9 Bridges

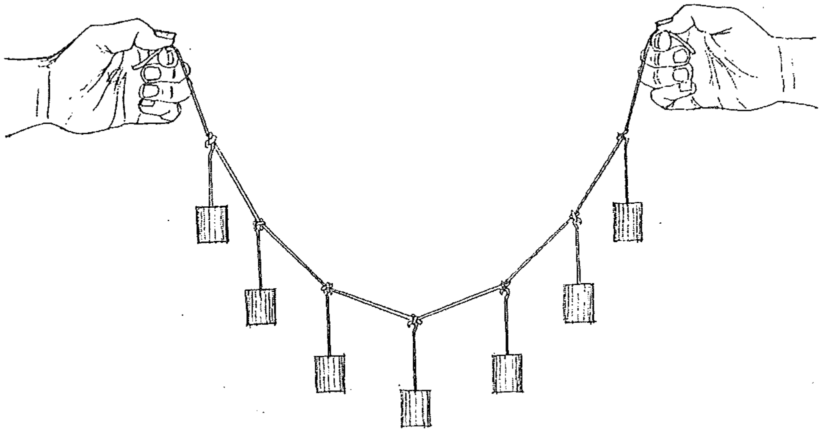
Arches

The world of bridges is so infinitely varied that the layman must be somewhat baffled by it. Why is one bridge as light and elegant as a suspension span and another as massive as a medieval castle of brick, arches, and buttresses? Why does one steel bridge have an arch above the roadway and another an arch below it? Why do some bridges have an arched shape while others are straight? Why are some made out of reinforced concrete and others out of steel?

The answers to all these questions, and many others, rest on the fact that the type of bridge best suited to a particular site depends on a large number of factors. The length to be spanned, the nature of the river banks, the free height required under the bridge, the variations in the river's water level, the materials and the specialized labor available for its construction, the kind of traffic present and that to be expected, the kind of road approaches usable, and, last but not least, economic and even aesthetic considerations together with the preferences of the engineer—all play a role in the choice of a bridge type. If one considers all the possible combinations of these factors, then no large bridge can be identical with any other. Each is, or ought to be, the best structural solution to a very specific problem and, since bridges are almost all-structure, one should look at them first from the structural point of view to understand how the various types work. Their behavior is quite simple to grasp as the infinite world of bridges divides itself into at most four or five basic types. Let us look first at the arch bridge.

If a weight is hung from a piece of string held in two hands, the string takes a triangular shape with two straight sides meeting at the point where the weight hangs. If two weights hang, separately, from the string, its shape changes to one with three straight sides. When many weights hang from the string, the string shape has many short, straight sides and looks rather like a curve (Fig. 9.1). The cables of a suspension bridge are loaded by a large number of weights hanging from the numerous *suspenders*. If we could look at them with binoculars, we would see a shape consisting of many straight sides, but so many of them that from far away the cables look smoothly curved. The varying shapes taken by a string or a cable under varying weights are called *string* or (from the latin funiculum-string) *funicular polygons,* that is, many-angled figures.

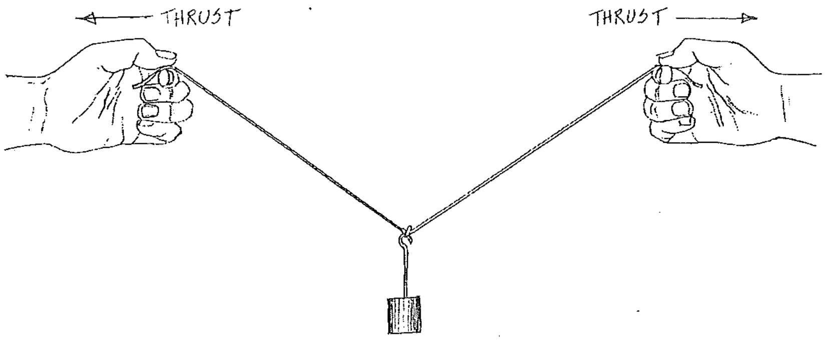
Very thin, flexible elements can work only in tension. Strings and cables are so flexible that they cannot resist compression or bending, as a beam does. They can only resist pulls, and since they straighten when pulled, they are always straight between hanging loads. This is why, in order to carry loads by tension only, cables must change shape whenever loads change in location or number.



9,1 THE STRING POLYGON OF MANY WEIGHTS

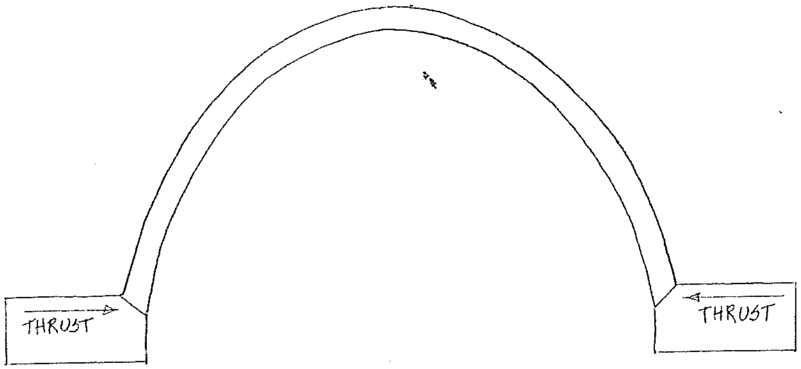
The adaptability of cables to carrying different loads in tension, while wonderful, presents practical difficulties. Our structures are submitted to varying loads, but it would be inconvenient to have structures change shape all the time. Thus, to stop a cable from changing shape, we must stiffen it by means of a beam or truss, which we have seen in Chapter 5 to be rigid in bending.

In supporting a single weight by means of a string held in two hands, we may notice an important fact. Besides pulling up on the string ends to balance the weight pulling down, we must also pull *outward* to counteract the tendency of the two string ends to move towards each other (Fig. 9.2). These outward pulls of our hands are called *thrusts*. Similarly, in a suspension bridge the anchorages (massive masonry or concrete blocks built into the ground,) pull not only down, but outward on the cables to provide them with the needed thrusts.



