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ARCHES: EVOLUTION AND FUTURE TRENDS

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Abstract: This paper try to establish the future trends in the design of the arches bridges also to give an idea about what are the maximum span that they can rise. It begin with the study of the bridges history: First stone arches, Roman, middle age and modern ones. The metallic arches: Cast iron, wrought iron arches and steel ones. First concrete arches, evolution and modern ones. Concrete Filled Steel Tubes Arches in China. Some theoretical arch bridge design and calculation and forecast about typology and maximum span they could rise**.**

1. INTRODUCTION

Arch bridges were first constructed in prehistoric times; there are archaeological remains of stone arch bridges dating back to the Sumerian civilisation in Mesopotamia, around 2000 B.C. The general consensus among architectural archaeologists is that in Europe the Etruscans were the first to use the genuine arch bridge, in Italy in around 800 B.C. By real arch bridge is meant a structure in which the stone segment are arranged in a radial way, as opposed to false arches composed of cantilevered brick or stone.

Neither the Egyptians nor the Greeks used so much the arch in their construction, although there is evidence to show that they were aware of its existence. It is with the Romans that the arch bridge became the almost universal method of bridge construction right down to the 18th century. If we date civilisation from the Mesopotamian cultures that arose in the region between the Tigris and Euphrates rivers, we see that arch bridge-building was a relatively late development, only becoming widespread in Roman times as from about 700 B.C.

The stone arch bridges went through various stages: Roman arch bridges, medieval arch bridges and the modern age arch bridges. From the last ones (built between the 16th and 19th centuries) we highlight the Concorde Bridge over the Seine in Paris, designed by J. R. Perronet, constructed between 1787 and 1791 and still in use today. It represents the historical moment when the approach to stone arch is done in a more academic and rational way. Though stone arch bridges will continue to appear, we doubt they will surpass the strength and elegance of the work of Perronet.

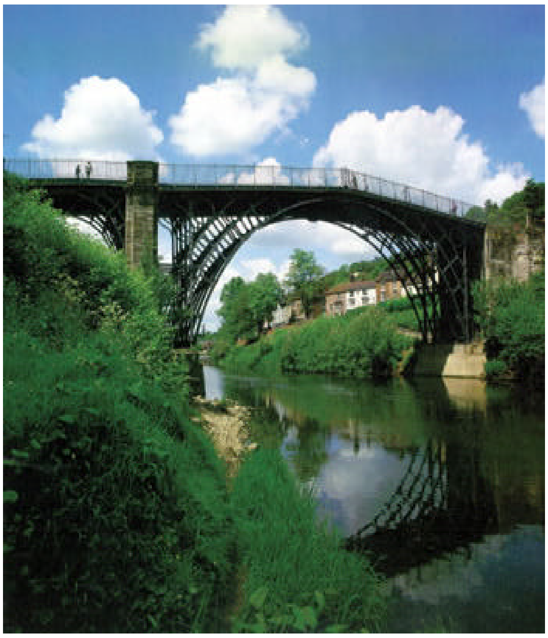

Figure 1 Iron Bridge in Coalbrookdale

The evolution of stone arches is a wide item and it has no many relation with arches of today. So it will not discussed in this presentation.

2. EARLY METAL ARCHES

2.1. Cast iron arches

The first metal bridges appeared in the 18th century, with the onset of the industrial revolution. The very first, the Iron Bridge over the River Severn at Coalbrookdale (Fig. 1), was designed by Thomas Pritchard for its builder and owner, ironmaster and businessman Abraham Darby III. The main span comprises five parallel cast-iron arches with a span of 30.5 m. The cast-iron forge were materials and technology known from the antiquity, but Darby's idea of constructing the bridge was to demonstrate the possibilities of production industrialisation applying hydraulic power to the operation of a standard iron forge. As often occurs with new technology, the cast-iron arch bridge mimicked the before stone arch typology. The result, however, was not unpopular, and a number of similar bridges were built, the biggest spanning a distance of 72 metres.

