THE ARCH BRIDGE AS AN ENDURING BUT ADAPTABLE STRUCTURAL FORM

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SUMMARY

The arch form has existed since at least the 3rd Century BC, and remains of arches can still be seen today in areas which were occupied by the Romans. Early arches used the materials with which people were familiar, and could be locally sourced, this being mostly stone, but this changed in the 17th Century, particularly in England, as the Industrial Revolution became established and production of bricks increased to keep up with the demand for housing for the increasing workforce, and suitable stone became less freely available. The coming of canals and then the railways to carry the increasing quantities of goods being produced changed the nature of arch bridges, hump-backed canal bridges and multi-span railway bridges becoming common. Cast iron appeared as a viable material in the 18th Century, then reinforced concrete at the end of the 19th Century. The early part of the 20th Century saw an increase in the spans of arch bridges in both reinforced concrete and steel, until modern times where materials are such that an arch can always be considered as a structural form when choosing the design of a bridge.

Keywords: *Stone, brick, Industrial Revolution, canals, railways, cast iron, reinforced concrete, steel.*

1. INTRODUCTION

The arch form in stone was the premier means of spanning large distances until such time as structural members which could sustain bending were developed. Before arches, spans were generally small, examples being clapper bridges, consisting of slabs of rock between stepping stones, timber bridges, or rope bridges. We only really know about clapper bridges because the material they were made from has endured, even though they may have been re-built a number of times over the centuries. The other materials, timber or rope, would have rotted away and been replaced, so that any that have been known to have been there for a long time cannot really be dated, and their presence can only be known of from historical records.

The Romans are generally credited with developing the structural form.

2. EARLY ARCHES

2.1. Roman arches

There is ample evidence, both in Rome and anywhere else that was occupied by the Romans, that they had developed skill in working stone, and from the extensive remains that have been left by them it is clear that they understood the principles of arches, i.e. that they work in compression, and that stone is the perfect medium for sustaining compression. It is a small step from incorporating arches into buildings to developing the form into bridging structures.

Examples of these are the aqueducts which brought the water supply to Rome, the first, the Aqua Appia, being built in 312BC in conjunction with the Appian Way; the remains of an aqueduct can still be seen both outside Rome and mixed in with the buildings of the town, although which one, it is difficult to identify.

There is not much evidence of arch bridges in Britain until the coming of the Normans after the Battle of Hastings in 1066AD, known as the Norman Conquest, a seminal event in British history.

2.2. Norman arches

Following the Conquest the Normans began a programme of building castles and churches to establish both their position as conquerors and the power of the Christian church. The construction of cathedrals depended on arches to support towers and the roofs, and once more the idea was extended to bridges, because the skill in working stone was already there, as was the need for structures to carry greater loads than just foot traffic; in many cases early arch bridges carried shops and other premises, including chapels and defensive gatehouses.

Arch bridges were built almost exclusively over rivers or other watercourses, because there was no other type of transport route to be crossed. Roads as we know them and railways were far in the future.

Fig. 1. *Old London Bridge in a freeze, as depicted by Abraham Hondius in 1677 (Museum of London).*

The famous London Bridge, of "London Bridge is Falling Down" fame, completed in 1176, is shown as having a very large number of very squat piers with short span pointed arches between them. This may have been because each pier was constructed to be able to withstand thrust from the arch it was carrying, instead of the thrust of adjacent arches balancing each other out as would be modern practice. This would have allowed the spans to be built one at a time, as arch centring would have been needed, and it would have been practically impossible to build all of the arches at the same time in a tidal river because of the damming effect it would have created. Even when completed, the obstruction the bridge presented slowed the river so on occasions it froze (Fig. 1), to the point where in December 1683 a Frost Fair was held on the river. The last Frost Fair was held on the Thames in 1814, and the old bridge was taken down and replaced in 1831, at the same time as the London Embankment was built.