9.2 CABLE THRUSTS

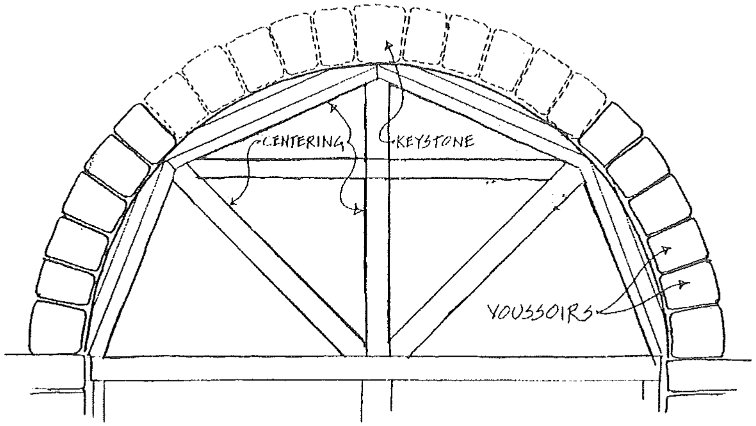
Once the behavior of a cable is grasped, one easily realizes that an arch is nothing but an upside-down cable. Imagine flipping a loaded cable over after freezing it in its curved shape. The cable becomes an arch. The pull (or tension) in the cable becomes a push (or compression) in the arch, and the outward thrusts on the cable become the inward thrusts on the arch, which prevent it from opening up (Fig. 9.3). Of course, to freeze the arch shape, often called the *anti-funicular* of the loads, we must make it stiff, and hence much thicker than a slender cable, or it will buckle, as all thin, compressed elements tend to do. And because the arch has to be stiff to prevent its buckling, it does not need a stiffening truss! It keeps its shape under a variety of loads and is said to be stable, while a cable without a stiffening truss is unstable.



9.3 ARCH THRUSTS

Since an arch is compressed all over—its own weight, the roadway, and the traffic loads all push down on it—it can be built of materials strong in compression, like stone, brick, and concrete. The availability of natural compressive materials explains why our ancestors built arch bridges and arched roofs over 2,500 years ago. The Romans, who were masters of masonry construction, used arches profusely and in a variety of applications. Masonry and brick arch bridges were found all along their road network and also in their monuments. The Coliseum's outer walls are pierced by arches, the Roman baths were covered by arched vaults, and the Pantheon has a large domed roof that works somewhat like a series of arches set around a circle (see Fig. 13.5). Their aqueducts carried water along the top of as many as three sets of superimposed arches. The maximum span of a Roman arch was about 100 feet and its shape was always that of a half-circle, because of the ease of erecting circular wooden scaffolds or *centerings* for their construction. While a long-span cable can be spun from tower to tower without any intermediate support (see Chapter 10), a masonry arch is built of separate blocks or *voussoirs* which must be temporarily supported on a centering, still usually made out of wood. The arch is started simultaneously from both ends of the centering and when the top block or *keystone* is wedged between the two adjoining blocks (Fig. 9.4), the centering can be lowered since each half-arch leans on the other, as Leonardo observed.

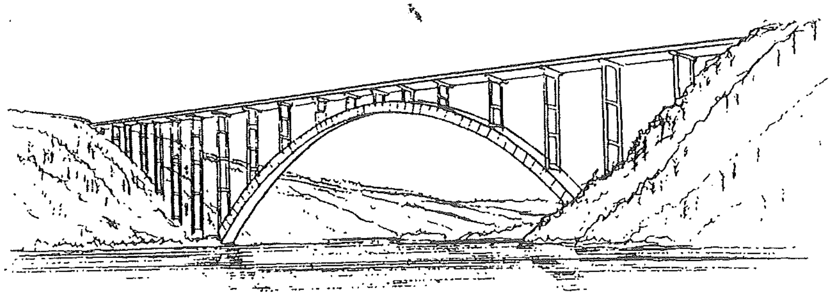
Once the arch is built, its ends must be prevented from spreading apart. The inward forces or thrusts needed to keep the arch from opening can be provided by the banks of the river when these consist of solid rock. Otherwise, heavy buttresses of masonry or concrete must be built



9.4 BUILDING AN ARCH

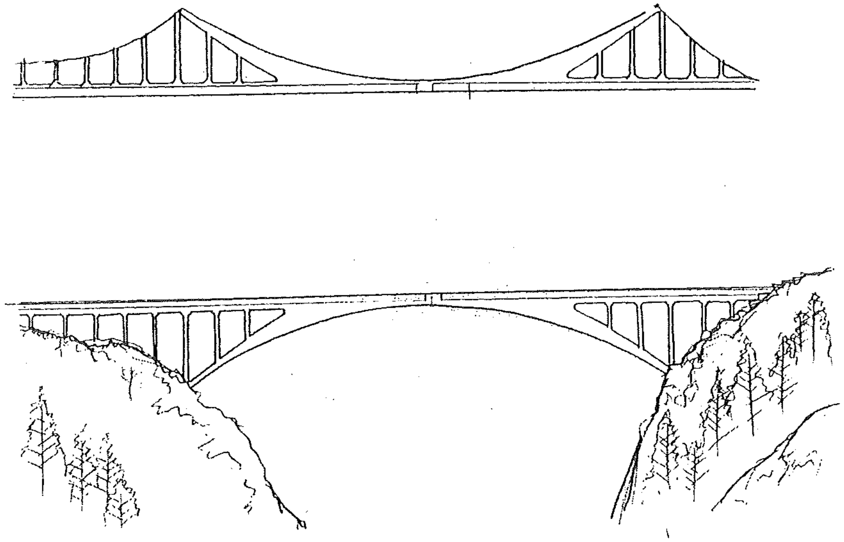
that resist the tendency of the arch to push outward, just as the anchorages resist the tendency of the suspension bridge cables to pull inward.

Modern arch bridges are often built of reinforced concrete poured in place or of large blocks (often hollowed to make them lighter) which are prefabricated on land and lifted on top of the centering, where their reinforcing bars are welded and the blocks are glued to one another by strong cement mortar. The longest reinforced concrete bridge built so far connects the Adriatic island of Krk to the mainland of Yugoslavia and spans 1,280 feet (Fig. 9.5). To carry the roadway, vertical columns or *struts* of varying length must be built up from the arch. (These are the counterpart of the suspenders in the suspension bridge.) The weight of the roadway and the vehicles pushes down on the struts that are compressed, while the roadway is supported by a series of beams spanning from strut to strut. These beams, stiff in bending, and the roadway itself contribute to the overall stiffness of the arch bridge and act very much like the stiffening truss of a suspension bridge. The extremely elegant bridges of the Swiss engineer Robert Maillart consist of very thin concrete arches (sometimes only seven inches thick over a span of 300 feet), which share the task of carrying the loads with the concrete beams and slabs of the roadway. An upside-down picture of a Maillart bridge looks exactly like a suspension bridge, explaining visually their opposite, but analogous behavior (Fig. 9.6).