It was on this same village that Telford built his first metal bridge, also of cast iron, several years after, in 1796 (Fig. 2). Its span measured 39.6 metres and required only half the amount of metal used for the first Iron Bridge. Telford's bridge, known as the Buidwas Bridge, opposed that we said about typologies, shows an original typology, employing a mix of pass through deck arch and variable depth beam.

Figure 2 Buidwas Bridge, Coalbrookdale

2.2. Wrought iron arches

Wrought, as opposed to cast, iron came into its own in bridges in the first half 19th century, thanks to its lower brittleness and greater resistance to tension. As a result, bridge spans increased spectacularly. Wrought iron arches take the three dimensional trusses typology in which members are wrought iron profiles.

Figure 3 Garabit Viaduct, France

The 165-metre Garabit Viaduct in the Massif Central in France, designed by Gustave Eiffel, was completed in 1884, making it a relatively late example of this type of bridge construction (Fig. 3). After all, the Bessemer converter had been patented in 1856, closely followed by the Siemens and Martins coverters, allowing steel to be obtained instead of wrought iron. Ten years before the Garabit Viaduct was built, the Mississippi had already been bridged using steel tubes as the main arches profiles. So, why did Eiffel build his bridge of wrought iron instead of steel? The answer seems to be that at the time the wrought-iron technical characteristics were more trustworthy than steel ones, aside from which until prices began to fall in America in the 1880s was still very expensive. When the Garabit was begun in 1881 wrought iron was significantly cheaper than steel.

2.3. Steel arches

The first major arch bridge partly using steel was that over the Mississippi at St. Louis (Figs. 4). The bridge is of three spans, made out of steel tube arches of 158.5 m. It was built between 1867 and 1874, and is known by the name of the Eads Bridge in memory of the designer, the legendary Captain James Buchanan Eads. It carries road and rail traffic at two different levels, on platforms supported on the arches through very close vertical members.

Figure 4 Eads Bridge, San Luis, Missouri, EEUU

Eads knew the Mississippi very well; not in vain had he spent thirty years shipping on rivers boat. He was well aware of the erosion able nature of the river bed. On one occasion during a flood he had been down in a diver's suit and had seen with his own eyes the way the sands of the river bed shifted. For this reason he did not waver in driving the foundations of his bridge deep into the bedrock beneath the river bed, approximately 25 metres down. The piers were driven by men working within compressed-air caissons, in one of the first applications of this very unhealthy means of underwater construction, now mostly discontinued. The arches were cantilevered out from the piers simultaneously until they met in the middle. Once in place, they were fitted with the uprights to which the roadway and railway platforms were supported.

3. CONCRETE ARCHES

3.1. First Concrete Arches

From John Smeaton's Eddystone Lighthouse of 1759 to the advent of the cement industry at the beginning of the 19th century (Vicat published his 'Production of Artificial Cement' in 1818) spanned a period of almost 50 years. Yet it took another 50 years before the appearance of reinforced concrete. During that period is the time of the plain concrete, for the arch bridges only a few works were made out with a compacted plain concrete, some with spans of as much as 36 metres, in both France and Spain.

Figure 5 Tilière de Chatelet Arch Bridge

Just who discovered reinforced concrete and when the discovery was made are matters which, as often occurs in historically research, raise the difficulty of separating the individuals who did something with reinforced concrete and those who actually converted it into a practical building material on a large scale. The first patent taken out was that of Lambot in 1855; he was a gamekeeper who had made a boat out of cement. He was followed by the gardener Monier, who took out successive patents from 1867 onwards and had enough business sense to make commercial use of his invention. In fact, the first reinforced concrete arch to be built, in 1875, was the work of Monier. It was a footbridge in the gardens of the Palace of the Marquis of Tilière de Chazelet (Fig. 5).

After the early pioneers came Hennebique who, at the end of the century, making better use of industrial processes and the radically new concept of the franchise, succeeded in extending the use of reinforced concrete around the world. He was given a prize for his efforts at the Paris Exhibition in 1900. And it was Hennebique himself who in 1904 built the Risorgimento Bridge in Rome, with a span of over 100 metres (Fig. 6).

