HISTORY OF THE DEVELOPMENT OF BRIDGES

by
William A. Henderson
Member and Past President*

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Engineers have spent much time peering back into the pages of the past and trying to determine just what the first bridges looked like. Such speculation can of course never lead to any tangible conclusion. But it is self-evident that from the earliest times the choice of structure type has been limited basically by the types of construction material available. The development of new bridge forms has proceeded hand in hand with the development of better and stronger materials.

Since the first recorded structures were built of available natural materials that were weak in tension, it is not surprising that they were arch forms. The first arches date from as far back as 1500 B.C., were of brick and were found in Babylonia, Assyria, and Egypt. The ancient Hindus had a saying to the effect that "an arch never sleeps", implying thereby that the constant thrust of the arch produces settlements that could become troublesome. Indeed the Hindus scrupulously avoided the use of arches. The Egyptians, for the same reason, used them but little.

Fig. 1. Pont du Gard at Nismes, France

*Senior Vice President, Universal Engineering Corporation, Boston, Massachusetts

It remained for the Romans to develop the use of arches, which they used in the construction of aqueducts, viaducts, bridges and buildings. For these structures they made extensive use of stone, partly because it was in plentiful supply but also because of the development of better cutting tools than had previously been known. Many of the Roman bridges were naturally over rivers. Where the piers for these bridges were founded on rock or ledge the structures endured amazingly well. Where the piers were on compressible or otherwise unsuitable material, the Romans invariably overcame the difficulty by widening the piers to decrease the unit pressure under the foundation. Wide piers had one additional advantage and, paradoxically, a serious shortcoming: if by chance one span in a series were to collapse, the wide pier could resist the unbalanced thrust from the adjacent span without undue strain. On the other hand, many arch structures were destroyed by undermining because of the high stream velocity from over-constriction of the waterway.

No discussion of arch structures would be complete without mention of the aqueducts in the design and construction of which the Romans excelled. These were composed of up to three tiers of arches superimposed one on the other, with total heights of as much as 160 feet. Remains of the Martian aqueduct, built over 2100 years ago, may still be seen. The original structure contained almost 7000 individual arches in its 39 miles of length. It can be seen that the Romans were well advanced for their day in the science of engineering.

After the downfall of the Western Empire there were few bridges built until the twelfth century. At that time travel and trade were increasing and the rapid development of cities made better stream-crossing facilities necessary. In Spain many bridges were built by the Moors, who in a great many instances made military considerations the prime factor. This is shown by their use of fortified approaches and by the occasional placement of angle points in the decks for better defense against attack.

The basic type in all this construction was still the arch, which has until now remained in high favor wherever particularly graceful or attractive form is required.

In the twelfth century the Benedictine monks formed an association called "Brothers of the Bridge" which devoted itself not only to the building of stream crossings but also to the construction of adjacent houses for the benefit of the sundry travelers. It might be said facetiously that this marked the beginning of the modern motel system. The bridges, mostly arches, were very narrow, varying in width from six feet to seldom more than twenty, and the largest span was approximately 110 feet, although the greatest over-all length is said to have been 2200 feet. Since the monks themselves raised the funds for building the structures, their coffers were seldom overflowing and the materials used in the structures were of rather poor quality. It is therefore remarkable that a few arches of a stone bridge built in 1177 across the Rhine at Avignon remain to this day.

Bridge of St. Benezet Across the Rhone at Avignon (1177 - 1187)

Actually of all the bridges built in the twelfth century and for the ensuing three hundred years, practically all were cheaply constructed, rested on unduly thick piers, and consisted of arch spans with earth-filled spandrels. It is surprising that the bulky houses supported on some of the narrow bridges remained as stable as they did.

A notable structure, begun in 1176 and completed in 1209, was the old London Bridge over the Thames. It consisted of a drawbridge and nineteen pointed arch spans, with houses resting thereon. The piers were so wide that they reduced the overall available waterway width from 900 feet to 194 and it is recorded that the restriction caused a drop of about five feet in the stream at the bridge. After eighty years it was in such bad shape that auxiliary supports had to be built for the houses. In 1758 the houses were dismantled and new arches built, and early in the nineteenth century the whole structure was replaced at a cost of over 40,000 pounds, a fabulous sum for those days.

