated structure, the lamella dome could have its stresses calculated using techniques that did not deviate from standard practice.[5] Today the prestressed and precast tee is widely used, though usually for parking garages, and precast concrete is more widely used as a surfacing material than a structural one.

The bóveda tabicada

Apart from steel frameworks and the occasional concrete ribbed structure, there was one other system prevalent in the late nineteenth and early twentieth centuries that fits the description of Leonardo's lattice: the *tabicada* or tiled dome. *Bóvedas* were traditional masonry domes derived from vernacular Arabic construction and used in Spain for such structures as wine cellars. Carried to Mexico by Spanish masons, they were used occasionally for house roofs. The technique allows a mason to form a domed roof without extensive formwork. Using quick-setting mortar and lightweight bricks, he can place one brick at a time in space, waiting long enough for the mortar to grip before moving on to the next brick.

In Cataluña the system was refined by the substitution of flat clay tiles for bricks, permitting very thin shells to be built over relatively large areas. The technique was used by Antoní Gaudí in several buildings, most spectacularly in his school building on the grounds of the Sagrada Familia church in Barcelona. Its undulating bóveda shell is supported by a central girder and straight rafters that form the frame for the shell. Gaudí never seems to have allowed the shells to become the whole structure, however. He depends on ribs to support the shells, as in the roof structure for the attic of Casa Milá and the crypt of the

Guëll chapel. The ribs themselves are built of the same tile, but used as straight compression membranes.

Le Corbusier noticed and sketched Gaudí's school roof, and then adopted the tabicada vault for his Maison Jaoul of 1955-57. We think of Le Corbusier as using reinforced concrete, but here he used this masonry construction technique in one of his important late works.

Guastavino vaulting

The man who brought the bóveda tabicada into the architectural mainstream was Rafael Guastavino Moreno, a Catalan of Genoan ancestry who began by building fire- and damp-proof vaults for wineries around Barcelona before emigrating to the United States in 1881. There he promoted the technique as a means of fireproofing steel frame construction, but he soon developed a complete structural system. He was able to convince McKim Meade and White to use his vaults in the Boston Public Library of 1895, and soon he and his son (also named Rafael) were supplying domes and vaults for many of the most important buildings in the United States.

Among the many projects to use what came to be called Guastavino vaulting were the Cathedral of St. John the Divine in New York by Heins & LaFarge, the Christian Science mother church in Boston, and the Shrine of the Immaculate Conception in Washington, while at the same time the tiles lined subways and train stations [Huerta 1999] and indoor swimming pools.

Guastavino achieved the geometric regularity not typical of traditional bóvedas by using a lightweight system of ribs and spacers. Unlike formwork for concrete, the frame did not support the weight of the shell but merely provided a geometric reference for the masons. At St. John a stiff wire was fixed to a weighted plate suspended at the radius point of the spherical dome and used to check the radius of the dome at each tile (fig. 13).

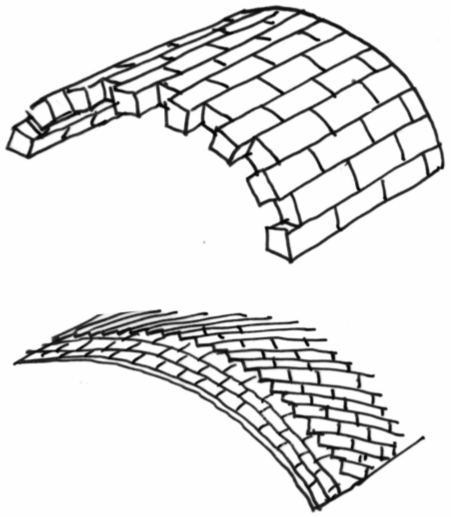


Fig. 13. a) Conventional masonry vault; b) Bóveda tabicada

Guastavino dealt with building codes by staging load tests. The system proved capable of supporting loads far in excess of structural needs, while being flexible enough to build hemispherical and shallow domes and curved planes such as the helix of a curved stair. To satisfy the code officers, Guastavino developed graphical analyses of the stresses of the dome based on conventional engineering.[6]

Guastavino vaults were even used by McKim Meade and White to restore Thomas Jefferson's Rotunda at the University of Virginia after it burned in 1895. They were used to fireproof the floors and porch roof as well. John Russell Pope, the original architect of Jefferson's memorial in Washington, used the system in Washington for the Masonic Hall, a pyramidal structure based on the Mausoleum of Halicarnassus. An unlikely candidate for a dome system, the building was highlighted in an advertisement for the Guastavino Company as being similar in its double-layered construction to, of all things, Brunelleschi's dome.