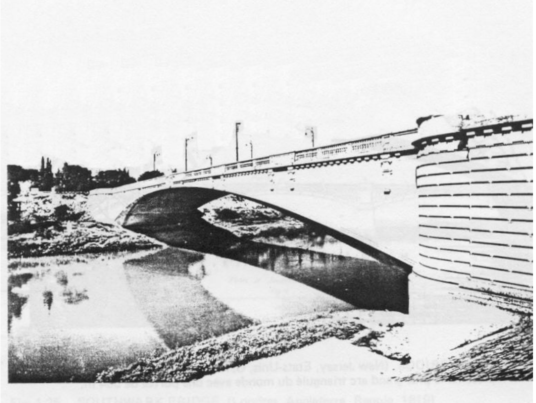

Figure 6 Ponte di Risorgimento, Roma

In Spain it was Eugenio Ribera who introduced the use of reinforced concrete at the beginning of the 20th century and designed the arches to be used as the official set of reinforced-concrete units for standard road bridges.

Figure 7 Sanginatobel Shuttering

3.2. Concrete Arches Development

Maillard and Freyssinet continued the development of concrete arches. The Freyssinet works had more interest to development than Maillard ones. Maillart's best-known work is the Salginatobel three-hinged arch bridge built in 1930 with a span of 90 metre. Contrary to the Risorgimento Bridge of Hennebique and previous Maillart bridges (such as that over the Tour in 1904), in this case he partially abandoned shuttered parapets in favour of piers set in the arch itself. In subsequent constructions he developed arches without parapets, thereby creating the classic design for overhead decks arches.

The biggest problem to build this arches was the difficulty in setting up the scaffolding. With reinforced concrete arches development scaffolding became a key issue, due to the difficulty of assembly and the resulting cost. The scaffolding for the Salginatobel was designed and constructed by Richard Coray (Fig. 7). It is a classic 'curtain' scaffolding, so called because the uprights are gathered together at fondation points high up on the hillside, thus reducing its height. Not surprisingly, by the mid 20th century reinforced concrete arches had undergone a temporary eclipse, due to the costs involved in their scaffolding construction.

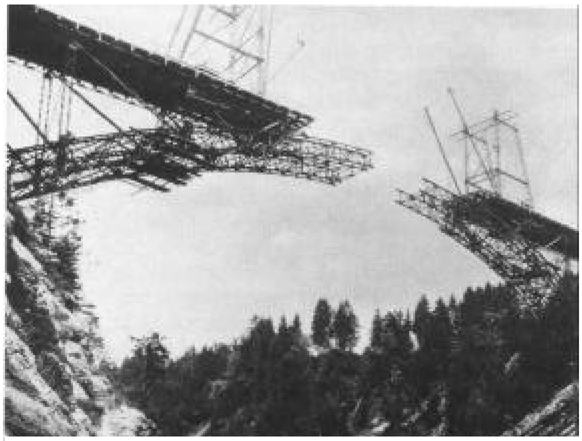

Figure 8 Ammer shuttering, Echelsbach, Austria

To avoid this difficulty, scaffolding to be embedded in the final structure was developed. One of the early structures of this type was that developed in 1898 by the Austrian engineer Josef Melan. He used an steel truss with chords, disgonals and vertical members which was cantilevered out. The bottom chord was a box truss and will acted after as the shuttering itself. The best-known bridge using this system was the Echelsbach Bridge in Austria, constructed in 1929 (Fig. 8). However, the procedure never caught on in Europe fully, as the costs of setting up the materials and the truss boxes were more expensive than the bridge itself. However, in the United States the system became popular, to the extent that one construction company was set up to specialise specifically in Melan system bridges.

Freyssinet design a series of arches in the first half of the 20th century which contributed significantly to the development of this kind of bridges. In 1910 he built a 100-metre-span arch at Villeneuve-sur-Lot which was so lightly reinforced that some authors regard it as a plain concrete bridge. In 1925 he constructed the arch bridge of Plougastel, with three spans, each measuring 180 metres. The most notable feature of these arches was the scaffolding (Figs. 9), which was floated into place from one arch to the next.

Figure 9 Plougastel arch shuttering

The difficulties in setting up the shuttering persisted, and Freyssinet had his work cut out finding ways of making the process cheaper. The arches of la Guaira, Venezuela, with spans of 152 metres, built in 1952 for the motorway linking Caracas to La Guaira airport, proved a significant step forward and the forerunner of modern construction methods.