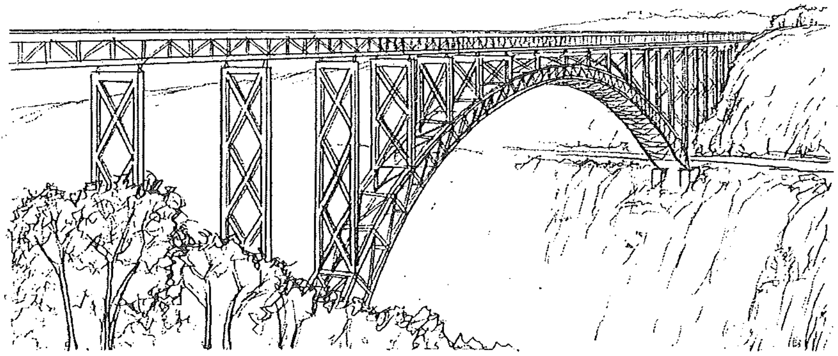


9.5 KRK ARCH BRIDGE IN YUGOSLAVIA

The longest arch bridges in the world today are built of steel. They look and work very much like reinforced concrete bridges and usually have the advantage of being lighter because of the high strength of steel in compression. Now (1980) the very longest is the New River Gorge Bridge in West Virginia, which spans 1,700 feet (Fig. 9.7). Previously it was the Kill van Kull Bridge, connecting Staten Island to New Jersey, but not by much: it was purposely made just five feet longer than the famous steel bridge at the entrance of Sydney harbor in Australia so that the United States could boast the longest steel arch bridge in the world.



9.6 MAILLART'S CONCRETE BRIDGE

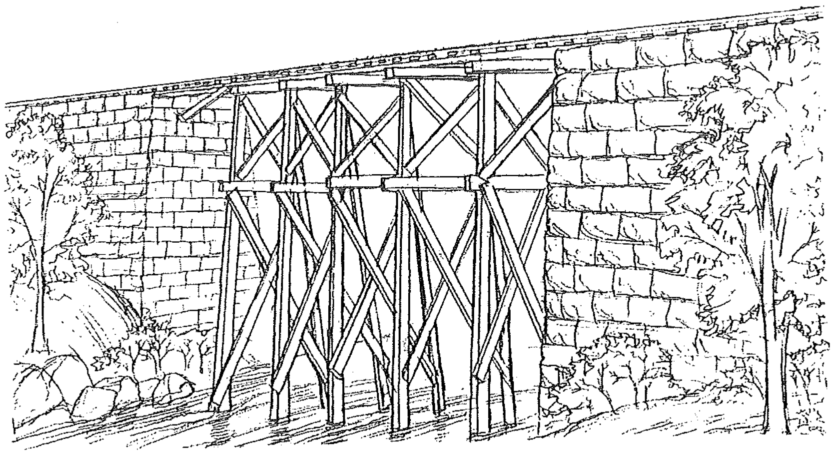


9.7 THE NEW RIVER GORGE BRIDGE IN WEST VIRGINIA

Railroad Bridges

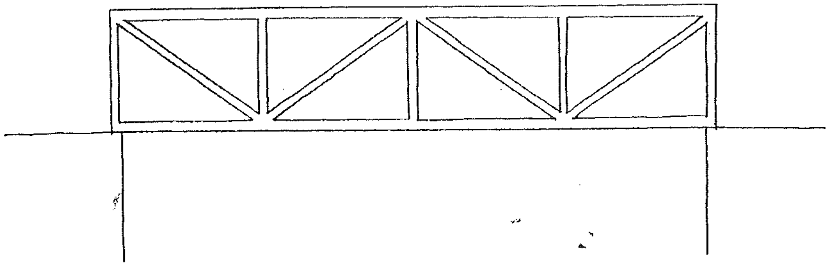
The heroic age of bridge construction coincided with the expansion of the railroads in Great Britain and the United States. The first modern locomotive, the Rocket, was invented and built by George Stephenson in 1829, and the first passenger railroad was inaugurated in England in 1825. But the greatest of railway achievements was the spanning of the American West in the nineteenth century—the networks of the Baltimore and Ohio, the Erie, and the Pennsylvania railroads and the first transcontinental railway, the Union Pacific, completed in 1860.

Forgetful of the violence and chicanery which characterized this era, we have developed a great nostalgia for the old railroads, manifested in the expensive and widely appreciated hobby of toy trains. Both children and parents actively participate in it and while the first outgrow it, the last often don't. To carry the unprecedented loads of the locomotives and the railroad cars across deep gorges and wide rivers, all kinds of new bridges had to be built, with great urgency and increased strength. After a few wooden spans were erected, mostly in the form of *trestles* (Fig. 9.8) with their high, narrowly spaced towers of timber connected by short, heavy timber beams, the miraculous new iron material, steel, was universally adopted. Steel arches, large trusses, cantilevered bridges, lift, bascule and pivoted bridges mushroomed throughout the country. Meanwhile, after the example of England, France had built by 1840 the largest railway system in Europe. Germany, Italy, and Russia followed suit. The railroad gauge had been standardized to a width of four feet eight and one-half inches by 1880, and for about 100 years the railroad reigned supreme all over the world.



9.8 WOODEN TRESTLE

Possibly the most common structure used in railroad construction to span rivers and valleys was the *truss.* Hence, a brief discussion of railroad bridges must start with an analysis of this most ingenious extension of the beam, involving straight bars of steel working only in tension or in compression. As the span of a beam and the loads on it increase, its dead load increases rapidly out of proportion with the loads it has to carry. We have seen in Chapter 5 how efficiency is improved by giving the beam an I-shape, provided its depth is increased and the flanges are set farther and farther away from each other. Consequently, the web connecting them becomes deeper and heavier. And here is where the basic idea of the truss comes in. To lighten the web why not open up holes in it, obtaining a perforated I-beam? Finally, as the dimensions of the beam make its fabrication as a single rolled element impractical or impossible, why not build it up by connecting the upper bar to a lower bar by means of inclined and vertical bars (Fig. 9.9) which constitute, so to say, a discontinuous web? To make this built-up beam rigid its *meshes* or holes, created by the web bars, should be of a triangular shape, since the triangle as the great bridge builder John Roebling put it, is "the most indeformable geometric figure." A *triangulated truss* is thus obtained which can be made as deep as necessary and is substantially lighter than a full-web beam.