Bridge at Kreuznach, Germany. Note the houses and the constriction of the waterway by the wide piers.

It is interesting on occasion to forget for a moment the technical side of our story and to take a quick look at the human phase. We find that in 1846 a certain Jonathan Edwards was commissioned to design an arch bridge spanning 140 feet over the Taaf River in Wales. But Edwards accepted a contract under which he agreed to rebuild the structure at his own expense if it failed to stand for seven years. Unfortunately for him, an unduly severe freshet occurred after two and a half years and Edwards rebuilt the bridge in accordance with the terms of his contract. The second bridge failed during construction, but noting that the crown of the arch had moved upward to cause the collapse, Edwards made the indicated revisions in design and finally produced a lasting bridge. When, or even whether, Edwards ever received payment for his work is not recorded.

Another incident, if we may go back still farther in history, concerns a new bridge in Toledo, Spain, in 1390. When the arch spans were nearly completed on the erection falsework, the designer realized for some reason that the bridge would collapse when the centering was removed. Terrified, he rushed home and told all to his spouse. She rose nobly to the occasion and that night set fire to the falsework and ruined the arch. Her husband's second construction attempt was suc-

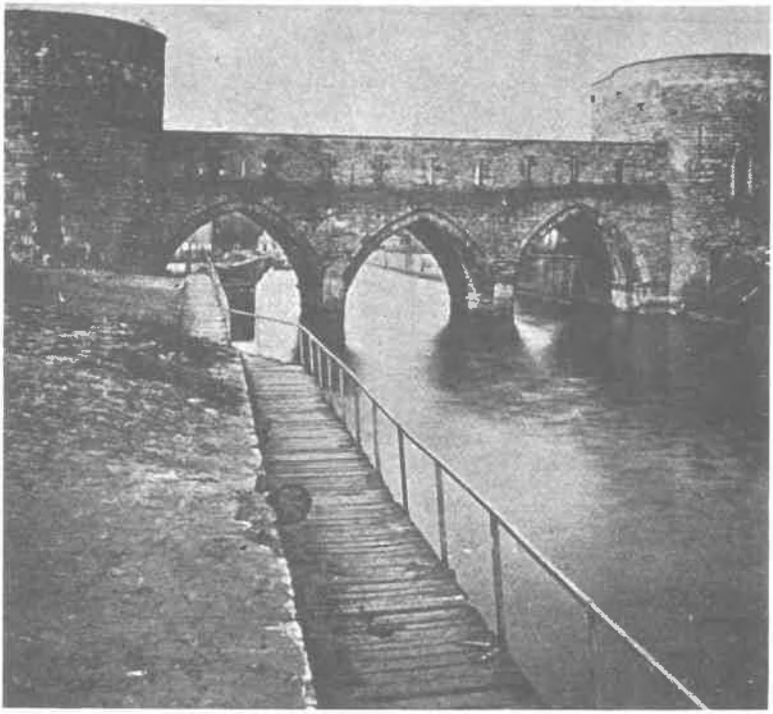

Fig. 4 Bridge at Tournai, Belgium. Note chapels at abutments.

cessful. But it is a known fact that on very rare occasions a wife cannot keep a secret, and the Archbishop under whose sponsorship the bridge had been built, heard the whole story. However, being a wise man, rather than reprimand the couple he congratulated the designer on having such a reliable spouse.

One of the earliest materials to be used was, of course, wood. Lumber was plentiful. One or two men with a saw and a pair of horses or oxen could snake out several logs a day, and the small local sawmill was very much a going industry. Wood was, in addition, easily worked and has been, until recently, comparatively cheap. It does have several disadvantages in that if untreated it rots readily when exposed to the weather, it is not particularly good in tension, and efficient end connections of tension members are not easily made. The development of treenails, or wooden pegs driven into pre-drilled holes in the members to be connected, went far toward the practical development of the wooden truss, and the covering of the trusses with shingled roof and sheathed sides practically eliminated the problem of rot. Indeed the wooden covered bridge became an inherent part of the early American countryside. Some were