The construction method (Fig. 10) consisted of advancing a wooden shuttering from the approach viaducts at both ends of the bridge. The scaffolding were stayed with cables from the approach piers, which were

Figure 10 The Guaira arches shuttering, Venezuela

firmly back-tied to the approach viaducts behind. This process gained 36 metres on each side, leaving a middle span of 80 metres. The end scaffoldings down slab were then concreted. Next, a shuttering for the remaining 80-metre span was lifted into place, using stay cable arch to maintain its shape during lifting. Lifting the central span, which weighed some 200 tonnes, was done by electric winches. Once in place, the 80 metres were concreted ring by ring, together with the remaining rings of the end arch sections. The stays were then struck.

Construction of the Sandö arch bridge, with a span of 264 metres, began in 1938, using a shuttering system similar to that of the Plougaste, floated into position. However, it sank during construction killing 17 people. The exact cause was never established and the new shuttering was much more conservative. It was series of very close piers that support the formwork and close the span temporary. The bridge was completed in 1942 and held the world record in span length until the construction of the Arrabida Bridge in Porto.

Figure 11 Lifting Arrabida central shuttering

The Arrabida, with a span of 270 metres, was inaugurated in 1963. It is a twin-arch bridge, each arch comprising a double caisson of reinforced concrete. In addition, the caissons are connected by reinforced concrete cross-trussed. The designer was Edgar Cardoso. The bridge was built using a metal self resistant steel shuttering for each of the arches covering the entire span. The shuttering comprised three longitudinal beams connected together by trusses horizontally and vertically. The assembly of the formwork was very similar to the process employed for the La Guaira Bridge (but using steel instead of wood). As then, the end sections of the arch were constructed first, using scaffolding and backstays anchoring them to the shore pier. Then the central section was winched into place from the semi-arch ends (Fig. 11). The shuttering platform was first situated downstream from first twin arch, when concreting manoeuvred upstream into place to concrete the second twin arch. Finally, it was positioned between the two twin arch to concrete the truss connection.

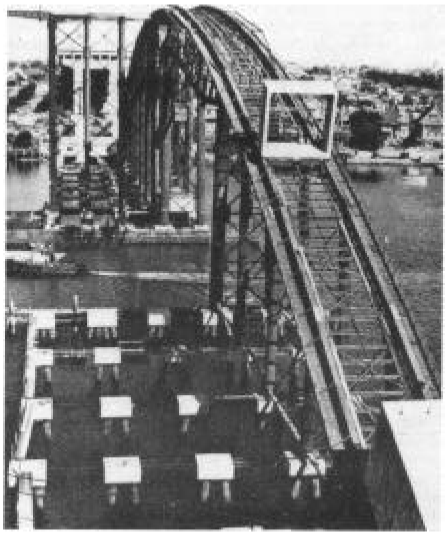

Figure 12 Glandesville Segment

The Arrabida held the span record for only a short time, as the arch bridge of Gladesville in Australia was inaugurated only shortly afterwards. Eugene Freyssinet was an advisor on the project. This is a 305-metre span bridge, also completed in 1963. The most important innovation of this bridge was the use of precast segment positioned over a falsework (Fig. 12), similar to the second shuttering arrangement of Sandö. the segments were without any reinforcement through the joints. Freyssinet had already built a series of five bridges over the River Marne using prefabricated segments with prestressed cables and without reinforcement through the joints, so this construction technique was already familiar to him. The new idea for the Gladesville Bridge was to change de prestressed cables used in the Marne bridges by the axial force of compression from the arch itself. Although the technique was called into question at the time, the fact is that the bridge has worked perfectly up to today.

3.3. Modern Concrete Arches

The next bridge to win the record for span was the Krk I in Croatia. This arch bridge was opened in 1979. It has a span of 390 metres. The designer was Ilija Stojadinovic. He was an engineer who had previously design a number of wide-span bridges along the cliff-strewn coastline of the Adriatic in Croatia, and finaly he design the Krk I and Krk II bridges to link Krk Island to the mainland.