An example of a free-standing arch can be seen in Warwick, England, where an arch forming part of a mediaeval bridge, long since out of use, still stands in the middle of the River Avon, the stocky piers providing the necessary resistance to arch thrust (Fig. 2).

Fig. 2. *Free-standing mediaeval arch at Warwick England (Author's photograph).*

3. LATER ARCHES

3.1. Changing transport needs

The major form of transport until the more widespread use of the horse-drawn coach was the horse, and for transporting goods, the pack horse or pack mule. Bridges to carry horses are distinguished by being narrow, although obviously wide enough for a horse carrying panniers, with low parapets to allow clearance for panniers, with refuges which generally echoed the shape of the cutwater on the pier below. These were generally triangular, and can still be seen in Britain today on minor routes; where there is insufficient width for modern traffic they are often light-controlled, otherwise motorists have to sort it out for themselves. An example of a bridge with refuges can be found over the River Wye in Hereford, England, where the present bridge has stood since 1490 (Fig. 3).

With increasing prosperity, for some at least, came the need for bridges of greater width to carry coaches and farm carts to facilitate trade. Many bridges were doubled in width, as can often be seen from beneath the arches where either a central line, or even a change in structural details can be seen. This happened at various times, but there is evidence that it became commonplace in the 19th Century, in Britain at least.

Fig. 3. *River Wye Bridge at Hereford, with refuges (Author's photograph).*

3.2 Military Bridges

In parallel with increasing prosperity during the period before industrial and other revolutions was the urge for various countries to take over other countries, which involved the movement of large numbers of troops, and this could be facilitated by constructing bridges over obstructions like watercourses or gorges.

Fig. 4. *Aberfeldy Bridge, built by General Wade over the River Tay, Scotland, 1733 (Wikipedia).*

A number of these military bridges, constructed by General Wade [1], can be found in remote parts of Scotland. Some, on the main transport routes are still in service, such as the Aberfeldy Bridge (Fig. 4), but many consist of just the arch barrel on the line of a long-forgotten military route. The purpose of these, built in 1720s and 30s, was to allow rapid troop movements when it was felt necessary to control the Scottish clans after the 1715 rebellion.

4. NEW MATERIALS

4.1. Development and use of alternative materials

However, in time the supply of suitable stone, and possibly of suitable craftsmen, began to disappear, and alternative materials, such as cast iron, began to be considered. Even what was deemed to be the first iron bridge in the world, spanning the River Severn at Ironbridge in Shropshire, did not use the spanning properties of cast iron, but was of arch form (Fig. 5). It is a ribbed arch, but the parts of the bridge are connected using all the details of a wooden structure, mortises and tenons fixed using wedges, for instance, because it was put up by a carpenter.

Insufficient confidence in the spanning properties of cast iron, probably because of unpredictable quality, was the driver behind retaining the arch form, but bridges could be constructed where stone was not easily obtainable, while the materials for making iron were, the Ironbridge Gorge being considered as the location of the beginnings of the Industrial Revolution in England, where the Museum of Iron is now located. There was also the advantage of lightness, which would make an iron bridge more easily constructible, and there would be no need for arch centring. This latter was important when spanning a river like the Severn, which is prone to flash flooding.

Fig. 5. *The Iron Bridge, Shropshire, England (Wikipedia).*

No-one knew how it had been built, until someone discovered that an artist from Sweden, touring Britain and painting scenes from life, painted a picture of the bridge arch ribs being built in two halves, one on each side of the River Severn, then lowering them into position from each bank, restrained by ropes, rotating about the lower hinge and meeting in the middle, thus avoiding the need for centring, as mentioned earlier.

This was in 1789. The bridge linked the town on one side of the river to allow it to develop on the opposite bank, and remains to this day. As now seen the footpath it carries rises very steeply to the crown of the bridge, but it was not always so. The sides of the valley of the River Severn at the point of crossing have been moving towards each other from time immemorial, because of erosion of the toe of the banks by the river, so the abutments of the bridge have been moving towards each other since the bridge was built, hence the lifting of the crown of the roadway. The process was stopped in 1975 by the building of a concrete slab at river bed level, which acts as a strut keeping the abutments in position, although the banks on each side keep closing together and being eroded.