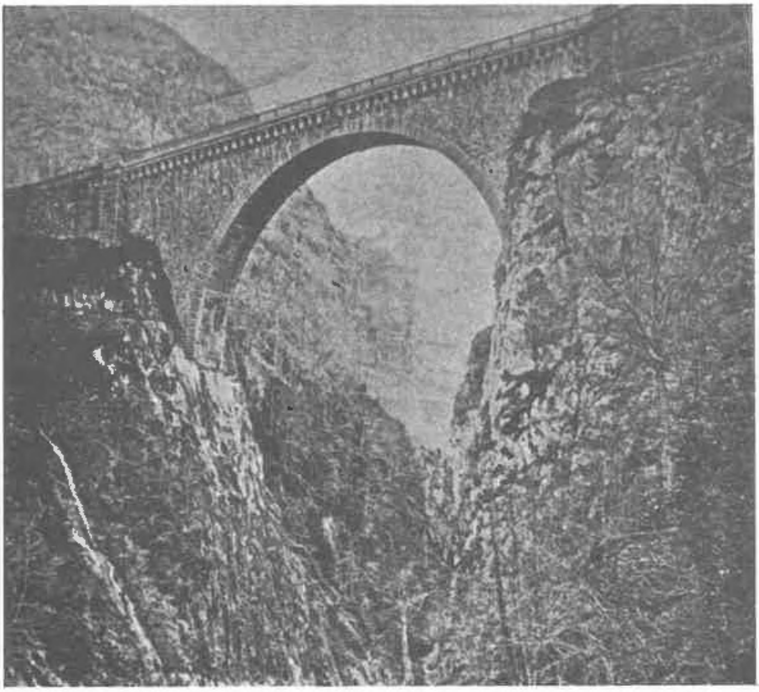

Fig. 5 Bridge of St. Sauveur in the French Alps

basically trusses, some were arches, and many were a combination of the two. While the exact distribution of load between arch and truss was never known, arch-truss combinations, known as Burr trusses, afforded a particularly stiff structure and lasted for many decades. Their obsolescence is the result of present day traffic requirements rather than their own decay, although during the last few years, partly due to the urging of the Society for the Preservation of Covered Bridges, the Commonwealth of Massachusetts has built such wooden covered bridges in Charlemont and Sheffield. But with increased standard for width and headroom, and with the virtual elimination of square crossings because of their inherently poor approach alignment, the modern bulky covered bridge is a far cry from the cozy little structure of nostalgic memory.

Wood structures are still used to some extent in the western part of this country and in such places as Alaska where the native timber is readily available. Preservation of the lumber is now obtained through creosoting or similar treatment, and the tension members, as in the past, are usually of metal.

The development of the manufacture of metals was of course a great boon to the evolution of bridges. Cast iron was first manufactured in the fifteenth century, though not in great quantity. Being crystalline in texture it is weak in tension and in resistance to shock and impact. The first bridge of cast iron was built in 1776 over the Severn River in England, consisted of an arch of 100 feet and was, at least until recently, still in use. Many other structures were built of the material, but the percentage of failures, especially of railroad bridges, was unduly high. The major use of cast iron later was for compression members or as bearing blocks at the joints of trusses.

Wrought iron, being superior in tension and in resistance to shock, superseded cast iron and was the most common metal in bridges from about 1850 to 1890, although the puddling process for making it had been introduced in 1780. It was rolled into many shapes and there are still hundreds of bridges of wrought iron in existence, especially on roads in the country where traffic is not excessively heavy. In the last decade of the nineteenth century the use of wrought iron was largely discontinued when steel was produced in quantity.

Although many truss bridges had been built before 1847, little had been understood about the theory of their design, and the proportioning of the members had been done through a combination of experience and a sense of the general fitness of things. But in that year Squire Whipple, an instrument maker in Utica, New York, and somewhat of a philosopher, produced two treatises outlining the theory of stresses in trusses and giving plans and details for wooden and iron bridges. Four years later, although it does not appear that he had ever seen Squire Whipple's essays, one Hermann Haupt in Germany published his work on the same subject, but in a much less complete form. The way was now open for rational and more precise methods of analysis of trusses and designers availed themselves of the opportunity to create larger and bolder structures.