Also in its advertising, Guastavino Company took on its main competitor, steel framing. In a graphically compelling side-by-side section drawing, the ad says that the system is "simple, economical, and the necessary materials can always be delivered promptly" – the last because they did not have to be fabricated specially for the project.

The Guastavinos were not the only ones to use tabicada techniques in modern times. In Spain Luis Moya built several buildings using vaults with and without tile ribs. For the church of Santa Maria de la Iglesia of 1966-69, he developed an elegant mechanism using a rotating steel frame to align the tiles. In Havana in 1961, the Cuban architect Ricardo Porro began the elaborate complex of the National Schools of Art, which linked domes of several sizes with a sinuous set of corridors roofed by tiled tunnel vaulting (fig. 14).

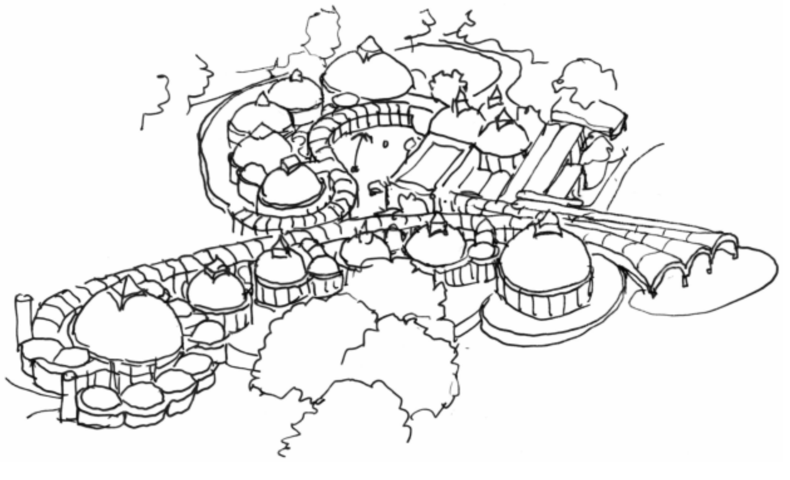


Fig. 14. Plan of Porro's project for the National Schools of Art

The elder Rafael Guastavino, having worked on vaults for Richard Morris Hunt's Biltmore, the Vanderbilt summer chateau near Asheville, North Carolina, had built a retirement home and studio in nearby Black Mountain. He worked with Hunt's local architect, Richard Sharpe, to build the church of St Lawrence, which features a large elliptical tile dome and several smaller chapels and helical stairways. When he died, he was buried in a tiled tomb in the church.

Snelson's tensegrity

By a coincidence of history, in 1949, the young Oregon sculptor Kenneth Snelson attended a summer workshop at the Black Mountain School, which by then was the home of several refugee Bauhaus figures, notably Joseph and Anni Albers. The architect scheduled to teach was replaced at the last minute by Buckminster Fuller. Snelson showed him a sculpture he had been working on using wooden struts connected by cables. Fuller asked to keep it, and shortly was touting what he called "tensegrity" geometry, which he privately told Snelson had been Snelson's idea, but publicly refrained from attributing to anyone but himself.[7]

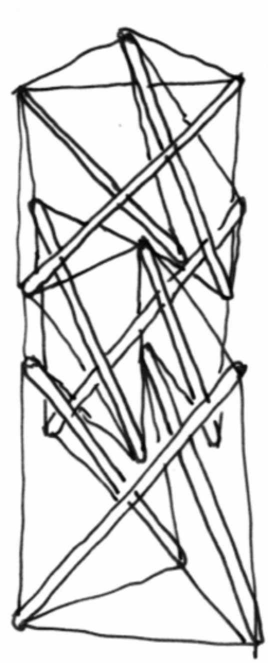


Fig. 15. Snelson patent drawing

Snelson in 1960 patented the system (fig. 15), which he more accurately if less memorably called "continuous tension, discontinuous compression structures". He clearly spelled out in his patent and in his sculptural works over the next half century his understanding of the significance of thinking separately about tension forces and compression forces in designing structures. He has made the analogy that the body should be considered as having a compression structure of bones linked by a tension structure of tendons and muscles. Structural freedom can be achieved by conceptually separating the two forces. This was the insight that had led to the suspension bridge, but Snelson's explicit understanding of it made much more flexible structures possible.