Another example of an early cast-iron ribbed arch bridge, still in use today, can be found at Chepstow in Monmouthshire. It is a five-span ribbed-arch structure, completed in 1816, as can be seen from a date cast into the parapet (Fig. 6).

Fig. 6. *River Wye Bridge, Chepstow, showing date of construction (Author's photograph).*

It was built by Hazeldine Rastrick and Co. to a design by John Rastrick, instead of a stone bridge proposed by John Rennie, which would have cost twice as much, demonstrating the economic potential of the new material.

It is located at a crossing point where timber bridges had been erected, and washed away by the river, since 1228; a contribution to the bridge's longevity is that the design allows flood water to pass through it instead of washing it away (Fig. 7).

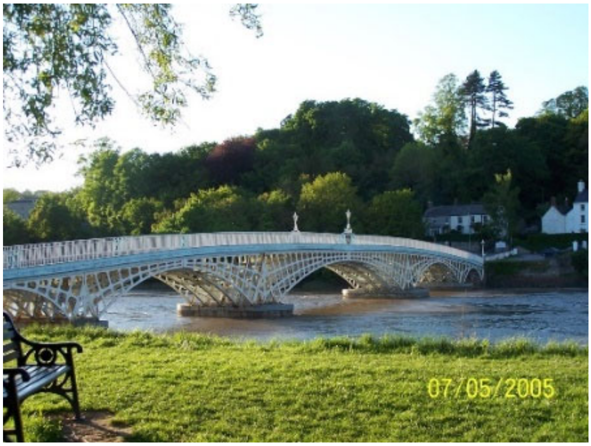

Fig. 7. *River Wye Bridge, Chepstow, east elevation (Author's photograph).*

4.2. The Industrial Revolution in Britain

The Industrial Revolution in Britain led to the development of canals and railways to carry the goods produced, and fuel for the factories to produce the goods, in a way which was more reliable than the road system which existed at the time. These were unsuitable for the transport of large quantities of materials; the state of the roads was such that in wet weather they were impassable because of mud, and in dry weather they were so rutted that goods being carried, particularly ceramic pots, were broken.

4.2.1. The development of canal arch bridges

The concept of the canal, or of rivers being made navigable for transport of goods, goes back to the time of the Egyptians and the Romans, and the Imperial Canal of China, connecting north to south, connecting Canton to Beijing, was completed in 1289, and transported goods into the heart of China. Canal systems were being developed in France and the Low Countries in the 16th and 17th Centuries, but they came late to Britain [2]. However with them came to need to cross the existing transport routes; as the essence of a canal is the need to keep it on one level as far as possible, the obvious answer was the building of hump-backed bridges which are familiar today to the many holiday-users of the canals.

The canal system began to be developed largely in the 18th Century, generally through areas where clay was the main material at formation level, or where clay was easily obtainable to line the "cut" with "puddle" as a waterproof layer. As a result of this the majority of bridges over the canals were built in brickwork (Fig. 8). They could be built in the dry, usually on spread footings, taking the highway over the top, before the canal was flooded to make a waterway.

Many of these bridges have been replaced by modern beam bridges, because neither the width nor vertical alignment over hump-backed bridges are generally suitable for modern traffic, but thousands remain on minor roads and farm tracks.

Fig. 8. *Brickwork arch over the Grand Union Canal, Rowington, Warwickshire, England (Author's photograph).*

4.2.2. The development of railway arch bridges

The Industrial Revolution in Britain also resulted in the development of the railways, so there was a need for viaducts and tunnels to maintain the permanent way at a reasonably constant level. The viaducts consisted mostly of stone or brick arches, dependent on where in the country they were built.