After the establishment of a rational method of analysis for truss design, it was only natural that there should appear many new types of trusses. Some were very practical and were in use for many years, while others, being highly theoretical, were soon forgotten. The parabolic truss, in which the stress in the straight chord is constant under uniform loading, became one of the more common types. So also did the truss commonly known as the lenticular or fish-belly, which has parabolic chords both top and bottom. This truss was built extensively in New England during the last quarter of the nineteenth century and several excellent examples still are in use on back roads where loads are not too heavy.

On the other hand, it was only three years after the publication of

Squire Whipple's treatise that the Bollman truss appeared. From the bottom of each vertical were two diagonals, of which one extended to each abutment. The large number of long diagonals and the difficulty in making the connections rendered the type unpopular, and deservedly so. Only one example of the type still remains. Its main advantage, i.e., that the stress in the chord was constant, could more readily and simply be realized with a parabolic truss. The Pauli truss, with two parabolic chords, was arranged so that the maximum stress in each chord was constant throughout its length. The slight saving in material was more than offset by the additional cost of fabrication and erection. The Schwedler truss was proportioned in such a way that the curved chord (the other chord being straight) would carry just as much of the shear as to eliminate any reversal of the stress in the diagonals and therefore obviated the need for counters.

It can be seen that contrary to what might have been expected, the first types of truss devised after Squire Whipple's treatise was published were rather complex and unwieldy, and that simplicity was obtained only after further development had been made. During this period there was a great difference of opinion among bridge engineers as to the relative merits of pinned and riveted connections. European engineers favored riveted joints because they provided a much more rigid structure, while American engineers preferred the pin connections because secondary stresses, in theory at least, were eliminated and the pins permitted much easier and faster erection of the structure. Indeed a pin-connected bridge about 160 feet long has been erected in this country in what is probably the record time of eight and one half hours. Because of the development of high strength steels in recent years, trusses are less common than formerly, but when they are used riveted joints are almost universally chosen.

It is generally supposed that the suspension bridge is strictly a modern invention. It is surprising to find, then, that the first record of a structure of such type had to do with one in China in 1667. The first suspension bridge built in this country had a span of only 70 feet, having been built in 1796. Within the next fifteen years or so, some forty suspension structures were in existence, with a maximum span of 306 feet. Taking into consideration the limited knowledge of structural theory available at the time, it must be concluded that these structures were daring indeed.

One suspension bridge built by Theodore Burr at Schenectady in 1808 was unique since the curved suspension members were fabricated of wood. There were three of these members, each made up of eight 4 in. by 14 in. white pine planks bolted or spiked at the joints. Some twenty years later it was found necessary to build auxiliary pier supports under the center of the spans in order to arrest a rather serious sagging, but the structure remained serviceable until 1873, when it was completely replaced.

Only two years after the building of the Schenectady structure a chain suspension bridge with a span of 244 feet was erected across the Merrimack River three miles above Newburyport in Massachusetts. There were two separate roadways and therefore three chains. The individual links were made of forged iron two feet long and one inch in diameter. Each chain, as it went over the supporting towers, was spliced into three smaller chains. From time to time various links were replaced with others of odd sizes. One of the chains broke in 1827 and the structure was rebuilt and lasted until 1907. It was said, however, that the wrought iron in the original chains, unpainted for seventy years, was still in excellent condition.

In 1847 a pedestrian suspension bridge over 1000 feet long was built across the Ohio River at Wheeling, West Virginia. Some fourteen years later a violent windstorm caused it to turn turtle, and as a result there was instituted a study of aerodynamics, stiffening trusses and wind bracing. Further and more advanced study recently had to be made in this area after the failure of the Tacoma Narrows bridge.

Shortly after 1850 there was found to be a need for two unusually large structures. The first, at Niagara, was to carry two decks, with railway traffic on the lower level. The second, a bridge at Montreal, was to be more or less of the same size and for the same purpose. Engineering opinion was greatly divided as to the superiority of one proposed type over the other. John A. Roebling designed and built a suspension bridge for the Niagara site while Robert Stephenson, whose name was equally well known, proposed a tubular bridge at Montreal, with trains going through the tube. The two structures were radically different in concept, but their general histories were remarkably alike. Each lasted about forty-three years, each was succeeded by a heavier bridge to take care of increased traffic demands, and neither was replaced in kind.