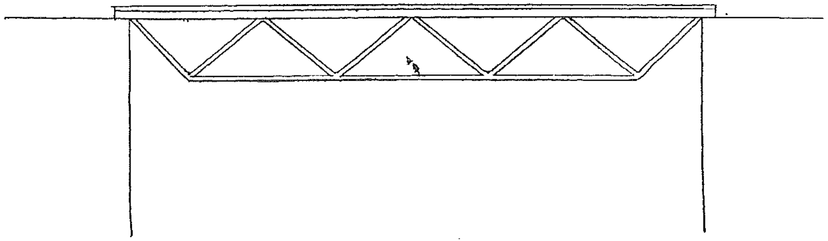


9.9 TRUSS BRIDGE

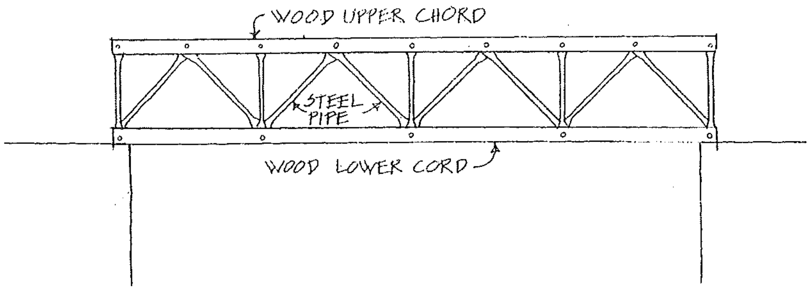
Since a truss supported at its ends is but a perforated I-beam, its upper flange or *chord* is compressed, while its lower chord works in tension (see Chapter 5). The web bars resist the equivalent tension and compression of the beam shear and work in tension or compression depending on their inclination. Since all the bars of the truss are either tensed or compressed, they work much more efficiently than the layers of a beam, in which the material near the middle, neutral axis does very little work at the expense of the material of the flanges. It is no wonder that trusses are used for 1001 applications in all kinds of structures, from those stiffening the core of high-rise buildings (which were called X-ed frames in Chapter 7) to the prefabricated trusses called *bar-joists* available on the market in lengths from 20 to 100 feet [with chords and diagonals of steel (Fig. 9.10a) or chords of wood and diagonals of steel pipe (Fig. 9.10b)], from the enormous steel trusses used in bridge construction to those made of laminated wood and used in roof construction.

Steel trusses with horizontal parallel chords were patented during the railroad era with a variety of patterns for the web bars (Fig. 9.11) and each is called to this day by the name of its inventor. But soon the concept of triangulating a steel structure was extended to trusses with one or both chords in a curved shape, and finally large steel bridges were built as triangulated arches, as they are to this day (see Fig. 9.7).

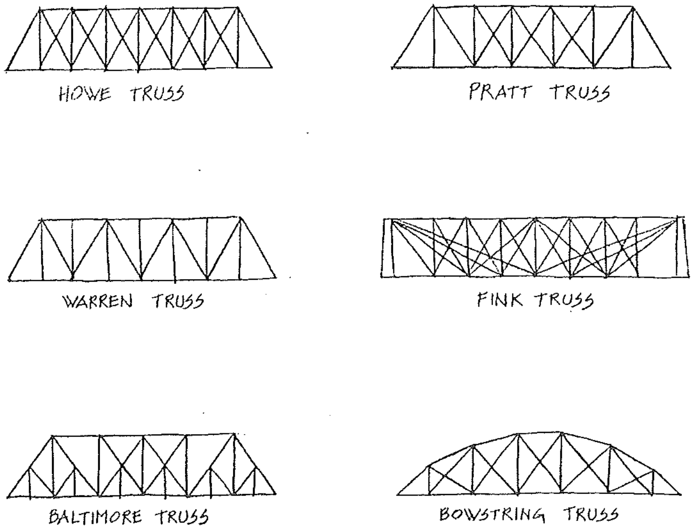
Prior to the advent of the railroad most of the freight traffic, of course, travelled through a network of canals and rivers on barges, pulled first by mules and eventually by locomotives. Memories of our canals still linger in the lovely songs of the nineteenth century and the words "Erie Canal" evoke dreams of peaceful travel on slow water through the locks. The canal lobby fought the railroads. Whenever a railroad bridge was planned to cross a river or canal at grade level, a cry arose about impeding the water traffic, and the bridge was required to cross high above the water.



9.10a STEEL BAR JOIST



9.10b BAR JOIST WITH WOOD CHORDS

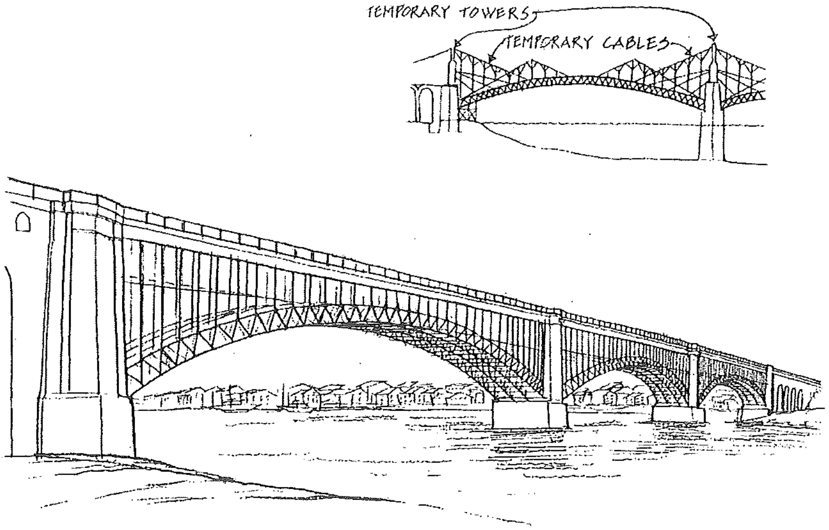


HOWE TRUSS
PRATT TRUSS
WARREN TRUSS
FINK TRUSS
BALTIMORE TRUSS
BOWSTRING TRUSS

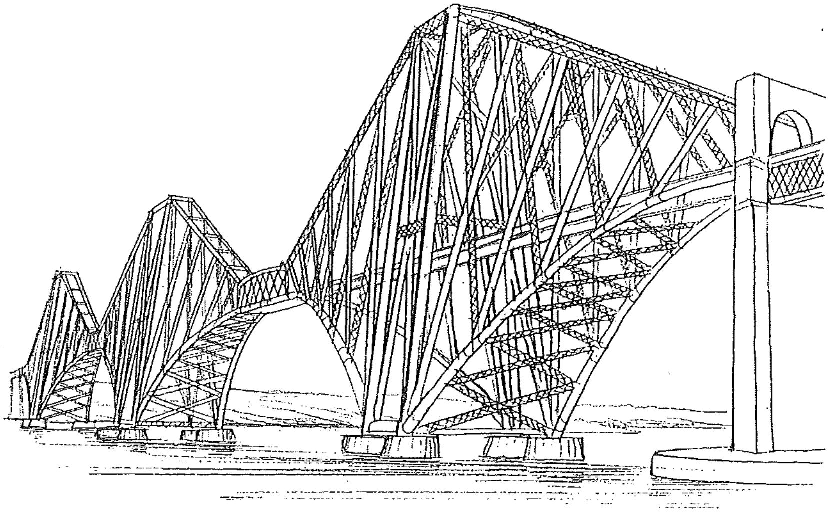
9.11 PATENTED STEEL TRUSSES

These clearances reached hundreds of feet under some of our important bridges, and such rules are even today strictly enforced by the Corps of Engineers of the U.S. Army, who have jurisdiction over water traffic. This makes the erection of a bridge at times a very costly enterprise. One of the reasons for the variety of bridge types lies in the effort to beat this problem. To begin with, the roadway of an arch bridge can be located at the level of its supports or *abutments*, whenever these are high enough above the river. Two birds are killed with one stone in this case, since the roadway and the approaches to the bridge are cheaper and, moreover, the roadway acts as a tie between the arch ends, preventing their spreading out, and supplying the needed thrusts. When the bridge crosses a deep gorge, an "inverted arch" can be set under the roadway, really acting as a tensed cable, with the advantage of allowing the use of smaller bars, since no additional strength is required against buckling in compression.