There are many examples of these in Britain; the Ribblehead Viaduct in Yorkshire, on the Settle and Carlisle Line in Northern England, is an example of a structure built mostly in the local stone, as are most of the houses in that area, although it had brick arch barrels. It was completed in 1875; in the 1990s, under the ownership of the then rail authority, it was deemed to be in poor condition due to frost damage, and demolition was proposed, but a public outcry caused a re-think and it was decided that the deterioration was not as extensive as had been first thought. It lives on to this day, carrying tourist trains, including those hauled by steam engines, which is a great attraction.

In contrast, a number of multi-span viaducts carrying the railways in urban areas in the English Midlands are constructed in brickwork, probably because of two factors. One is that bricks were more freely available than stone, partly because of the ready availability of brick clay, and the fact that the need for housing for people coming into the town to work in the factories which were being built as part of the Industrial Revolution had led to the setting up of many brickworks, a second being that more people were being trained as bricklayers, rather than stone-masons, and bricks are easier to handle than stone blocks.

4.2.3. The additional use of railway arch bridges

It has long been the case in Britain that where there is a multi-span brick railway viaduct within a city, with the optimum span length and height, these spans are rented out as commercial premises, as in Fig. 9.

Fig. 9. *Railway arches used as commercial premises, Leamington Spa, England (Author's photograph).*

Fig. 10. *Durham Viaduct – stone spandrels and voussoirs, brickwork arch barrel (Author's photograph).*

Of course, these spans suffer from the same defects as most arches which is, where the arch barrels are not waterproofed and drained properly, water will leak through the brickwork, so either internal drainage paths have to be created to take away any water which would otherwise leak into the premises below, or special attention must be paid to ensuring that arch barrels do not leak. In some more urban locations, viaducts can be found which combine the two materials, with stone voussoirs and spandrels, for appearance, but with brickwork being used for the barrels for ease of manufacture and handling (Fig. 10).

The construction of both brick and stone arches for both road and rail persisted into the 20^{th} Century, until the use of reinforced concrete became more common in the 1920s and 30s.

4.3. Reinforced concrete arches

Reinforced concrete had its beginnings in the continent of Europe in the latter half of the 19th Century, but only began to be used in Britain in the first decade of the 20th Century, being brought to this country by Hennebique and L.G.Mouchel. It began to be taken seriously as a material for construction of larger bridges, in Britain at least, only in the 1920s, a notable example being the Royal Tweed Bridge at Berwick-on-Tweed, near the border between England and Scotland. This is a four-span ribbed-arch bridge, 328.5m long between the ends of the approach viaducts, built between 1925 and 1928 (Fig.11). A stone bridge had been considered, but rejected in favour of the new material [3].

Fig. 11. *Royal Tweed Bridge, Berwick, Northern England (Photo by Nilfanion-CC BY – SA3.0).*

The design of concrete bridges also became bolder as the 20^{th} Century developed and as the strength of concrete and reinforcing steel became more controllable. Early examples of concrete bridge were of fairly short span, and replicated similar structures in stone or brick, but one of the first, if not the first, example of a new and bold design, is the Salginatobel Bridge, designed by Robert Maillart, and built in the Salgina Valley in Schiers, Switzerland [4]. It is a three-hinged reinforced concrete hollow box girder arch bridge, with a length of 133 m, spanning a deep river gorge, and was opened in 1930. Legend has it that the authorities allowed Maillart to erect the bridge at the location chosen because of its remoteness, and the fact that it serves a small town of only 2500 people, the thought being that if the bridge should fail it would affect only a small number of people.

The style of bridge, looking as if it is holding the sides of the gorge apart, has been repeated many times around the world, an example being found over the M1 Motorway in Yorkshire, England (Fig. 12).