In fact (Fig. 13), Krk I extends underwater by virtue of the fact that the arch is divided into two struts at either end (precisely where it reaches a span of 390 metres). One of these strut is submerged, while the other is just out of the water. It seems that this design was used to simplify construction of the submerged section. When it came to establishing the span of the arch, it was declared that the submerged section was not part of the span but of the foundation abutment, a highly arguable assertion. If the submerged sections at each end were considered part of the arch for the purpose of measuring span, Krk I would still hold the world record today.

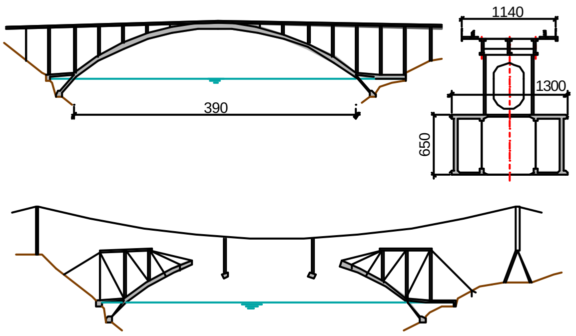

Figure 13 Krk IArch, Croatia

The bridge was constructed by cantilever with temporary diagonal stays. The main arch employed single-cell prefabricated segments to which were affixed the side cells using longitudinal and transverse joints. The blocks were lifted into place using a cableway with a lifting capacity of only 10 tonnes on each side.

A paper given at the previous Arch´01 international conference by engineers from the University of Croatia reported that the current condition of this arch was poor, as a consequence of the high number of prefabricated elements, employing multiple joints, in a harsh environment and poor-quality execution, thus threatening the useful life of this magna construction. At present work has begun on surveying and repairing the damaged components of both Krk I and Krk II.

Figure 14 Waxian arch, China

The present world record for the span of a concrete arch bridge, is held by the Wanxian Bridge over the Yangtze River in China. In addition it is ranked fifth in the list of steel arches. It has a span of 420 metres (Fig. 14) and has a three-cell cross-section. The Waxian arch was designed by W. Li and completed in 1996. It was built using embedded formwork comprising a latticework structure of concrete-filled steel tubes (CFST) (Fig. 15). Extensive testing has produced exact knowledge of the performance and resistance of these CFST. The concrete filling improves compression, which is an essential requirement when using them in a lattice arch. Formwork positioning and concreting was carried out by means of a cable crane. Concreting was done ring by ring transversally and section by section longitudinally, to avoid overloading the formwork each time.

Figure 15 Waxian Shuttering

The Wanxian arch bridge bears an extraordinary resemblance to that design by Martín Gil in Zamora in Spain, having a span of 209 metres, which was the world record for a rail bridge in its day, 1947. Martin Gil originally intended to use conventional wooden formwork, which was accordingly set up. However, the Spanish Civil War intervened and the bridge could not be concreted. By the time the war ended the formwork was in a sorry state and Eduardo Torroja was commissioned to come up with a solution for the unfinished arch. Torroja opted for embedded girder formwork that he build over the old wooden scaffolding, using a cable crane to present the building materials. As the construction photographs and the final arch show, the resemblance with the Wanxian arch is astonishing. In addition, the transverse sections are also identical as was the ring by ring concreting, as first executed by E. Torroja on Martin Gil's arch.

Figure 16 Los Tilos arch, La Palma, Spain

In Spain the arch having the longest span is that of Los Tilos on the Canary Island of La Palma (Fig. 16). It was inaugurated in 2004 and designed by this paper author. It has a span of 255 metres, with a span/height ration of 5.3, a single-cell box structure measuring 3.0 by 6.0

metres throughout, with concrete piers and a composite deck 12.0 metres wide. Thus the arch-pier-deck combination presents exceptional slenderness against wind during construction and also against instability out of its plane. Both the arch and the piers are constructed of high-resistant concrete H-75 which permitted that thickness webs and slabs only 20 and 25 centimetres could be used.