If the roadway cannot be located in its lowest position, it may be built half-way up the arch or above it. In its lowest position the roadway hangs from the arch; in its highest it is supported on it by means of compressive struts; in the intermediate location it is partly hung and partly supported.

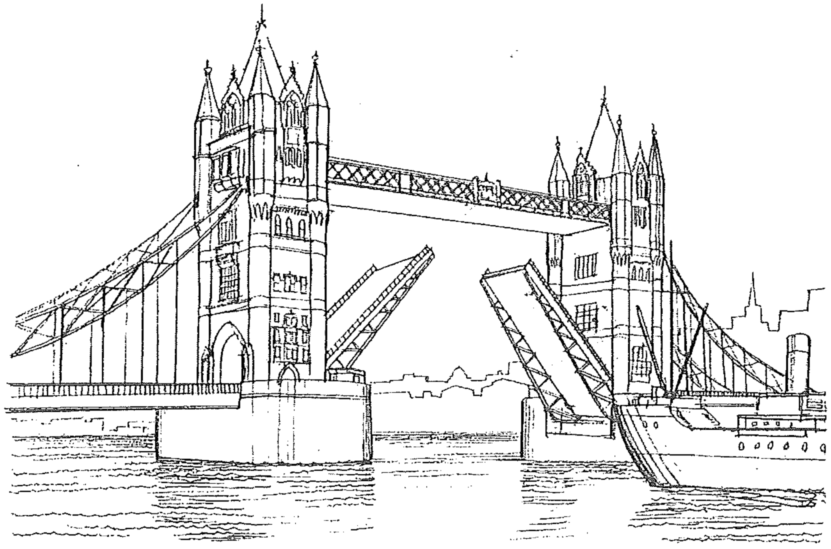


9.12 CONSTRUCTION OF EADS'S MISSISSIPPI BRIDGE



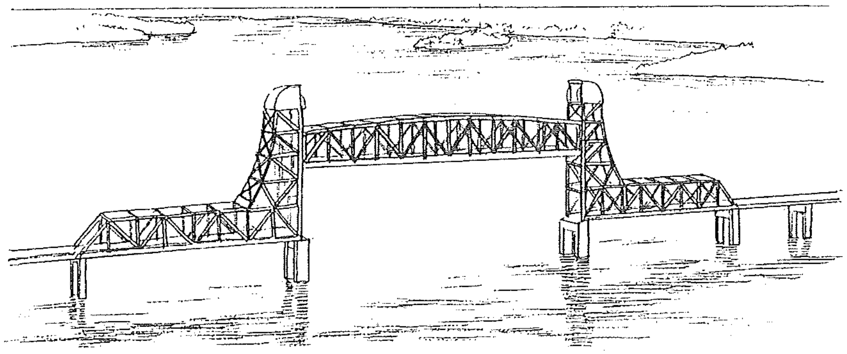
9.13 FIRTH OF FORTH BRIDGE

The next ingenious idea is aimed at allowing a free flow of river traffic during construction of the arch by eliminating its centering founded at the bottom of the river. It was Eads, the great bridge engineer of the second half of the nineteenth century, who first conceived of erecting the two halves of the arch as cantilevers by supporting them at their tips with cables from temporary towers until the two cantilevered halves met and were joined at midspan. The great three-arch steel bridge over the Mississippi was built by Eads by this daring new method in 1867 (Fig. 9.12). It was almost a natural step to build next cantilevered arches in which the temporary cables were replaced by permanent steel members, thus obtaining a bridge supported both by its upper members acting as cables and its lower members acting as arches. One of the greatest bridges ever built, the Firth of Forth Bridge in Scotland with a span of 1700 feet, cantilevers its three sections from three piers but has in addition two truss bridges end-supported on the tips of the cantilevers (Fig. 9.13). Although erected in 1890, it remains the second longest bridge of its kind in the world and was overtaken by the Quebec Bridge only in 1917.



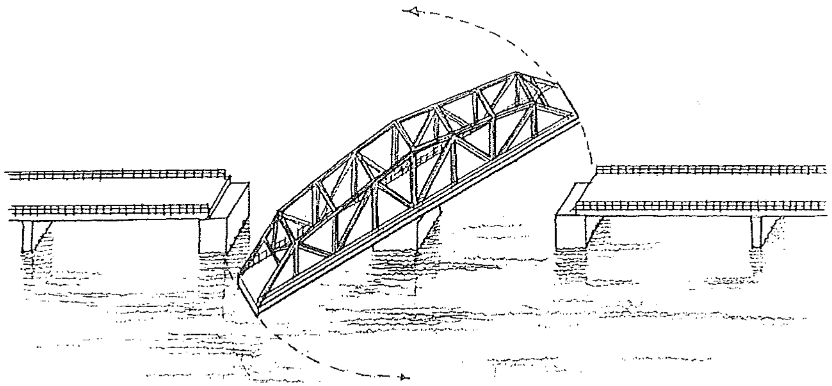
9.14 BASCULE BRIDGE

The last expedient to free the navigable channel from impediments during the arch (or truss) construction consists in building the arch on its centering away from the site, then floating both centering and arch to the site, and finally rapidly connecting the arch to its abutments. This procedure is also most efficient when the waters under the bridge are subject to short, violent floods or storms. The greatest of French concrete engineers, Freyssinet, used this method to erect the monumental Plougastel Bridge in northern France in 1920, lifting the heavy arch from the centering by means of hydraulic jacks.



9.15 LIFT BRIDGE

To get a low bridge out of the way when river traffic must go through, a variety of movable bridges has been invented. In one type the center span consists of two trusses, each pivoted at one end and capable of rotating upward when a boat needs to go by. It is called a *bascule bridge* (Fig. 9.14). Or the center span may be lifted between two end-towers, as in so many bridges in the New Jersey industrial area and the large bridge over the Harlem River in New York, the first link of the Triborough Bridge system (Fig. 9.15). Or finally the entire center span of a bridge may be made to rotate horizontally on a central pier, as in some of the bridges crossing the Harlem River, thus clearing two separate channels on the sides of the pier (Fig. 9.16).