An even bolder design of in-situ concrete bridge has been built just downstream of the Hoover Dam in Colorado, USA, and was completed in 2010. Known as the Mike O'Callaghan – Pat Tillman Memorial Bridge, it is an open-spandrel type, being built as a cantilever from each side of the gorge. It has a length of 1900ft (579 m) and a span of 1060ft (323 m), and a clearance below of 900 ft (270 m). However, the design follows closely the Bixby Creek Bridge, built in 1932, in Monterey County on the West Coast of the USA, although Bixby Creek is to a smaller scale, having a length of 714 ft (218 m), a span of 320 ft (98 m), and a clearance below of 260 ft (79 m), this perhaps reflecting lack in confidence in the properties of reinforced concrete, as a fairly new material, or perhaps just because of the dimensions of the creek being crossed.

Fig. 12. *Bridge over the M1, Barnsley, Yorkshire, England (Wikipedia).*

4.4. Steel Bridges

Modern materials now have the strength characteristics to overcome the size limitations which previously dictated where arches could be used, which has led to spectacular arches being built, particularly over river gorges, where they allow navigation beneath, and are clear of flooding. There are historic ones to be found all over the world, including the Victoria Falls Bridge over the River Zambesi in Zambia, built in steel in 1904-5, with a span of 513ft (156.5m), supporting a railway from Zambia and Zimbabwe from beneath; Hell Gate Bridge in New York, built in 1912, again in steel, as a through-arch carrying the Amtrak Northeast Corridor rail line, with a span of 978ft (298m) [5]; Sydney Harbour Bridge in Australia, completed in 1932, modelled on the Hell Gate Bridge, and carrying both rail and road traffic [6]; plus the Tyne Bridge at Newcastle on Tyne in the North East of England, which is a steel two-pin arch, completed in 1928 [7]. It is a through-bridge carrying road traffic. Hell Gate, Sydney Harbour and the Tyne Bridge were all built such as to allow navigation height for ships using the rivers at the time of their construction.

A more recent long-span bridge in Britain is the Runcorn-Widnes, which was opened in 1961. It is a steel through-arch bridge of 1082ft (330m) span, built to replace a previous transporter bridge which was an inefficient means of crossing the River Mersey as the volume of traffic increased, although it has been widened to cope with the ever-increasing volume of traffic [8]. It also allows navigation on the river beneath (Fig. 13).

Fig. 13. *Runcorn-Widnes Bridge over the River Mersey and the Manchester Ship Canal, England (Wikipedia).*

Fig. 14. *Bridge over the Avon, Warwick, England (Author's photograph).*

On a smaller scale, arches are suitable for footbridges, particularly in steel, because they can be prefabricated and lifted into place, and example from 1996 being found over the River Avon in Warwick, England. In this case the arch form was chosen because, being a footbridge, the arch could link the two approach ramps on a pleasing vertical curve, which would not have been the case with a beam bridge (Fig. 14).

Similarly, where a footbridge over a road is required, a steel arch can be the ideal solution, with the arch rings spanning required distance, supporting the walkway from hangers, allowing sufficient headroom for traffic below (Fig. 15).

Fig. 15. *Heath Town Footbridge, Wolverhampton, England (Author's photograph).*

4.5. Precast concrete arches

Precast concrete arch units, to be used as permanent formwork, are commonly used for situations where centring is impossible, such as over a canal or railway. Many types of precast concrete arches are available, in spans of around 4 m to 30 m. They can be designed as either semi-circular arch units as permanent formwork to act in composite with in-situ concrete, or to act as a traditional arch when back-filled with granular material.

Fig. 16. *Precast concrete arch unit being placed (Macrete, Co. Antrim, N.I.).*

The example shown in Fig. 16 is a patented design of flexibly linked units which can be stowed compactly for transport, but opened out on site into a semi-circle for placing.

These are delivered to site for placing on prepared foundations, after which they are carefully back-filled with granular or other engineered material, saving a great deal of time on site [9].