One of the most notable of all suspension types is the Brooklyn Bridge, completed in 1883. The original structure was found to be slightly lacking in stiffness and auxiliary stays extending out from the towers were added at a later date. The Brooklyn Bridge marked the first use of galvanized drawn steel wire. During the next two decades or so, several other suspension spans were erected in or near New York. The earliest of these were supported on masonry towers that were strictly practical but of poor appearance. For the design of the Manhattan Bridge an eminent firm of architects was engaged, and for the first time slender and attractive steel suspension towers were evolved.

One of the most daring engineering feats of this century was the building of the George Washington Bridge since the length of its main span more than doubled that of any predecessor. Up until that time most of the suspension bridges had been built in the vicinity of New York, and for a rather good reason. The cost of such structures is tremendous and their use is justified only in heavily-populated centers where heavy traffic is almost continuous. Recently large suspension bridges have been built on the west coast, notably around San Francisco, but the record for span length rests with the Verrazano-Narrows bridge at the mouth of New York Harbor.

Fig. 6 Bridge over Bixby Creek in California. A slender and attractive concrete arch.

The intended life of a bridge should be measured in decades rather than in years, and since its life expectancy is so great, it should be pleasing to the eye as well as utilitarian. As we have seen, the first bridges were arches, a form conducive to attractive appearance. The early artisans took great pride in their work and generally spared no pains to produce a handsome structure. For that reason early structures that are still extant have a value to our civilization far more important than merely their roots in history. They are a part of and fit into the landscape itself.

With the coming of the steel age and the greater understanding of structural theory, ugly bridges, particularly truss and girder types, proliferated throughout the country. The rapidly spreading railroads were

Fig. 7 Modern Orthotropic Steel Bridge in British Columbia. Courtesy of United States Steel Corporation.

prime offenders in this respect since, being profit-making organizations, they insisted on building the least expensive types and the cheapest was seldom the most pleasing. Although many well-proportioned bridges have been recently built, it is an unfortunate fact that a bridge design, except the larger or monumental ones, is still selected far more for reasons of economy than for appearance. Many bridges constructed recently to standardized architectural concepts would appear to have been designed by the mile and cut off in the required lengths. Not only have we perpetuated unattractive bridges, but we have alienated many a young engineer because of the extreme monotony of designing continually the same structure type. It sometimes appear that in this country we alternate between extremes rather than follow the middle of the road, however the pendulum now would appear to be on the downswing. There seems to be dawning an awareness that we should re-assess the value of aesthetics in our structures and emphasize appearance at the risk of slight loss of economy.

And what of the future of bridges and bridge engineering? What new types will be evolved? What will be the general trends? Obviously the engineer would be most rash even to guess. But some things are known. Successive generations in history have reviewed all the events of their immediate past and have concluded that so rapid has been the advance of knowledge and the arts during their lifetime, surely the end must have been reached. Surely man had discovered everything there was to be learned. And yet the following generation has never failed to advance knowledge even at a far greater pace than has previously been thought possible. The development of bridges and bridge theory is an example. Whenever the engineer has had to stretch out into hitherto unexplored fields, he has been able, through theory and research, to develop new concepts and new standards to meet his specific requirements. Recent extensions and refinements of aerodynamic theory are a case in point, or when foundations had to be made in deep waters, the pneumatic caisson was evolved.

When the Brooklyn Bridge, with its main span of nearly 1600 feet, was completed over eighty years ago, it was rightly regarded as an engineering marvel. Yet such has been the ensuing increase in structural theory and knowledge that it is now dwarfed by the suspension bridge across the Narrows at the entrance to New York Harbor. There is now contemplated another such bridge in Japan with a main span of a little less than a mile.

With the continuing development of lighter and stronger materials and of research methods, this writer would hazard the guess that future development of bridge types will be limited only by the far horizons of the electronic computer and of that even more remarkable machine, the human mind.