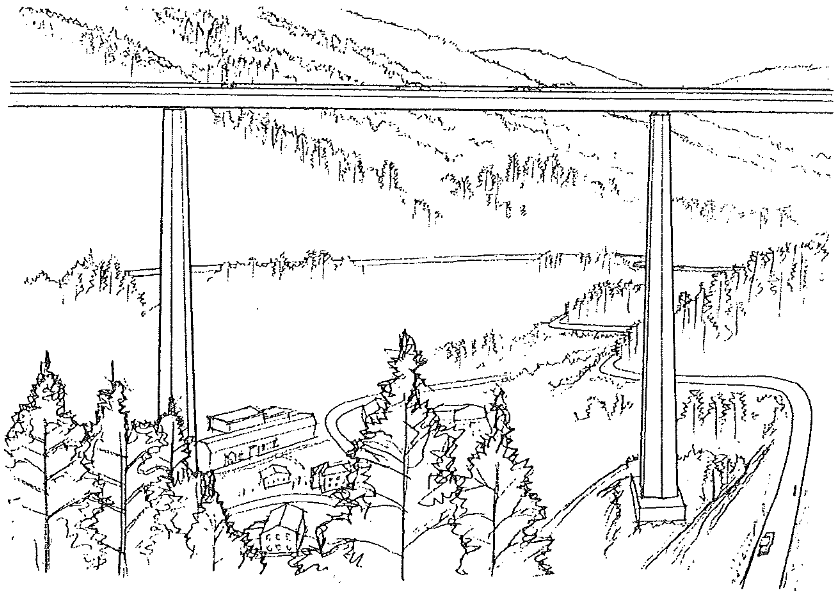
9.16 SWING BRIDGE

Concrete Bridges

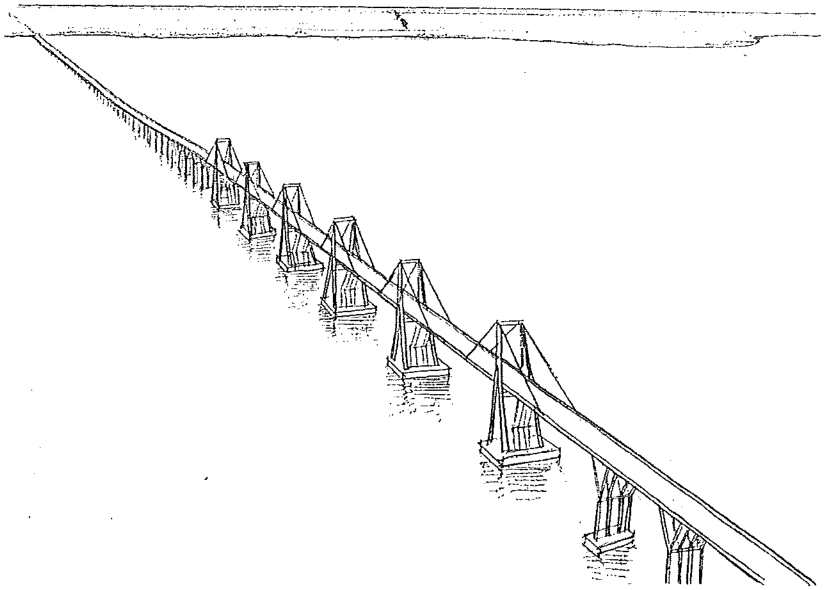
Some if not all of the bridge concepts born under the impact of the railroads and executed in steel have been extended to concrete. The trestle, built of wood at first and then of steel, has acquired a new elegant expression in the long viaducts built in Europe. These consist of hollow piers of reinforced concrete, at times 200 to 300 feet high, over which runs a roadway of hollow reinforced or prestressed concrete pipes of rectangular shape which are prefabricated on the river banks and slid into position. In the latest application of this principle the roadway pipes are extruded continuously, like spaghetti from a pasta maker, from both ends of the bridge until they meet at midspan. The simplicity, slenderness, and pure geometric shape of these viaducts make them works of beauty (Fig. 9.17), showing that high technology does not have to sacrifice aesthetics to economy.

One of the longest bridges in the world, over five miles long—the Maracaibo Bridge in Venezuela (Fig. 9.18) designed by Riccardo Morandi—is built in concrete with a complex sequence of twenty end-supported spans of 120 feet, followed by seventy-seven spans of 150 feet (cantilevered from trestles and supporting shorter spans on their tips), and by five 780-foot cantilevered spans supported by cables at their ends, which in turn support short spans on their tips on the same principle as the Firth of Forth Bridge. The construction of this monumental work took only forty months, and its roadway has a clearance of 150 feet over the navigable channel.

Longer bridge and tunnel systems are used to cross wide stretches of water, like the Chesapeake Bay Bridge, consisting of twelve miles of concrete trestles and including a two-mile long tunnel. But the longest bridges in the world are those that do not have to contend with water traffic and can be laid right on the water. These *floating bridges* consist of reinforced concrete hollow barges or *pontoons* anchored to the bottom of the water by draping steel cables (Fig. 9.19) and connected to each other by elastic joints that allow them to move slightly with respect to each other in case of violent storms. If water traffic is necessary, one of the pontoons rotates on a vertical pivot at one end and opens up a gate while floating in the water. The Hood Canal Pontoon Bridge in the estuary of Puget Sound is 6,250 feet long.