Figure 17 Ricobayo arch, Zamora, Spain

The arch was constructed by cantilever with temporary diagonal stays (a procedure the designer had ample experience of when building the Ricobayo arch, 170 m span, Fig. 17). The key of the arch was closed with a previous opening of 16-centimetre to compensate elastic shortening, shrinkage, creep and temperature difference with the annual average.

Figure 18 Hell Gate, New Cork, EEUU

4. EVOLUTION OF STEEL ARCHES

In parallel with the evolution of concrete arches, steel arches also evolved extraordinarily. We shall only refer to the four with greatest span currently in existence.

The arches of Hell Gate, Sydney Harbour and Bayonne are linked by a common history. In fact, when the tender for the Sydney Harbour arch was organized, they had initially thought of suspension bridges. However several persons of the jury visited New York to see the Manhattan bridges and saw the beautiful arch of Hell Gate over East River before it reached Manhattan Island (Fig. 18). After that, they decided that the Australian bridge had to be similar to Hell Gate in New York. And the tender was awarded to an arch that was practically a replica of Hell Gate with the only difference that the New York arch had a 200 m span and the Sydney one 503 m (Fig. 19).

Figure 19 Sydney Harbour, Sydney Australia

The story did not end there as the Bridge Authority of Manhattan Island, jealous of new world record and the replica they had made, decided to build an identical bridge but with an additional 1 m. in span. It was Bayonne Bridge (Fig. 20), which joins New Jersey with State Island and has a span of 504 m. Contrary to the two previous ones, the Bayonne arch has no

Figure 20 Bayona arch, New York

stone towers at its abutments. Aesthetically is less beautiful and statically confirms that these towers are not really required, although with their weight help to incline less the resulting thrust arch.

The next steel bridge that was a world record was the New Gorge River near Fayetteville. It is located in a privileged area as it crosses a valley at great height over a national park in West Virginia USA. The arch has a span of 518 m. It was designed by Michael Baker and built in 1977 using Corten steel and bolted joints. The construction started by laying a cable using a helicopter as a cable guide for a cableway between both sides. Two towers were built after that in order to position the cableway, which would be used as a crane to carry and place the large steel parts for the arch, the piers and the deck. These parts were big in order to minimize the number of joints; they were manufactured in a workshop (pre-assembly included) and transported by train and road to the site. Progress was achieved through cantilevers with stays to the part of the bridge already constructed at the access viaducts (Fig. 21). The arch was closed by previous opening it using hydraulic cylinders to compensate elastic shortening and differences with the annual average temperature.

Figure 21 New Gorge River Arch construction

As already stated the arch was made of Corten steel and, because the climate in West Virginia is tough in winter, salt was used to fight ice on the pavement. This caused interference in the formation of the copper oxide protection patina as copper chloride was formed instead; therefore the corrosion progressed. Fortunately this problem was discovered in time and proceeded to clean the salt off the bridge and use other chemical agents against ice thereafter.

Figure 22 Lunpu Arch, Shangai, China

The Lupu steel arch over the Huangpu River in Shangai, was finished on 28 June 2003 and its span of 550 m. currently holds the world record for arches (fig 22). The arch was part of a shadow toll highway that connects the North and South of the city.

It is a pass through deck arch that uses cables over the deck as stays. The arch is formed by two lateral arches sloped 1H/5V in relation to the vertical plane, which almost touch in lock. The span rise ratio is 5.5. The cross section of each of these arches is formed by a steel unicellular box of constant width (5 m) and variable depth (6 m in key and 9 m in starters). The deck is itself a steel cross section orthotropic slab with two boxes on the ends. The deck also has prestressed horizontal cables on its ends to absorb the arch thrust. The deck is 39.5 m wide and has a constant depth of 2.7 m. The deck on the side span is modified to a closed section with the same depth. There are 27 cross bracing beams, at a distance of 13.5 m between arches on the deck under arch section and some additional ones below the deck on the deck over the arch sections. These beams also have a totally closed box section.