Snelson has described his system as based on weaving techniques, where the connections between members are determined by the ways in which they overlap or interweave.[8] Analysis of woven structures allowed him to think about polyhedral analogies, with edges of polyhedra conceived as fibers that bypassed each other in regular ways. And separating compression from tension allowed him to convert what he called "weave polyhedra" to tensegrity polyhedra using compression struts connected by cables. Modules could be interconnected by stacking and extending. The interlaced framework of his structures bears a remarkable formal similarity to Leonardo's grids, especially in the way that the beams must overlap in a specific sequence in order to work. Like Snelson's sculptures, the frames can be right- or left-handed, depending on the way the beams overlap.

So, from analysis of the most widespread structures man has made – weavings – Snelson has developed a theoretical system capable of using, as Leonardo had wanted, simple elements easily connected to produce structures of great flexibility and variety.

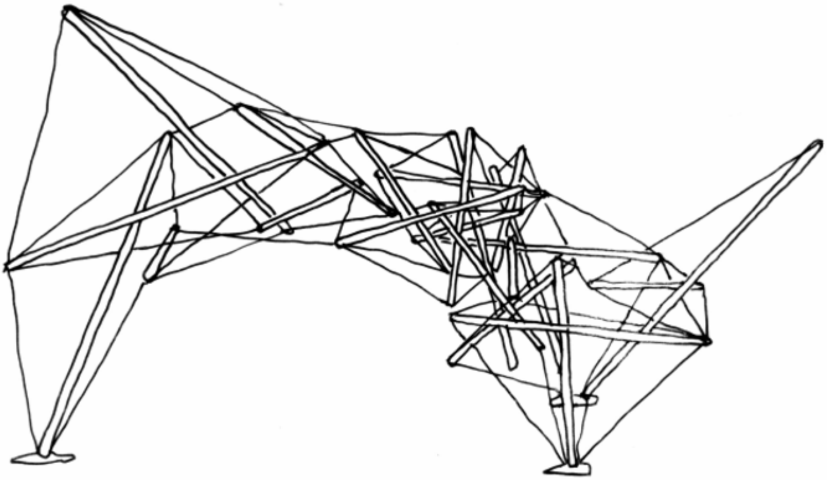


Fig. 16. Snelson's *Free Ride Home*

Snelson's most well known sculpture is the *Needle Tower* of 1968 at the Hirshhorn Museum in Washington. A more exciting example is the *Free Ride Home*, one of several at the Storm King Sculpture Park in New York. While the needle tower is dramatic, *Free Ride Home* (fig. 16) shows the possibilities for irregular shapes the system allows.

Snelson insists that the true utility of the tensegrity system is for dramatic sculpture forms of the kinds he creates. More sober engineers, however, have used his system to span the large spaces like those of athletic fields – the same use that Fuller envisioned for his domes. Some twenty years after the steel lamella dome of the Astrodome, David Geiger designed stadiums for the Seoul Olympics. The Fencing Arena in particular shows the basic tensegrity system: a compression ring at the top of the stands supports cables that hold the tops and bottoms of vertical compression struts suspended over the arena (fig. 17). From the tops of the struts another similar system of cables and struts extends further into the space. Yet another set extends further in, until the system converges at a central hub. The dome is given its final shape by tightening the bottom cables in sequence, as shown in the figure.