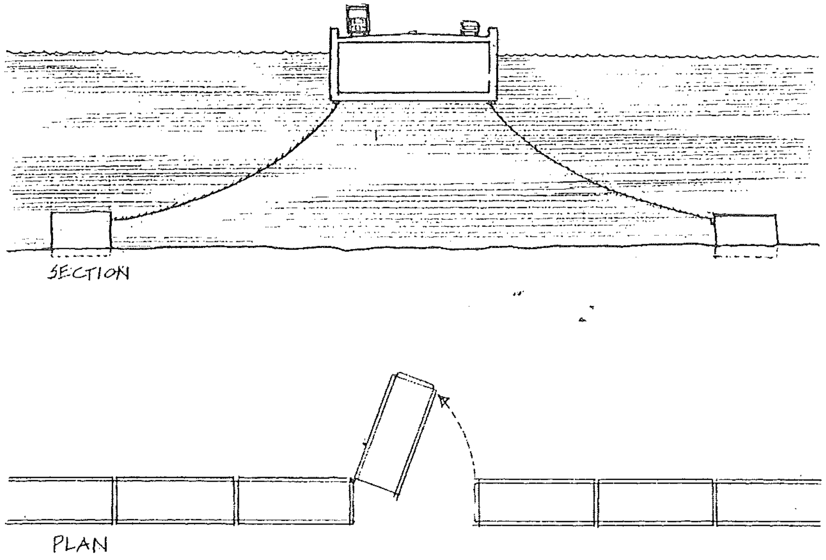


9.17 CONCRETE VIADUCT



9.18 MARACAIBO BRIDGE IN VENEZUELA

If the magnificence of modern bridges cannot be appreciated from a fast moving automobile, there are few experiences to equal crossing a large bridge on foot. The half-mile walk over the red Golden Gate Bridge in San Francisco, suspended over the blue waters of the Pacific and profiled against the cloud-dotted sky, the short promenade over the middle deck of the Brooklyn Bridge against the background of the New York skyline, the leisurely bicycle ride over the George Washington Bridge with the view of Manhattan from the high-rises of the Columbia Medical Center to the towers of the World Trade Center, are as exciting as the passage along the heavy cantilevered trusses of the Queensborough Bridge or that on the Williamsburg Bridge reached through the cavernous stairs in its towers. And what is more exhilarating than to cross the suspension bridge over the Tagus River in Lisbon, surrounded by a landscape of incredible beauty and the memory of Columbus sailing for the Indies, or to walk the Bosphorus Bridge connecting Europe to Asia? Human enjoyment rests on physical contact with reality. Bridges can best be



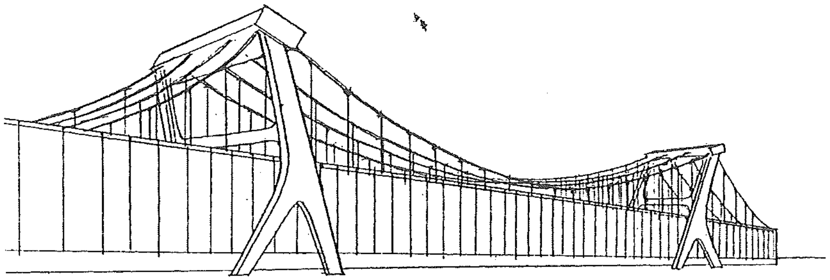
9.19 FLOATING PONTOON BRIDGE

understood and appreciated as expressions of the human spirit and works of subtle beauty when crossed on foot. Humanly useful technology can, in fact must, go hand in hand with beauty. The hideousness of some of our surroundings is not inherent in the development of our technical culture.

Space Frames

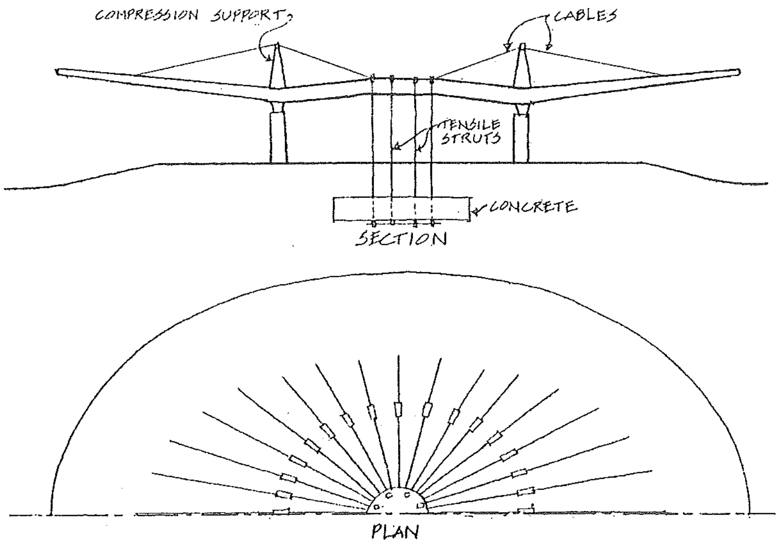
A large horizontal roof over a rectangular area, unimpeded by intermediate columns, is but a bridge in two dimensions, which can be crossed from any of the walls supporting it to its opposite wall. Some of the bridge systems in steel and concrete have, therefore, been adapted to fill the roofing needs of our large convention and exhibition halls.

The inventiveness of Pier Luigi Nervi suggested the use of a suspension bridge for the roofing of a paper plant in Mantua, Italy, which demanded a clear span of 830 feet with a width of 100 feet. The roof towers were inclined backwards to resist the thrusts of the cables and were propped by shorter concrete struts so as to look like gigantic Greek letters lambda, while the roof surface was the "deck" of the suspension bridge (Fig. 9.20). In collaboration with the steel engineer Covre, Nervi thus produced one of the longest roofs in the world with great economy and, as usual in his work, pleasing aesthetic results.



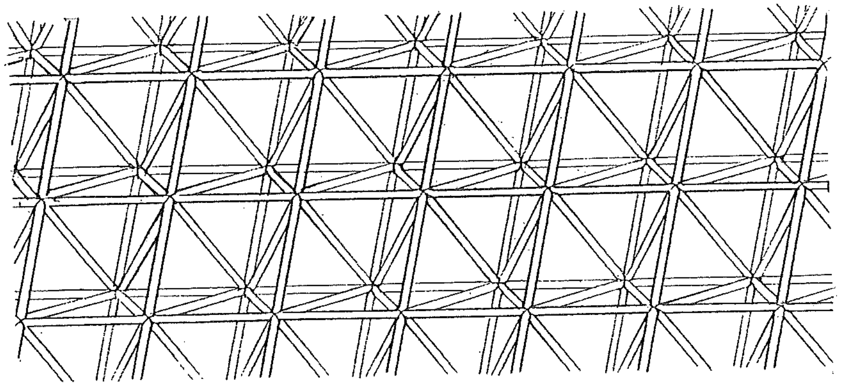
9.20 BORGO PAPER PLANT IN MANTUA, ITALY

The same principle of the suspension bridge, but in a cantilevered form using essentially one-half of a bridge, has been used in airplane hangar roofs, which require one entire openable wall to allow the entrance and exit of the planes. Such cantilevered roofs can be seen in some of the hangars at the J.F. Kennedy Airport in New York and in other airports around the world. At JFK a cantilevered cable-supported roof has been arranged in an elliptical pattern for the Pan Am terminal with cantilevers of 150 feet (Fig. 9.21).



