AN ABRIDGED ACCOUNT OF THE HISTORY, STRUCTURE AND SAFETY OF BRIDGES

Presented to

The Athenaeum Society

Hopkinsville, Kentucky

By

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January 7, 1999

An Abridged Account of the History, Structure and Safety of Bridges

This paper is a result of an inordinate curiosity about bridges. Almost every day we unquestioningly trust our lives to the strength of these spans. I, for one, feel safer on a massive steel bridge constructed with numerous triangular braces above, or below, the roadway, and find comfort and assurance in the huge steel cables of suspension bridges holding up their dangling roadways, e. g, the Brooklyn Bridge or the Golden Gate Bridge.

It is somehow far more difficult for me to accept as equally safe the support of a stone arch bridge, or of one of those slim bridges supported by extremely long and narrow beams of prestressed concrete. What keeps an arch bridge from falling, anyway? And doesn't concrete break easily? How can a concrete beam span hundreds of feet, considering the weight of- and the brittle nature of- concrete, and not only support itself but support as well lumbering trucks and heavy swaying trains?

Before addressing these problems, let us first, in our time honored Athenaeum fashion, quickly review the history of bridges. Joseph Gies, author of "Bridges and Men," makes this statement about bridges: "The oldest engineering work devised by man, it is the only one universally employed by him in his pre-civilized state."

The earliest known bridges were constructed in post and lintel style and made of stone. They were and are called "Clapper" Bridges, and fit in the first category of bridges, or "span" bridges. The other two categories are "arch" and "suspension" bridges. Both of these, in any advanced form, postdate the "span" bridges.

The "span" bridge of stone was satisfactory for short distances between pillars, and served only for narrow streams.

It is estimated from archaeological findings that about 5000 B. C. the "arch" concept was first discovered and used in brick and stone construction. This took place at one end of the "Cradle of Civilization" or "Fertile Crescent" near the mouths of the Tigris and Euphrates rivers. This culture first used sun dried bricks, later fired bricks. Window and door openings required closings to be made above them. Lintels could be used, of stone, or bricks could be extended outward from the lower walls one-half brick at a time, and, finally, meeting above the opening. This mason's device is known as "corbelling." It was then discovered by some unknown inventive genius that an arch solved the problem far more satisfactorily, and with the arch in hand civilization lurched ahead. Arches were first constructed with regular rectangular bricks or stones, but by 4,000 B. C. these were discarded in favor of the "voussoir" or wedge shaped members. These were tremendous discoveries, for with them organic architecture was born. With the arch practicality and beauty were wedded. Barrel vaults, spectacular domes and rose windows were to be logical extensions of these discoveries. The soaring beauty and majesty of temples and cathedrals became possible with this new device of the masons. But as simple as the concept was, the arch was still unknown in the new world when the European explorers arrived.

In the flow of history myth and fact often are blended, as in one supposed historical account, dating according to the author somewhat before 2,100 B. C., and, he states, about 100 years after the Flood. Nimrod, the third ruler following Noah, a member of the new Semitic culture then dominating all of Mesopotamia, had a bridge constructed to connect two palaces on opposite sides of the Euphrates. The bridge is described as having a single brick arch spanning 660 feet, and being 30 feet wide. Such an arch span is, we know, quite impossible, thus there were, no doubt, many arches. The distance is assumed correct, however, as Herodotus later gave a description of the oldest timber bridge on record, one built at Babylon to span the Euphrates between the royal palaces. This bridge had one hundred stone piers erected in the deep water. Above, the roadway was constructed of Cedar, Cypress and Palm beams. The length is again given as 660 feet, the width as 35 feet. In case of a threat of invasion, the bridge floor could be removed at night.

The first Roman bridge of which there remains any record was made of wood. It was named the "Pons Sublicus" (translated - Bridge of Piles) erected across the Tiber in 621 B. C. In the ceremony of dedication a number of virgins were hurled off the bridge and drowned, thereby appeasing all of the river gods. The chief priest in charge of building the bridge bore the title of Pontifex Maximus. This now well known title later was adopted by the Roman emperors and, ultimately, in Christian times, became a title for the Pope. While it now seems incredible, this bridge of piles was continually kept repaired by the chief priests and lasted 900 years.

The Romans made full use of the arch in their bridges and viaducts, creating lasting structures of stone, some now 2000 or more years old and still in use. They employed only one configuration, the semicircle, and cut their stone so carefully that no mortar was needed. With sturdy stone bridges the Via Appia could be continuous; ferries and fordings were unnecessary. Travel then was much like today's- bridges were accepted simply as a continuing part of the road.

Among the beautiful and notable surviving Roman structures is the great aqueduct at Nimes, build by the order of Agrippa, son-in-law of Augustus Caesar, in 19 B. C. Towering 155 feet above the valley, and 885 feet long, it still is functional, according to one account, taking mountain water down its gently sloping trough to the inhabitants below. It is a beautiful structure, consisting of a series of arches stacked on arches, three high. Some of the stones used weighed many tons. Getting them lifted so high, then placed so perfectly, commands our respect for those Roman engineers even today.