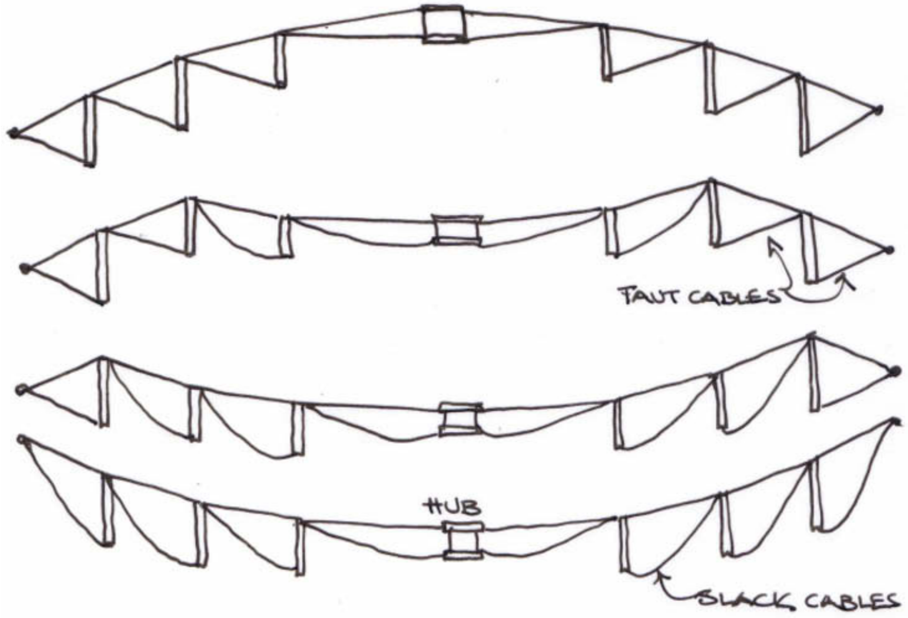


Fig. 17. Fencing Arena section. Circumferential cables connecting bases of masts not shown

This dome and the several others built by Geiger and by Weidlinger Associates take Snelson's poetic spatial constructions and turn them into economical utilitarian roofing systems, competitive with inflatable or cable-hung fabric structures. Cable-hung structures are a development of the suspension bridge, with compressions masts and tensions cables used to support a roof rather than a road. The Millennium Dome (now the O2) is a recent example of that system.

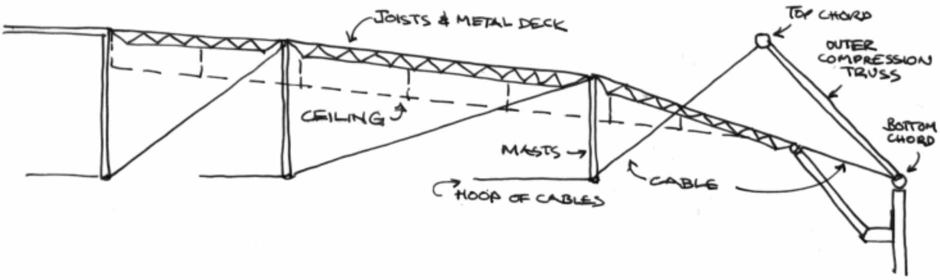


Fig. 18. Georgia Dome

The tensegrity system is not limited to flexible fabric roofs but can accommodate conventional roofs made of panels supported by the simple open web joists and corrugated steel roofing of factories and warehouses. The domes need not be circular. Weidlinger's Georgia Dome is an oval, 235 by 186 meters (fig. 18).

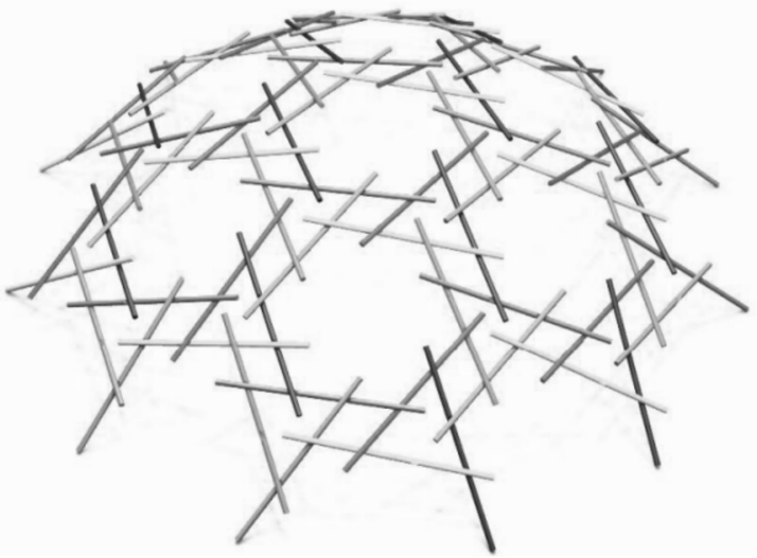
As a new century begins we have extraordinary capacity to invent new structural shapes using existing understandings of compression and tension — Snelson's bones and sinews.