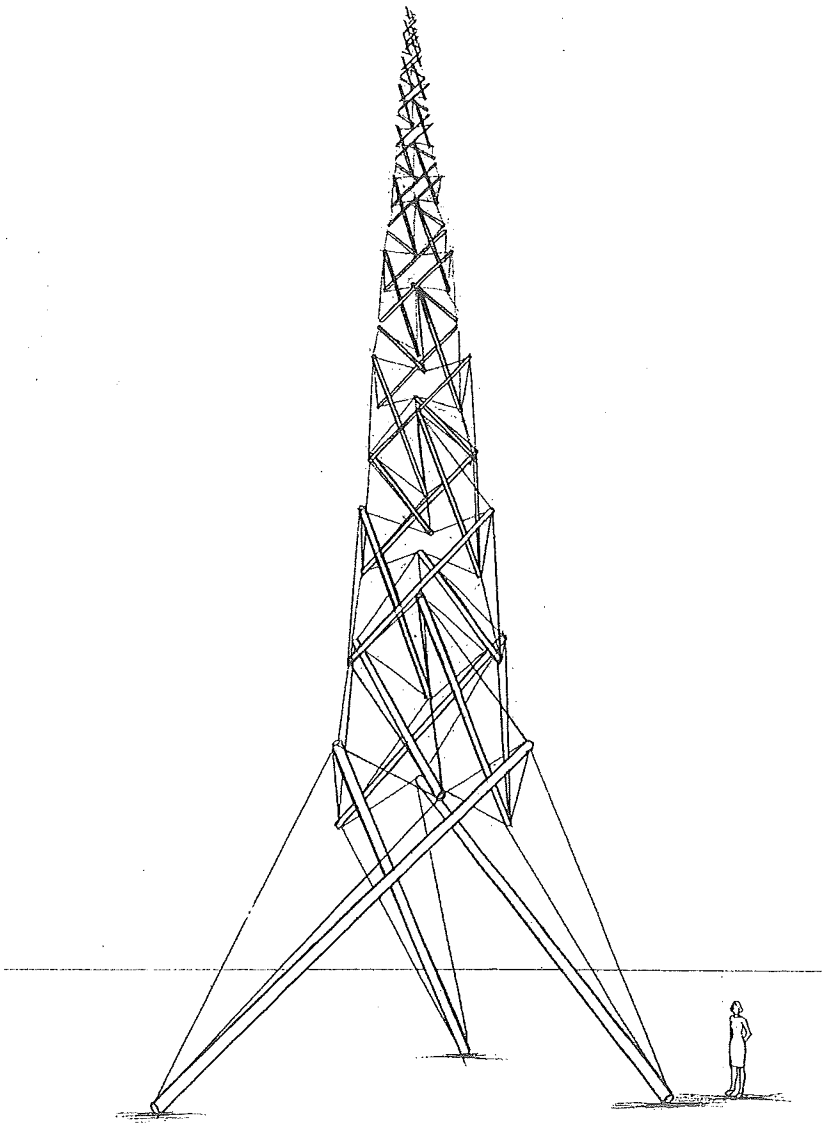
9.21 THE PAN AM TERMINAL AT JFK AIRPORT IN NEW YORK CITY

For more nearly square areas, like those of convention and exhibition halls, it would seem logical to support the roof surface on a rectangular grid of vertical trusses which can be built of bars of few different sizes. Such systems would be practical but for two reasons: the cost of the joints formed by the trusses meeting at right angles and, more importantly, the fact that the system consists of rectangles, and rectangles are not inherently stiff. One of the great minds in the field of American invention, Alexander Graham Bell, was the first to realize that if such a roof could be triangulated in space, it would acquire a much greater stiffness in all directions and hence could be made lighter. Thus the modern *space frame* sprang from the mind of an electrical engineer and gave rise to a whole family of roofs having the enormous advantage of modular construction, easy assemblage, economy, and visual impact. These roofs consist essentially of a number of pyramids, some with bases up and others down, creating two parallel horizontal grids of bars interconnected by zigzagging bars in at least three directions (Fig. 9.22). One obstacle postponed their adoption: the mathematical calculations required by their design are so time-consuming that they did not become practical until the advent of the electronic computer. Thus one field of engineering had to rely on another before a new conception could become reality.



9.22 SPACE FRAME

The space frame is today one of the most economical structures for covering large areas. The largest was erected in Brazil, where the translucent plastic roof of the exhibition hall at Anhembi Park in São Paulo is supported by an aluminum space frame covering an area 853 feet square, subdivided by tubular tripod supports into squares 197 feet on each side. Such is the visual appeal of the zigzagging bars of a space frame



9.23 TENSEGRITY SCULPTURE BY KENNETH SNELSON that they were used (by I.M. Pei) in the roofing of the magnificent main hall of the new wing of the National Gallery in Washington as well as in the roofing of the immense Air and Space Museum in the same city. And just for the sake of their appearance, vertical space frames have been used as transparent walls on entire sides of large buildings or as roofs over interior courtyards. The structure of both the walls and the roof of the new Convention Hall in New York City, occupying an area of two by five city blocks, consists of a single space frame covered with reflecting glass.

It is hard to put into words the many reasons for the visual appeal of space frames: their lightness, their transparency, and their geometry, which seems to vary dramatically with a change in vantage point, certainly contribute to it. But their aesthetic content is so high that Kenneth Snelson has become famous the world over for his beautiful Tensegrity sculptures, which are nothing but space-frame towers and girders floating in space. Tensegrity, invented and patented by Snelson, has added a new component to the elegance and airiness of the space frame. Since its bars work either in compression or in tension, Snelson uses aluminum or steel pipes as compressed members and connects them with a continuous steel cable that constitutes the tension bars. He does this in such a way that no two pipes touch each other (Fig. 9.23). Thus, no continuous compression path can be discovered in the structure of his sculptures, and the compressed pipes seem to float independently in space.

Down-to-earth engineers of the nineteenth century invented the humble truss for purely utilitarian purposes; now it has become an expression of art. This may be a lesson to the detractors of technology, who emphasize its negative aspects and ignore the many faceted meanings of so many of its fruits.

10 The Brooklyn Bridge

The Creator of the Bridge

On May 24, 1883, the mayors of Brooklyn and New York, Low and Edson, Governor Cleveland of New York and President Chester Arthur, followed by a throng of thousands, inaugurated the Brooklyn Bridge (Fig. 10.1). The engineer in charge of its construction, Washington Roebling, was not there. Paralyzed from the waist down by the "bends" he suffered while working in the underwater caissons for the towers' foundations, he watched through binoculars from his house on the Brooklyn shore. What he saw was a masterpiece conceived by John Roebling, his father, thirty-six years earlier and built by the son over a period of fourteen years.

The Brooklyn Bridge was a reality and a symbol: the longest suspension bridge in the world with a main span of 1595.5 feet, a monument to the persistance of two men and a woman, the two Roeblings and Emily Warren, Washington's wife. It is, perhaps, the most beautiful bridge in the world. There is no view more exciting than that of the Manhattan skyline at sunset seen through the network of inclined stays, vertical suspenders, and curved cables of the bridge. It made Greater New York a possibility by uniting its two most populous boroughs. It was conceived so wisely that, notwithstanding the unexpected increase in traffic, it needed strengthening only by the addition of light trusses, seventy long years after its construction. Designated a landmark in 1964, it carries a