We tend to forget that the Roman empire spread over so many countries.

Spain was one, and there is found another marvel of Roman bridge engineering, the Puenta Alcantara, built in A. D. 105, over the Tagus River. This bridge is 170 feet high, assembled without mortar, and its stone arches have a 98 foot span. Stones in it weigh as much as 8 tons each. Upon completing it the builder, Caius Julius Lacer, made a statement: “Pontem perpetui mansuram in saecula mundi” (I have built a bridge that will last for eternity.) So far, he is right. The bridge is still there, even though the French, during the Peninsular War, took out one arch by heavy bombardment. The arch was replaced, but the engineers found that they were unable to rebuild it to match the original. Seventeen centuries later, they simply couldn’t put it together without using mortar.

Typically, one-half the cost of a bridge lies in constructing its foundations. The Romans made use of a device first discovered by the lake dwellers of Switzerland, who built houses of timber on platforms of timber over the lake. To support the platforms they developed a method for driving piles into the lake bed, and the timber pile and trestle bridge, as well as the pile driven method for constructing caissons, derived from their discoveries. These same lake dwellers first used trusses as roof supports, a basic tool later adapted to bridge spans. These Romans were indeed among the first great engineers of civilization. They learned to treat wood with preservatives, built with stone, brick, tile and even discovered natural cement, which they seldom used because they were so proficient in shaping stone that they had little need for it. One exception was in the construction of the dome of the Pantheon, which took place during Hadrian's rule. To shape this magnificent dome, the builders poured 5,000 tons of concrete over wooden forms. The Pantheon still stands, and causes us to marvel at the advanced ability of architects, engineers and builders of that age, who made full use of pulleys, levers and capstans in their machines.

While the great Roman empire later crumbled, the old engineering skills were preserved by some all-but-forgotten religious orders of the church, who taught their monks carpentry, masonry and plastering. There was even innovation in the ranks. As one example a shepherd boy, later turned cleric, interrupted the bishop's sermon one morning at Avignon, telling him with absolute conviction that God had chosen him to build a bridge across the Rhone. The very passion of the statement convinced the bishop, who commissioned him to build it, and this was done in the years 1178-1188. The result was a beautiful arch bridge of stone, but the design departed from the former semicircle by flattening the arch, employing three radii, and as a result of his amazing skill and great success, the former shepherd boy was named a saint, with the name Saint Benezet.

At about the same time Peter of Colechurch, in England, had his own dream or vision of a stone bridge to span the Thames at London. The money for this bridge, which was to be called London bridge, was raised through popular subscription, and building began in the year 1176. 33 years later, four years after the death of Peter of Colechurch, the bridge was completed. It was to stand there for more than 600 years, and without question made London the remarkable city that it is today. This was by virtue of its being a "Nodal" bridge, i. e., one which so effectively blocked any heavy seagoing traffic from traveling upriver that London, as a result, became a center of trade. Merchants were drawn there along with great warehouses, a network of roads and, later, railroads, all spreading from London as from a hub.

The constant flow of water in the Thames made the construction of piers not only difficult but extremely hazardous, thus accounting for the extended time for construction and claiming more than 200 lives of its workers, mostly from drowning.

Just like some of its sister bridges in Italy, London bridge was a social center. Shops and houses bordered it. It was a high rent area, affording excellent sewage disposal. The raw justice of the crown was frequently on display, with thieves suspended on hooks, and severed heads as ornaments.

Henry VIII, in the process of disassociating himself and his kingdom from papal interference, created a spectacle when the Pope sent John Fisher, Bishop of Rochester, a cardinal's hat. Enraged, Henry declared "Mother of God, he shall wear it on his shoulders for I will leave him never a head to put it on!" The head of Cardinal Fisher was subsequently removed and parboiled before being hung on a hook over the tower gate of London bridge. For some reason it did not decay readily, just kept on shining or glowing in the sunlight and attracting great hordes of the faithful. This was insufferable, so the order was given to the executioner to pitch it into the river by night. Shortly thereafter it was replaced by the head of Sir Thomas More.

Venice is the home of a remarkable bridge built by Antonio da Ponte back in 1588. This now famous Rialto bridge had to be constructed over a rather soupy or water logged landscape, and there was much concern that any structure would have an extremely short life. Ponte solved his problem by driving piles, 6000 birch and alder trees to serve as a solid base for each abutment. Now, more than 400 years later, the bridge remains standing and is still being used.

Present day bridge builders have the advantage of new materials and, while still confined to the three main types of construction, i. e., the span, arch and suspension bridges, and their combinations, have designed and built some exceptionally beautiful and awesomely functional bridges.

While metal had been used in early times, its use had been, for iron, the binding together of stone, dowel fashion, with the iron sometimes welded together with lead. Not until 1779 was the first all iron bridge constructed. It was of cast iron, an arch structure spanning the Severn River, 100 feet in length, designed and built by Abraham Darby. This pioneer of iron bridges has been well maintained, and still stands.