The construction was performed simultaneously from both banks of the river. All on-site joints were executed through welding. The arch sections under the deck were built first including their piers and deck. After that progress was made with the cantilever tied provisionally to temporary towers, which were built precisely on top of the ones for the main arch. Once erection reached the key the arch was closed by a segment welded on one side and secured temporarily by bolts on the other, which meant it was possible to wait for a temperature of 20º (estimated as the average annual temperature) to close the arch. The deck was then raised from the arch using lifting equipment mounted on wheel machinery that rolled over the arches (fig. 23). Dehumidifiers were installed inside the deck and arches and they have been monitored to review their future structural behaviour.

Figure 23 Lifting Deck, Stays and horizontal cables

It is worth highlighting that, in relation to the alternative solutions reviewed during the preliminary analysis, the arch was cheaper than a suspension bridge and slightly more expensive that a stay bridge. It is also worth highlighting that the type of closed-web arch is different than the bridges that had held the world record until that time (which were trussed); the justification provided by the designers for this decision was purely aesthetic, but there is no doubt it must have increased its cost.

5. FUTURE EVOLUTION OF ARCHES

5.1. Concrete arch bridges

In the tender for the Millau viaduct in France, Jean Muller and Alain Spielmann presented a concrete arch solution with a span of 602 m. The solution included two variants; one with a concrete deck and the other with a steel deck. The arch (Fig. 24) had a hexagonal box section with a continuous depth of 8.0 m. and variable width from 8.0 to 18.0 m. The span between piers over the arch was 85 m. approximately; in the key area, the deck and arch are connected over a 105 m stretch. The construction process was similar to the Guaira bridges. First the

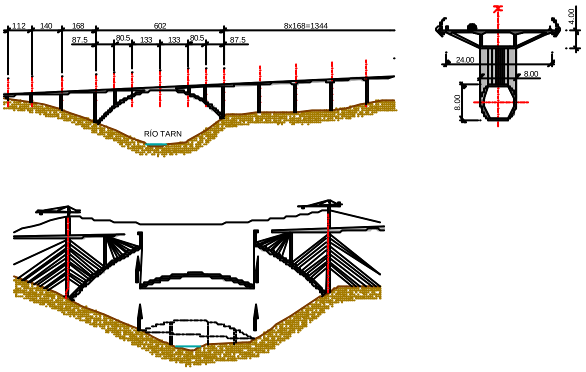

Figure 24 Millau arch, dimension, construction

arch cantilever starters were built tied to the arch starter pier up to 170 m. Then a steel truss scaffolding was built with a concreted lower slab and then raised by "lifting" with a weight of 2,300 Tm. According to the budgets prepared for this quotation, the solution competed with the multiple span stay viaduct that was built.

5.2. CFST arch bridges

China has built several arch bridges in recent years (see page 816 of Arch´01 proceeding). Of the 24 recorded arches with spans extending more than 200 m., 19 are of CFST truss type. Similar to the falsework used for the Wanxian but without concreting afterwards; i.e.: it has a definitive arch truss. This would seem like going back to the type of trusses established as typical for major steel arches; only, in this case we could say these are composite trusses as the steel pipes are filled with concrete. In addition, most of these arches match the type of intermediate deck (middle of rise in many cases).

As part of this CFST type, we should highlight the Wusha arch over the Yangtse River (fig. 25) near the Three Gorges Dam. This arch bridge has a span of 460 m., which surpasses the concrete bridge record, held by Wanxian with 420 m., and gets close to steel arch bridges (Lunpu 550 m). The rise/span ratio has an unusual 3.8 value (which is quite low); i.e.: it is a highly rised arch as can be seen in the only photograph available of this arch on the Internet. Its construction was finished recently and is based on cantilevers tied to temporary towers over the starter pier.

Figure 25 Whusa arch, Yangtse river, China

Another arch with documentation and pictures is the arch of Yajisha over the Zhugiang River (fig. 26) is a highway bridge with a span of 360 m. (spans similar to the longest concrete arches). The cross section are two arches, one on each side of the highway and each arch section has the particularity of holding two concrete slabs as lower and upper chords. It is also an intermediate deck arch, which was built using an ingenious double rotation system. First, they built half of each arch and the lateral spans on each side in parallel to the river; then they erected the semi-arches of the main span to its position by turning the horizontal axis and using stays to a temporary tower over the starter pier; finally, the set of semi-arches and counterweight side spans where turned on the vertical axis of the starter pier to its definitive position. After completing the turn, it was closed with a key segment.

