

PROCEDURES FOR THE CONSTRUCTION OF LARGE CONCRETE ARCHES

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Abstract: *There are different procedures for building large concrete arches. Most of them were first used in steel arches and later on in concrete arches. Therefore, to learn about the evolution and the development of the concrete arches construction, we ought to go back to steel arches.*

The first construction procedure used in concrete arches was concreting on a centering. The cost, however, made this procedure unfeasible for large arches. Another variant is that of a scaffolding truss that consists of building the arch using a stiff reinforcement that serves as a centering. The world's largest concrete arch was built using this procedure.

The construction procedure using free cantilevers has been applied in many arches both the steel and concrete ones. There are various possible variants here: cable-stayed cantilevers, cantilevers with provisional supports, and lattice structure cantilevers using semi-arches, deck, vertical elements and provisional diagonals.

The last procedure studied in this article was used in two arches we built in Bilbao. It consists of building the semi-arches in a quasi-vertical position and then rotating them by means of provisional hinges placed at the arch feet and a back stay until joining the two semi-arches at the keystone by means of another provisional hinge.

1. INTRODUCTION. THE ARCH AND ITS CONSTRUCTION

Every resistant structure, just like any other material object, has a shape. But when we speak of the arch we can say that the shape itself is the structure. In this quality of the arch, which is a structure that resists due to its shape, lies its greatest advantage as well as its biggest inconvenience, since in order to be able to function as an arch it has to be complete. Therefore, all partial structures that may arise during the construction of the arch have little to do with the final structure. It is this fact that the difficulty and the cost of construction of large arches stem from.

Throughout history, the same construction procedures have been used in steel and in concrete bridges and, leaving aside rare exceptions, all these procedures were first used in steel bridges and then later applied to the concrete ones. This is due to the fact that, in the first place, steel bridges began to be built one century earlier than concrete ones, and secondly, steel bridges are lighter, which makes their construction easier and leaves more room for innovation.

In arches, in other types of bridges, there are two possible systems of construction:

A. The use of an auxiliary structure that supports the arch until it is finished.

This system includes both centerings and scaffolding trusses.

B. Building the arch by means of partial structures, using different resistant structures, until closing it at the keystone, which is when the arch begins to function.

The partial structure that has been used most often, both for the construction of large steel arches as for those made of concrete, is the free-cantilevered construction of the two semi-arches until closing them at the keystone. These cantilevers usually require an additional structure because free-cantilevered semi-arches have no resistant capacity.

Another construction procedure consists of building the semi-arches in a quasi-vertical position on the abutments and rotating them over hinges placed at the foot by means of a stay which holds them until they are joined at the keystone.

2. ARCH CONSTRUCTION USING AUXILIARY STRUCTURES

As we have said, all the bridges until the 19th century were built using this system. All stone bridges were built using wooden centerings. This is a system easy to use that is still applied and will continue to be applied in the construction of small and medium span arches. However, in large-span arches, the cost of the centering became almost the same as the cost of the bridge itself, which has made the construction by means of a centering not economically feasible in these arches. This is why great concrete arches stopped being built for some



F-1. Plougastel Bridge. A. The centering. B. The first arch cast and the centering in the second.

time, until



F-2. Sando Bridge. A. The first centering. B. The second centering.

266 m span arch finished in 1942. However, when the arch concreting began, the centering collapsed causing a great number of casualties. The centering was rebuilt using a palisade supported on piles arranged close together.

Another wooden centering similar to the above one also caused problems. It was that of the railway viaduct over the Esla River 209 m long. This centering was built before the Spanish Civil War and it remained deprived of all maintenance during the three war years. Once the War was over and after the Sando River centering collapsed, it was decided to use it only to build a light scaffolding arch-truss. When the arch truss was completed the centering was removed. The bridge was finished in 1942.

Other remarkable wooden centrings are those built by Richard Coray for the Swiss arches spanning the gorges in the Alps. He built them using cantilevered construction until closing the arches at the keystone. The Salgina-Tobel Bridge by Robert Maillart has a 90-m span while the Trient Schlucht Bridge by Albert Sarrasin is 98.6 m long.

construction procedures that avoided using centerings became widespread.