Iron as a building material for bridges really began to realize its potential with Thomas Telford, a Scotsman. Telford built, in 1814, a handsome cast iron arch bridge, 152 feet long. This was the Craigellachie Bridge across the River Spey at Elgin, Scotland. It was innovative, engineered to take advantages of the superior qualities of iron in its design, as compared to slavishly imitating the older carpentry and masonry concepts and practices in arch building.

Telford followed with a breathtakingly beautiful suspension bridge in Wales, completed in 1826 across the Menai Straits, spanning an open space of 570 feet, something not dreamed of before his time. In the building of this bridge, Telford left nothing to chance. The wrought iron was rigorously tested up to a fracture point of 90 tons, although the load was only 35 tons. The iron bars which, linked together, made up the supporting cables, were cleaned, heated, and bathed carefully in linseed oil before assembly, then painted with oil based paint. Lewis Carroll, a contemporary, found Telford's meticulous approach to be amusing, and wrote in Alice in Wonderland, "I heard him then, for I had just/ completed my design/ To keep the Menai Bridge from rust/ By boiling it in wine."

Telford's suspension bridge, with its massive stone towers and shallow catenary of its linked cables was to influence suspension bridge design through the next centuries, with new soaring bridges of ever-increasing spans; among many others the Brooklyn Bridge clear span 1,595 feet, the Golden Gate Bridge, 4,200 feet, and, finally, there was to be completed this year by the Japanese their $7.6 billion Akashi Kaikyo Bridge, linking the islands of Honshu and Shikoku with a suspended center section measuring a staggering 6,526 feet, just shy of a mile and a quarter. The Romans would have loved seeing all of this. They enjoyed doing such spectacular and near-impossible things themselves, and pushed the limits with the materials they had available.

Wrought iron and steel certainly changed bridge engineering, but another material discovered but little used by the Romans, concrete, recently has had wide-ranging applications. Something I did not know, and had not thought about, came to my attention during a discussion with two of my friends who happened to be retired architects. Prestressed concrete supports are not straight, they informed me. These girders are themselves arches, however slight the curvature, thus satisfying the old configuration which supports both itself and its load. Referred to by the architects as concrete/ post-tensioned, these concrete girders are constructed with longitudinal perforations extending the entire length of the member, through which steel wires are fed and attached to plates at either end or face of the girders. When the assembly is complete each individual wire is tensioned to a predetermined level and firmly attached to the plates.

Earlier, mention was made of the three categories of bridges; span, arch and suspension. The remarkable fact is that this carefully engineered prestressed concrete girder answers to all three of these categories, when we think about it: it is certainly a span; without question it is an arch, and its tightened wires act to suspend what might otherwise be a somewhat brittle or crumbly material, thus it contains the elements of a suspension bridge.

Note, the next time you drive across a slender concrete bridge, that you are traveling in a curved path, although it is slight—nothing like the old Roman semicircle. Elapsed years and new materials have successively flattened the arch, but if you want to know what keeps you from falling in the murky water below, it is still an arch.

Speaking of falling bridges, Thornton Wilder, in his novel "The Bridge of San Luis Rey," tells of the fall of an old and flimsy rope suspension bridge in South America, with emphasis on the ones who perished in the accident and just why they were the ones fated to die at that particular time and place. This made for an interesting novel, but what about some of the greater disasters, such as the collapse of the Tay Bridge in the nineteenth century? A passenger train, the Edinburgh Mail, carrying seventy-five passengers across the Tay Bridge at Dundee, Scotland, traveled to mid-bridge and then, suddenly, in a violent storm, both the bridge and the train were gone. No books were written about that. The reason for collapse were subsequently apparent: inquiries determined that substandard materials were used. Additionally, the designers had greatly underestimated the wind forces which would be exerted on the structure.

Not only passengers have lost their lives to bridges. It is estimated that, for every 10 million dollars spent in building bridges, one worker loses his life to an accident. Some construction deaths, by their very numbers, have been overwhelming.

The most common cause for bridge disaster has been poor design. As the need for longer and longer spans confronted the builders, design error claimed its total in human lives. In 1907 the massive Quebec cantilever bridge collapsed before its completion, and dropped to the bottom of the St. Lawrence River together with seventy-four workers. All of them died. The reason? The design was too weak: trusses already set were tearing at their fastenings, but these impending failures were ignored.

To appreciate bridges they must be seen. There is something about viewing bridges that brings back ones early sense of pleasure experienced in building with tinker toys, or, for members of more recent vintage, Lego blocks, perhaps. We sense or feel the beauty and the wonder of something immense, thought-provoking, exciting, something to marvel about and enjoy in our own special civilized way. For that reason I brought these few pictures of bridges both ancient and modern, in the hope that it might stimulate your own interest in, and curiosity about, bridges.

Frankly, even after reading and hearing about the reasons for strength and safety of stone arches and prestressed concrete bridges, I still retain some measure of apprehension in crossing them. So, should you have something reassuring to tell me, I shall certainly welcome your comments.