Figure 26 Yajisha arch, Zhugian riverChina

6. CONCLUSIONS

6.1 Average and minor span arches

Firstly, it seems easy to predict that: arches of average span (between 125 and 250 m) will continue to be built considering that the three existing construction methods without shuttering (Stays, temporary diagonals and rotation) makes them very competitive in this span range compared to other types (Suspension bridges for high spans and Stay cable bridges for short ones). Even below these spans, arches will continue to be built for purely aesthetic reasons, especially arches with a lower or intermediate deck where the structure is visible to users.

6.2. Big span arches

Structural behaviour

Secondly: Regarding the long spans, we have made some design and calculations with high resistance concrete arch bridges. We have calculated single arches with a span of 600 to 1000 m. and reasonable geometries in terms of wide, depth, thickness, etc. and twin arches for highways, separating the two carriage-ways in two decks and cross-bracing both arches with horizontal beams between them. The conclusion is that the structural limits of these arches, including the stability in and out of the arch plane, extend beyond 1000 m for the single one and let say 2000 m for the twin ones. So it is not a problem of structural strength.

It is a financial problem, construction difficulties and the alternatives provided in other types. What are the limits of cantilever construction of shuttering? What are the spans when other types become more competitive? Or said in another way, what are the essential competitive advantages and disadvantages of these other types compared to arches. As already stated, the competitive type is Stay cable bridges and further away is Suspended bridges. We define the current span range for Stay cable bridges to be from 200 to 1000 m. and suspended from 750 to 3,500 m. we could perform the following conceptual comparisons:

Typology

In comparison with Stay cable bridges we find that, long spans around 1,000 m., the towers are around 20% of the span; i.e.: 200 m., which undoubtedly penalizes the cost of these bridges. Inasmuch as the piers of an upper deck arch are very high (for a classic span /

deflection ratio of 5.5, we would have piers over the abutment of almost 200 m which would heavily penalize the cost of the bridge. Hence it would seem that for long spans, one should use the intermediate deck design as was performed with almost all long spanned steel arch bridges (in particular the current record holder: Lupu Bridge) and the Chinese CFST bridges (in particular the Wusha). Therefore with a span / deflection ratio of 6, one could obtain abutment piers of 70 m and a maximum height of the arch above deck around 100 m for hanging cables; these cables could be cheaper than cables of Stay bridges, which are inclined and more than 540 m long.

In these conditions it would seem that a high resistance concrete arch bridge, composed or with lost steel falsework, with intermediate deck and span / rise ratios around 5.5 or 6 and a good foundation to absorb the thrust of the arch could compete with Stay cable bridge with a span up to 1000 m. It does seem likely that longer span arches can compete with suspension bridges. After all, suspension bridges are arches working on traction, much easier to build and, today, without stability problems thanks to testing of new sections in wind tunnels.

New materials and construction process

In terms of new materials, it seems that high resistance concrete and superplastified and self-compacting concrete will be most used. On one hand, the towers of Stay cable bridges with 1,000 m span should be made of high resistance reinforced concrete rather than steel in order to be competitive. Therefore in the case of arches, these should be concrete arches erected over steel shuttering. This way, the shuttering could be erected (with much less weight than the definitive arch) in cantilever with temporary diagonals and/or stays. In addition, one should try to maximize the collaboration of the shuttering material in the final arch in order to cost optimize. Shuttering erections (such as Ricobayo or Wanxian) to leave it as a part of the definitive arch. Or filling the tubes with high resistance self-compacting concrete but without external concreting (like the Wushan an another Chinese arches), would be most competitive.

By the other hand we do not think that the new organic cables will be successful for general application in the future, because of its price and technical characteristic.

Biggest an average spans

Therefore in terms of span: The average range of spans (i.e.: optimal spans or span range) where arches would be more competitive will be around double the existing ones, around 300 or 400 m.

In terms of maximum spans, it seems that the current span up to 550 m. could be extended in the most advanced designs to around 1000 m. This means the field offered to the imagination of structural engineers is still very wide in terms of arches.