MASONRY ARCHES.

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(Class of 1901).

The first masonry bridge was a slab of stone laid across an opening. From this developed an arrangement of stones so laid that the ones next above overlapped the stones upon which they rested, until finally the sides approached close enough together to be connected by a single slab. Such a structure is, however, not a true arch in the general acceptation of the term. An arch is any structure having reactions with horizontal components induced by vertical loads.

The first true arch consisted of two large stones leaned up against each other in the form of an inverted V. Such an arch with the two stones placed at the proper angle, and resting upon suitable abutments, is perfectly reliable and makes an effective method of spanning openings for some purposes. In some of the oldest stone structures we find the lintels of the doors protected by such arches. It is not uncommon in mountainous districts to find huge masses of rock, dislodged by some cause or other, lodged at the bottom of a ravine in such a manner as to form an arch; likewise at the entrance of a cave or underground passage. The arch manifests itself in nature in many places. Take the foundation out from under a part of a brick wall and some brick will fall down leaving a triangular or A shaped arch in the wall. The remaining brick above the opening are supported by this arch. In digging tunnels, it is often noticed that the dirt in falling from the top leaves an arched form to the roof. Indeed it is altogether probable that the arch roof was first copied from nature.

Arches of this type are maintained in equilibrium by the force of gravity, and the resistance of the material to shear and crushing. The first theories of the arch were based upon the principles of statics. As the masonry arches built by the Romans were in themselves very many times heavier than the heaviest moving load, this theory could not introduce considerable errors. But no such reasoning can with safety be applied to some of our modern arches. They have been made lighter, thus giving a more graceful and pleasing effect, yet their strength is quite sufficient.

Many attempts have been made to determine the real condition of the stresses in the arch ring, and numerous devices have been used to measure the various deflections of the arch when under different conditions of loading, yet there remains so much uncertainty as to the actual conditions of these forces that but few engineers will attempt the design and construction of the masonry arch on purely theoretical lines with a reasonable factor of safety. According to the elastic theory the deformations should be proportional to the loads applied until the elastic limit has been reached. The tests made by the Austrian Society of Engineers and Architects have verified this theory, for they showed that the deflections increased nearly in a direct proportion to the loads applied, thus showing that the stresses in the masonry arch may be studied by the aid of the law of elasticity. In nearly every case the cracks occured at the points under the greatest tension, and the arches finally failed at these points when loaded until rupture occurred.

When the arch is subjected to a vertical load, uniform horzontally, then there is but little uncertainty as to the stresses, but in practice we do not often meet such conditions and with moving loads that vary in their intensity and points of application resting upon an arch, the engineer finds the problem becoming more complicated.

By the study of a weighted cord suspended from two points the static forces that act in an arch similarly loaded, may be determined, with the exception that the parts in tension in the cord are in compression in the arch; however, the relations between the external and internal forces are analogous. This curve assumes the form of the equilibrium polygon applicable to the investigation of an arch of similar loading and equal span. But it is not the object of this paper to dwell upon the theory of the arch.

Arches may be divided into the following classes according to the shape of the arch ring: the semi-circular, the segmental, the elliptical and Gothic or pointed.

In the semi-circular arch the arch ring is a half circle. In the segmental arch the ring is less than a semi-circle. The semi-circular arch possesses the economic advantage of having a small horizontal thrust on the abutments for a given span and load which adapts it for many purposes, while the segmental arch is used in many places where the rise is limited, and resistance can be offered to the horizontal thrust. It is considered one of the most graceful and best suited forms for ornamental bridges and other structures.

The ring of the elliptical arch is of course flatter than the semi-circular and is largely used because of the grace and beauty of its outline. Very often instead of following the line of an ellipse this arch is, for convenience of construction, composed of segments of circles tangent to each other the shorter radii being at the ends. As many as three different radii are thus used, making what is known as a five center arch.