While the current, rather conventional uses of tensegrity domes are exciting by virtue of their lightness and immense scale, if we look at *Free Ride Home* and think of some of the formal adventures of people like Frank Gehry, Zaha Hadid, and Santiago Calatrava, the possibilities of incorporating tensegrity structural techniques with architecturally adventurous forms would excite even Leonardo.

And perhaps, especially in parts of the world where labor is more available than manufactured materials, the Guastavino dome and even the Leonardo grid might make a comeback.

The Leonardo Sticks Project

After attending the conference on Rinus Roelof's rediscovery of Leonardo's domes I returned home full of enthusiasm for the system. I made myself a set of Rinus's small sticks and showed them off as often as I could find occasion.



One person I showed them to was an architectural client of mine, Joseph Stanislaw, who became as excited as I was about them. He in turn had a friend who had a company reproducing classic toys and games. Joe and I decided to use his connections to have sets of the sticks manufactured in China. We set up a small family company to handle the legal and logistical work, and I designed the box and information for the set. We offered royalties to Rinus on the sales of the sets, which of course we envisioned would take off as the latest craze.

Unfortunately for our enterprise, neither Joe nor I had the time to devote to marketing the sticks effectively, and despite several promising possibilities we have had few actual sales, either directly or to wholesale buyers. After four years, we have decided to liquidate the company, with several hundred sets from our original order still unsold.

Like Rinus, I have been demonstrating the sticks in various venues, notably the classes I have taught at Bowdoin College. Everywhere they are demonstrated the attract attention and interest. One reaction that has been of special interest is the idea that the system should be adapted to emergency shelters. Especially in climates where bamboo is available, a sizeable shelter could be quickly put together from available materials.

I think there is a place for a professionally marketed sticks kit, and an opportunity to develop an emergency shelter system. What would be most useful for Leonardo's system to enter the public consciousness, however, would be a large structure based on the system. What stand in the way of that is what hampered Fuller and Guastavino: an accepted means for calculating the stresses and therefore assuring the stability of the structure. We have seen that it works. Now the task is to prove it.

Notes

1. [King 2000] provides a good introduction to the splendid adventure of the Duomo.
2. After I lectured on this material at the Bath Scientific and Literary Institute in October 2007, Nicholas Lewis told me about the Piccolomini. I have not had an opportunity to verify whether this is in fact a reciprocal structure or a decorative ceiling, but given its date it is not inconceivable that Leonardo might have seen it.
3. While on the subject of Palladio's bridges, I would note the similarity between his arched bridge, plate V of Book III, described in chapter VIII, which bears a remarkably similarity to the Leonardo sketch described above.
4. In an interesting reversal, Biosphere's successor the Eden Project in Cornwall, whose enclosure is by Nicholas Grimshaw, uses a newer flexible version of the geodesic dome. The flexibility derives from separating the regular polygons of the skins from the bracing system. This system has similarities to the tensegrity systems discussed later in this article.
5. For this reason the first major sports arena in America, the Astrodome in Houston, would use a lamella dome rather than a geodesic dome. For a discussion of lamella structures and the Astrodome in particular by L. Bass, see [Davies 1967], available online at: http://www.columbia.edu/cu/gsapp/BT/DOMES/HOUSTON/h-lamel.html.

6. Gaudí had used similar techniques to determine the slope of his retaining wall at the Parque Guëll, and in general to guide his departures from rectilinear geometries. See [Sweeney and Sert 1960: 74].
7. This information is from a letter from Kenneth Snelson to R. Motro, published in *International Journal of Space Structures* (November 1990). It is available at *http://www.grunch.net/snelson/rmoto.html*.
8. See http://www.kennethsnelson.net/main/structure.htm for his description of the principles involved.

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