For many years large-span concrete arches were built using wooden centerings. This is how Freyssinet built his arches. An outstanding one among these bridges is the Plougastel Bridge over the Elorn River with three arches and a 186 m span, built over an only centering, a wooden arch, in its turn, of the same span as the bridge arches with a bottom stay. The centering was supported on two barges under the arch feet, by which they were transported from one arch to the other. The centering was supported on the abutments used for the arch concreting. Once the concreting was over, the centering was removed by means of the stay. The centering remained supported on the barges in order to be moved to the next position. This bridge is one of the engineering masterpieces of all times, basically due to its construction procedure.

Another centering, similar to that used in Plougastel was used in the Sando Bridge. This is a



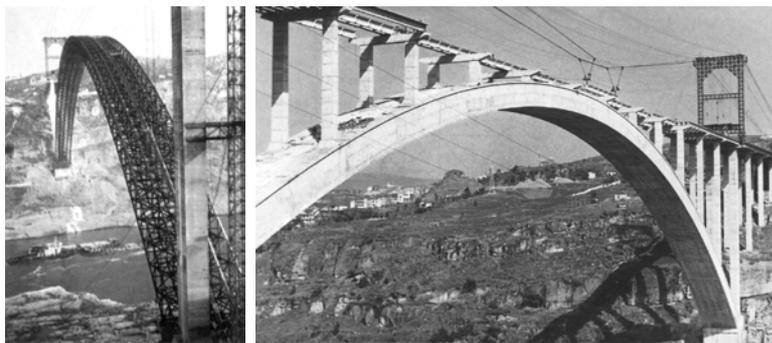
F-3. Echelsbach Bridge built with scaffolding truss. A. Steel arch construction.

In some great arches the centering consisted of a steel arch made of a box section whose span had the same dimensions as the definitive one. This is how the 181m span Traneberg Bridge in Stockholm was built in 1934, as well as the 270-m span Arrábida one in Porto, built in 1963. This is also how the twin vaults of the bridges were built with the centering moving transversely. In the Arrábida Bridge it was later attempted to use the centering to build a railway bridge of the same span but it was not possible and the centering had to be sold as scrap iron. The cost turned out to be disproportionate.

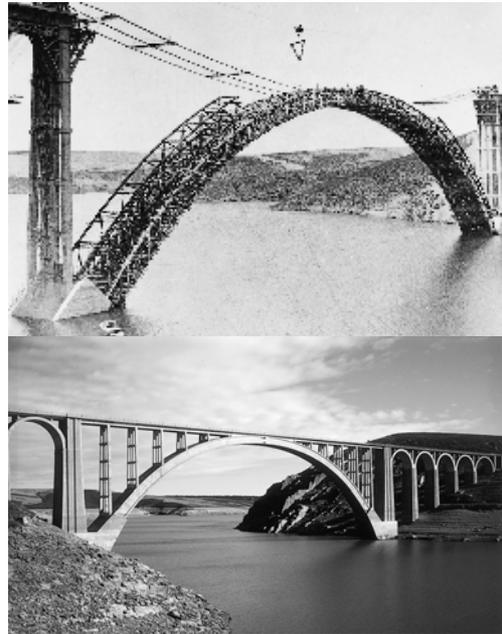
The constructing system using the scaffolding arch truss was invented by the Czech engineer Joseph Melan. It consists of building a steel lattice arch first, which serves both as the scaffolding truss and as the reinforcement of the definitive arch. The disadvantage lies in the fact that the amount of steel required by the initial arch is greater than the reinforcement required by the concrete arch.

What is really achieved using this system, the same as with the Traneberg and the Arrábida centerings, is to exchange the difficulty of the construction of a heavier arch such as the concrete one for a lighter arch such as the steel one. This initial steel arch has to be built using any of the methods not requiring a centering, except in the case of the Esla Viaduct we mentioned above, where the metallic arch was built on a centering.

In the concreting of the Esla River Viaduct, Eduardo Torroja introduced the variant of concreting the arch by partial segments going from one end to the other. This was performed in such a way that for the concreting of a segment, the concrete of the previous ones collaborated in the stiff reinforcement, which allowed the reduction of the amount of steel used for the reinforcement.



F-5. Waxian Bridge. A. The scaffolding arch-truss.



F-4. Esla Bridge. A. Erection of the steel arch on the wood centering.

This procedure was also used to build the Waxian arch over the Yang Tse River in China with a 420 m span, completed in 1997, currently the largest concrete arch in the world. The scaffolding truss was a tubular structure and the arch was concreting segment by segment as in the Esla Bridge.