The Gothic or pointed arch is a two centered arch and consists of two equal segments of equal radius circles intersecting at the highest point of the ring. They have been chiefly used in the walls of buildings to span windows, doors, and like openings. They were probably first devised as an expedient to replace the circular arches in the old cathedrals in Europe which developed weaknesses due to the horizontal thrust.

Arches may again be divided into classes according to the materials of which they are built. There are the stone and brick arch—built of separate blocks,—the concrete or monolith arch, the steel arch, and the concrete–steel arch, this last being a combination of the two immediately preceding.

Probably the best stone out of which to construct an arch is granite, for it weathers better than almost any other kind and has a great resistance to crushing and is without seams. It also receives a very high polish but this must be done at great expense. The chief objections to this stone are its cost and the difficulty with which it is worked into shape. Marble makes a strong, beautiful and durable bridge. Lime stone has been used in a large proportion of the stone arches in some sections, while sandstone is extensively used in others. Nearly all of the great number of stone arches built by the Pennsylvania railroad have been constructed of sandstone, as is a part of the famous Cabin John arch.

In general it will be expedient to build stone arches only in places where an abundant supply of good building stone is at hand, otherwise the cost of the structure will be found to be very high; for it is the labor on, and the transportation of, the material that is the main item of cost.

The Romans built their arches either of stone or brick, or concrete faced with stone. Their concrete was made of Pozzuolano in which was often embedded large stones. While their concrete was poor, compared with ours of the present day, which is made with manufactured cement and crushed stone or gravel, yet the inferiority of their product was due to the materials with which they had to work, for their specifications for concrete were practically identical with ours of to-day. In order to protect their concrete they faced it with stone and the result is that their works have resisted the forces of nature for centuries.

The Pont du Gard bridge of France is a very old stone bridge with semi-circular arches. The Cloaca Maxima of Rome was built in 641 B. C., and is one of the oldest arches in existence. Surely steel and wooden bridges last but a moment as compared with such as these. The aqueduct of Bourgas is another notable stone structure built in the sixth century. It is 720 feet long and 109 feet high. The arches are of small span, being about 50 feet, and small openings were left in the piers for the purpose of saving material.

This aqueduct is a notable example of the Gothic or pointed arch.

There are some very beautiful stone arches in America. The most notable of these is the Cabin John stone arch which is the longest span of any masonry bridge in existence, it being 220 feet in the clear. It is over 100 feet high from the creek bed to the crown. The roadway is 20 feet wide. The stone used was granite and sandstone.

The largest stone arch ever built was constructed over the river Adda in 1380. It had a clear span of 251 feet, but it was destroyed in 1427 and now only part of the arch remains. Another very notable bridge is the Croton Aqueduct. On account of navigation it was necessary to have a clear height of 100 feet above the high water mark and spans of 80 feet. The top of the parapet is 116 feet above high water mark. The total length of the aqueduct is 1460 feet. This aqueduct carries three huge cast iron pipes, the largest being 7½ feet in diameter, across the Harlem River at New York for the purpose of supplying Manhattan Island with water. There are numerous other stone arches such as the Wheeling stone arch, the East and West bridges of Elyria, O., the Schenley Park arch, Pittsburg, and the Wissahickon arch, Philadelphia, which are very beautiful and interesting to study.

The concrete arch has within the last fifteen years become very popular in both Europe and America, due largely no doubt to the increased manufacture of cement and the dependence that is being placed upon it. This popularity is also due in part to cheapness and the ease with which concrete can be worked into the various forms. The stone arch is built to stand compression only, while some authorities recommend that concrete be allowed to undergo tensile stresses to the amount of one-tenth of the working compressive stress.

Broken stone or good coarse gravel can usually be obtained within a short distance of the proposed bridge site, while good building stone is found in comparatively few localities.