4.6. The arch in contemporary use

With its long history the arch form has been identified as being adaptable to a number of crossing situations, the prime considerations being that, where situations allow, large distances can be crossed without the need for a central support. Arches have the ability to be either supported on foundations which can resist the thrust, or the springings can be tied together, which contains the arch thrust within the structure, allowing it to be built off line and moved into place.

Despite, or because of, its historical use in materials which were available at the time, the arch form has its merits today, because of its adaptability to new materials, and is frequently used in situations where speed of construction and minimizing of interruption to the daily life of the public are considered to be major considerations.

The development of modern road layouts has led to the desire for overbridges without a centre pier, a solution to this problem being the development of steel tied-arch bridges which are light enough to be built offline, to be transported to their final location by heavy-lift vehicle, or on the approach roads to be launched or dragged into their final location, because, being a closed system, the arch forces are constrained within the structure itself, removing the need for robust abutments at the arch springing. In this way the bridge can be built with minimal interruption to the obstruction being crossed, thus saving time and money.

5. DISCUSSION

The arch form has existed from Roman times to the present day and has been adapted from using the materials which were in common use at the time, and which were capable of withstanding high compressive forces, namely brick and stone, to reinforced concrete, and structural steel, as used today. Until the coming of the Industrial Revolution, principally from when it began in Britain, obstacles to be crossed were natural, namely watercourses, because transport was by road, and bridges were mostly constructed in stone; for many centuries it was common practice for bridges to carry shops and other commercial premises, or to form a defensible approach to mediaeval towns, but in time, often because the bridge had been washed away, the practice was generally abandoned, and bridges were either widened or replaced but, because of lack of alternative materials these were generally still in stone.

As cities or other centres of population developed, so the sophistication of arch construction changed, and larger spans with a lower span-to-rise ration became possible, with improved construction techniques allowing arch centring to be designed which reduced the risk of its being washed away in the event of a river rising while the bridge was being constructed; it must be noted that at this time watercourses were still the main obstacles to cross, since neither the canals nor the railways were in place until after the middle of the 1700s, in Britain at least.

However, the arches were still largely constructed out of stone, and although bricks were available, these were mainly for domestic purposes, and were not available on a large scale. Away from towns, where stone was the vernacular building material, it is generally true that only stone bridges can be found, bricks not being available.

A major change occurred in Britain around the middle of the eighteenth century, with the coming of the industrial revolution, and with it the construction of canals and railways. The canals, which came first to Britain in the 18th Century, crossed existing roads, which meant that bridges were needed. Because of limited technology at the time, and because of the increasing use of bricks for house building as towns developed with increasing industry, these were generally constructed as brick arches. As the canals were built in the dry, prior to filling, conventional centring could be used, with no fear of being washed away by flood water.

As cast iron emerged as an industrial material, its potential as a material from which bridges could be made was realised in 1789, but still in arch form. However, the whole structure could be lighter because ribs could be thinner, with cross- bracing, for construction over rivers which were prone to flooding.

Many cast-iron ribbed arch bridges were made during the nineteenth century, until two developments occurred, those of more reliable steel, with its capacity to sustain tensile forces, and reinforced concrete.

Reinforced concrete was initially restricted to small-span bridges of the same proportions as they would have been in stone, but the coming of new processes for making steel sections provided opportunities for constructing the larger-span bridges which were starting to be required at port-cities built at the mouth of various rivers.

As the theory of reinforced concrete developed it became possible to create larger span arch bridges using techniques of construction which did not involve falsework supported from the ground below the span, by cantilevering out from the supports. In this way large waterways could be crossed without fear of flood damage during construction, and at a high level to allow the passage of commercial or naval shipping beneath.

6. CONCLUSION

In summary, the arch form has been adaptable to developments in materials from stone in the earliest times to steel or reinforced concrete in modern times, and the reasons for choosing the arch form have changed from being because of limitations in materials available, to being able to span large distances without central supports, or to construct a tied arch away from its final location and to lift it into position, or to construct a precast concrete span prior to filling it, without lengthy interruption to other activities, thus saving time and money.

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