Presently there is a variant of stiff reinforcement being used of a box section arch that is later filled with concrete, leaving the steel arch exposed. This is therefore a composite structure arch. Examples of this system are the Tamaraceite Reservoir Bridge, a 160m span arch with an intermediate deck built in 1993, the 170m span Ricobayo Bridge built in 1996 and the Bridge over the Ebro River in Zaragoza, a 120m span upper arch built in 2002.



F-6. Sydney Bridge.

3. FREE-CANTILEVERED CONSTRUCTION OF ARCHES

The most frequently used method for the construction of large arches, both steel and concrete ones, consists of building the two semi-arches in free cantilevers beginning at the arch feet until closing them at the keystone. In most arches, the free-cantilevered semi-arches do not, themselves resist; which is why they require an auxiliary structure until closing them at the keystone. Four different procedures may be considered within this construction system:

- A. Construction of the semi-arches by means of free cantilevers.
- B. Construction of the semi-arches by means of cable-stayed cantilevers.
- C. Cantilevered construction of the semi-arches with provisional intermediate supports
- D. Simultaneous construction of the semi-arches, the deck and the vertical elements, adding provisional diagonals in order to achieve lattice cantilevers.

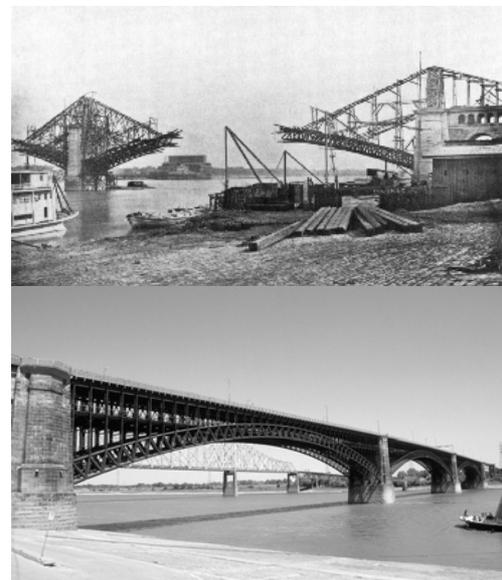
3.1. Construction of semi-arches by means of free cantilevers

In some steel arches made of a lattice structure, the cantilevers of the semi-arches required a minimum auxiliary structure and we can therefore consider the construction to have been performed in free cantilevers.

The arch that was actually built using the free-cantilevered construction system was that of the Sydney Bridge a double-hinged 503 m span arch built in 1932. The semi-arches were provisionally built-in lengthening the arch's upper chord by means of stays.

The semi-arches were then completed using the free-cantilevered construction system.

The Hell Gate Bridge in New York has a 298 m span, and was built in 1917. It also has a double-hinged arch and in this case the provisional build-in was performed using top bars that are actually the



F-7. San Louis Bridge

cable-staying system of the first part of the arch although most of it was built in free cantilevers.

The 329m span Birchenough Bridge, which was completed in 1935, was built in a similar way as the New York Bridge, with a single stay.

3.2. Construction of semi-arches by means of cable-stayed cantilevers

This is the most widely used system in the construction of large arches. It consists of provisionally cable-staying the subsequent cantilevers of the semi-arches until closing them at the keystone.

The first bridge built following this procedure was the San Luis Bridge over the Mississippi River, finished in 1874, also called the Eads Bridge in memory of John Eads, its designer. It has three arches of 152+157+152 m spans.



F-8. Garabit Bridge

This is one of the most innovative bridges in history for various reasons. The main reason is that this is the first bridge to be built using free cantilevers, not only amongst arch bridges but in any other bridge type as well, included girder ones. After this bridge was built, the free-cantilevered construction procedure quickly spread in all bridge types.



F-9. Shanghai Bridge under construction

The two classical methods of free-cantilevered construction were used in this bridge: the compensated cantilevers progressing symmetrically from a pier with symmetrical stays and simple cantilevers progressing from an abutment with stays anchored in the ground.

Many steel arches were built applying this procedure. Among these are the two great Eiffel arch bridges: The Maria Pia Bridge over the Duero in Porto of a 160 m span, built in 1877, and the Garabit Bridge over the Thruyere gorge, built in 1884.

The world's two largest arches were built using this procedure, by means of provisional towers placed at the arch feet:

The New River Gorge Bridge in the U.S.A., built in 1976, has a 518 m span and a lattice arch and was for a long time the largest arch in the world.