The latest development of the concrete arch is the concrete steel system. Jean Monier is generally recognized as the inventor of the combined use of concrete and steel. He lived in Paris in the latter part of the nineteenth century, and being a gardener and wishing to make some large tree pots, he hit upon the scheme of embedding wire netting in the concrete to make it stiffer. Finding this plan to succeed beyond his expectations, he applied his system first to floors, water tanks and sewers, and finally to bridges.

The first system used in this country was the one known as the Melan, in which stiff steel ribs or curved I beams are embedded in concrete to form the arch ring. The steel beams furnish resistance to bending and thus decrease the amount of concrete necessary, and at the same time expensive centers are not always needed in its construction. The fact that when steel is *properly* embedded in concrete, it is supposed to have absolute protection from corrosion makes the combined use of these two materials for constructional purposes a very desirable one. Iron rods have been found free from rust, having been embedded in concrete below water level for four hundred years. The concrete iron bridge has all of the advantages of the stone arch with a cost often lower than a substantial steel bridge for the same span and width as will appear from data given at the end of this article.

Due to the uncertainty of the existing stresses in a solid masonry arch, some hinged arches have been designed and constructed. The hinges will allow more deflection and settlement of the abutments, without injury to the arch.

Von Emperger gives the following advantages in concrete iron construction:

1st. That there is no expense necessary for maintenance of the bridge, the iron being entirely covered.

2nd. That there is no expense necessary for maintenance of the road, or, at least, no more than for any other part of it.

3rd. That there are no vibrations and practically no noise, and that it is not seriously affected by the change of live load.

4th. That such bridges are tornado and high water proof.

5th. That they have a solid appearance, which can be architecturally developed in accordance with the surroundings.

6th. That their construction is cheap wherever sand and gravel are at hand.

Too much reliance can hardly be put upon the fact that the masonry bridge if properly built is high water proof. Very convincing proof of this is found in the fact that the Conemaugh stone railroad bridge, directly below Johnstown was not affected in the least by the famous Johnstown flood.

The Melan arch bridge of Topeka is the longest of its type. It has one arch of 125 feet, two of 110 feet, two of 97½ feet and cost $150,000. The Melan concrete railroad bridge at Detroit, Mich., has a 50 foot span and carries six tracks, and a large signal tower. The Melan arch foot bridge at Stockbridge, Mass., is certainly a curiosity, for it has a clear span of 100 feet, and a rise of only 10 feet and is only 9 inches thick at the crown. Other bridges of this type are the Melan arches at Cincinnati, O., Patterson, N. J. and Hyde-Park-on-Hudson; many concrete-iron arches are found in Europe, especially in Austria.

As a country grows older and wealthier, the tendency is for an increase in the permanency of its public works, and with this tendency has come a greater interest in the masonry arch, which while representing the most permanent type of all bridges, is also the most beautiful. Probably the first masonry bridge of any note was built in France and is known as the Pont du Gard bridge. It was constructed nineteen hundred and twenty years ago by a son-in-law of Emperor Augustus. This bridge is 873 feet long and 160 feet high and has three tiers of arches; those of the lower tier having spans of 80 feet and 5 inches. In 1743 the lower tier of arches was widened on one side to form a road way. While this is the oldest bridge known, it yet remains unsurpassed in beauty and grandeur and will no doubt remain standing many years after our best iron and steel bridges have turned to dust and been scattered by the winds.

From our present knowledge of materials we know that iron and steel, and wood are only reliable for a comparatively short time. Iron and steel waste away very rapidly by oxidation when unprotected, and yet no paint has been prepared that will permanently protect these metals from the injurious effects of air and moisture. The average life of the ordinary metal bridge is said to be between forty and fifty years. The wooden bridge is shorter lived yet—unless covered perfectly and kept so covered. Compare the life of such bridges with the Pont du Gard or some of the Roman aqueducts which have stood for two thousand years without care. Think of the number of times one of our best types of modern steel bridges, with a life of even one hundred and fifty years, would have to be rebuilt to have served as long a time as the Pont du Gard masonry arch bridge, which was built 19 B. C. Such a bridge would have to be rebuilt thirteen times and not one of those fourteen modern bridges would compare with the masonry arch in beauty; and probably one-fifth of the time these thirteen bridges would have been considered of doubtful security as each one wasted by corrosion, and all of the time they would have required more or less attention and expense.

The durability of certain kinds of stone is well known, yet for reasons of true or supposed economy it has not generally been considered in this country an economical building material. The tendency toward the building of the more substantial structures in this country can be seen by noting the growth of a city. At first the city had only wooden buildings, then as the population increased and money became more plentiful, the old frame buildings were replaced by brick or stone structures. A similar development is true of the bridges, for about a half a century ago the wooden bridge was, with few exceptions, the only kind built in the United States. These were followed by combination wood and iron and then by cast iron and wrought iron bridges, which were a great improvement over the wooden bridge, and within the last fifteen years, steel has developed into the chief material used in bridge construction. The next important material in bridge construction will be concrete, and the masonry arch will be considered more favorably when engineers more thoroughly understand the actual condition of the existing stresses in such a structure. However where long spans are required the steel bridge will stand unrivaled.

Some few railroads are using masonry arches of medium span, while most, if not all roads are building nearly all of their culverts of stone and concrete; the tendency is to build more and more masonry work each year and to apply it to bridges of longer span. The railroads of Europe have built a large per cent of their bridges of masonry. The reason for this is easily understood, for when the railroads of Europe came into general use, the country through which they ran was fully developed and the land valuable, so the road beds and bridges were made as nearly permanent as possible. In America the railroads developed the country through which they ran, and for the want of sufficient funds no permanent bridges were built.

Europe has already recognized the superiority of masonry over steel in bridge construction; and some countries have expressed their preference in favor of masonry in public structures.

Austria has the longest railroad masonry arch in the world, the clear span being 213 feet, and the Austrian Railroad Commissioners have indicated their desire that the use of iron bridges should be abandoned in favor of stone arches.

The steel bridge is generally used because it is thought to be cheaper, and it is true that most of the light frail bridges are put up at a less cost than the masonry arch, but the more permanent ones very nearly equal and sometimes exceed in cost the masonry arch.

Of late years, due to the importance of the improved street pavements, the bridges are being floored with a solid pavement of macadam, brick, asphalt or concrete to match the pavement of the other parts of the street. The plank floors on highway bridges required constant repairs and renewals, and are a source of expense to the community. Now the steel bridges with macadam pavement, because of the extra weight carried, became so expensive, it was soon evident that bridges of this construction were nearly as expensive as the masonry arch, and in some places even more expensive in first cost alone. Another important advantage that the masonry arch has over the steel bridge is in the relative ratio of the moving loads to the weight of the structure itself. This is especially true of railway bridges.

The weight of a steel bridge for openings such as would be spanned by a masonry arch is small compared to its moving load, hence any great increase in the weight of the moving load over stresses the bridge members. The great and steady increase in the weights of locomotives and freight cars have caused many bridges to fail and consequently the railroads are busy putting in new bridges. Failure will not occur in the masonry arch for this reason, because the weight of the arch itself is many times that of the heaviest loads which pass over it. The moving load could even be doubled without greatly lowering the factor of safety used.

Alfred W. Buel says that a railway steel girder span 60 feet long, with a solid floor, costs about $1,600 and that the capitalized cost of maintenance and renewals amounts to about $400, giving a total cost of about $2000, while the equivalent part of a masonry arch can be built for about $1,800.

The stone arch highway bridge over Turkey River at Elkader, Iowa, is said to be the longest and best constructed highway bridge west of the Mississippi River, and east of the Rocky Mountains. The river had been spanned by an iron bridge which cost much in the way of maintenance. Bids were invited for the construction of either an iron or a stone bridge, but the bids for the same width of structure showed that an iron bridge of proper strength would be more expensive than the stone arch. The arch constructed consisted of two spans each 84 feet in the clear with a rise of 27.9 feet.

The width was 34 feet, containing a 24 foot macadamized roadbed and a 6 foot cement sidewalk. Cost $13,000.

The Wissahickon bridge on the Philadelphia and Reading R. R. is 510 feet long; 103 feet high above the foundations and has five semi-circular arches each of 70 foot span. It was built in 1881-2 by Mr. C. W. Buchholz, Mem. Am. Soc. C. E., and it cost $375,000 or a little less than $3 per horizontal sq. ft.

An X shaped concrete bridge was built at Le Mans, France, across the river Sarthe in 1898. It was necessary to build this plan of bridge due to the location of two electric railways, which cross each other on the middle of the bridge. The bridge was built of concrete with a metal skeleton. The point of interest is the low cost of construction. The floor area was 5,382 sq. ft. and the total cost was $5,600 or about $1.04 per square foot.

It may be of interest to note that the cost per square foot to the county of that part of the clear floor supported by the trusses of the bridge over Iowa River at Iowa City, now under construction, will be $1.65. The cost to the contractor will be close to $2.00 per square foot.

Below is given some data showing the relative sizes and costs of masonry and steel bridges.

MASONRY BRIDGES

Bridges	Length	Width	Cost	Cost Per Sq. Ft. of Area
Elkader, Ia., (s)........	246′	34′	$13,000	$ 1.67
Hyde-Park-on-Hudson (s)	90′	28′	12,500	4.96
Germany (hinged c).....	262′	13′	4,285	1.25
Pittsburg (s)............	341′	85.5′	112,201	3.84
Cornell University (s)...	63′	33′	6,260	3.00
Including removal of old bridge.				
Over Danube (3 hing. c).	144′	13′	5,310	2.83
Belleville, Ill. (c).......	85′	52′	10,500	2.37
Cincinnati (m. c)........	70′	32.5′	7,130	3.13
Over Danube (hinged c).	164′	25′	10,898	4.12

Bridges	Length	Width	Cost	Cost Per Sq. Ft. of Area
Stockbridge, Mass. (m. c)	100′	7′	1,475	2.10
Cour. St. Arch N. Y. (s).	510′	64′	137,937	4.22
Andrews St. N. Y. (s) . . .	280′	60′	72,537	4.31
Kankakee, Ill. (s)	64′	55′	2,700	0.76
New Brunswick, N. J. . . .	818′	36′	99,000	3.36
Baltimore, Md.	480′	100′	319,915	6.66
Mt. Vernon, Va.	220′	62′	30,000	2.19
Gour Noir, Fr.	358′	30′	67,000	6.24
Topeka, Kan.	625′	40′	150,000	6.00
Le Mans, Fr. . . . . sq. ft. =	5382′		5,600	1.04
Wissahickon, Pa.	510′			3.00
Over the Enz.	147.6′			3.20
Over the Enz.	67.6′			2.09
Over the Glatt.	68.2′			1.46
Over the Murr.	139.7′			2.43
Waterloo.	560′	54′	60,000	1.98

STEEL BRIDGES

Plategirder, Monmouth, Ill.	105′8″	9′	5,450	5.73
Paris over Seine.	569′	63.75′	404,000	11 14
On Chicago and Eastern R. R. { Saline creek steel, via. . .	845′	9′	44,700	5.87
On Chicago and Eastern R. R. { Grasshop'er creek, via.	650′	9′	38,000	6.49
Kinzua Viaduct in Pa. . .	2050′	10′	112,000	5.46
Lightning Creek thro' G.	102′	13′	64,000	4.82
Little Missouri R. Deck span.	102′	9′	48,000	5.22
Denver Viaduct.	2105′	50′	425,000	4.03
Messalin Bridge	121′	16′	4,800	2.48
Iowa City (new)	350′	17′	10,450	1.65