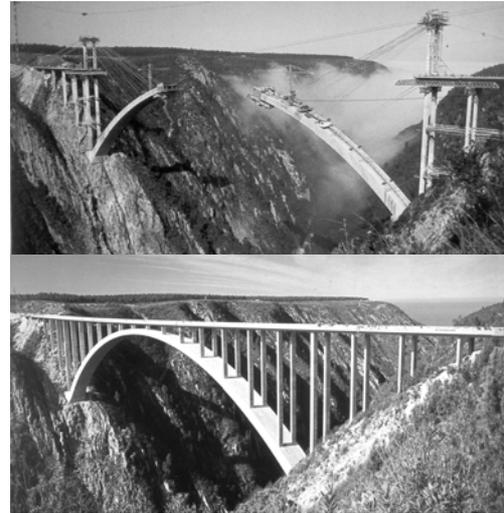
F-10. Caracas-La Guaira Bridge.

The recently completed Shanghai Bridge of a 550 m span is currently the largest arch in the world. This bridge has an intermediate deck with a double-T arch.

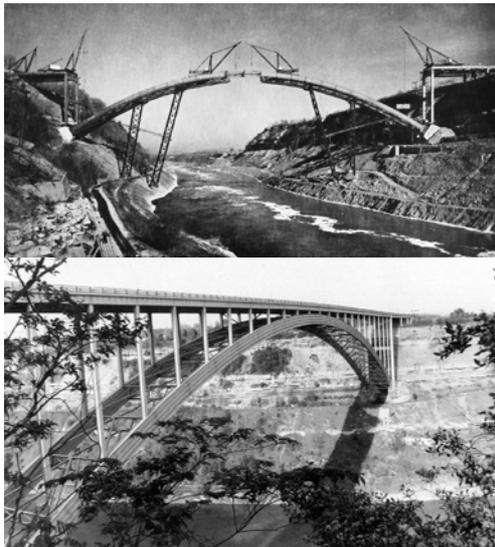
The first engineer to use this procedure in concrete arches was E. Freyssinet in the Caracas-La Guaira Motorway Bridge of a 152 m span, built in 1952. However, he used it only partially because he used this procedure just in one part of the semi-arches. He then arranged a centering suspended from the ends of the parts of the semi-arches already built and concreted the central part of the arch over it.

In 1964, in Great Britain, the Taf Fechan 68 m span arch was built. Its semi-arches were completely cable-stayed until they were closed at the keystone.

After this bridge, the free-cantilevered construction system became widespread in great concrete arches. Among those built using this procedure the great arches in former Yugoslavia are worth mentioning. The largest one of them is the Sibenik 246 m span arch built in 1966. Other outstanding arches were built in South Africa: the Van-Stadens arch of a 200 m span, built in 1971 and Bloukrans arch of a 272 m span, built in 1984. The latter is the largest concrete arch built using this construction procedure.



F-11. Bloukrans Bridge.



F-12. Lewinston and Queenston Bridge

3.3. Construction of arches using provisional intermediate supports

This procedure consists of reducing the free cantilever by using isolated provisional supports. This is how the Bayona Bridge over the Kill Van Kull in New York was built. This is an upper 504 m span arch, built in 1932 and was the largest in the world for a long time.

The same procedure was used in the bridge between Lewinston and Queenston over the Niagara River of a 305 m span, built in 1962. Inclined provisional supports were used in order to allow them to be placed on the riverbanks.

3.4. Simultaneous construction of the semi-arches, the deck and the vertical elements, adding provisional diagonals to achieve lattice cantilevers

This system allows us to turn the arch structure with its vertical elements and diagonals into a *cantilever* beam. The deck must be anchored to the ground in order to resist the bending moments in the arch feet due to the cantilever formed until the arch is closed at the keystone.



F-13. Hokawatsu Bridge

The first concrete arch built using this procedure is that of the Hokawatsu Bridge in Japan of a 170 m span, built in 1974.

The largest of all concrete bridges built by means of this procedure is the one at the Krk Island in former Yugoslavia of a 390 m span, built in 1979. It was the largest concrete arch in the world for a long period of time.

This bridge did not use the deck as the upper chord. It used stay cables instead, which lightened the cantilever whole. Once the arch was closed the stays were removed and the deck built.

3.5. Construction of the arch through the rotation of the semi-arches

This procedure consists of building two semi-arches in a quasi-vertical position over the abutments and rotating them later on by means of a back stay, until closing them at the keystone. We think that there exists no better illustration of this construction procedure than the dual definition of the arch by

Leonardo Da Vinci: “*a strength caused by two weaknesses... it is composed of two quarters of a circle, each one extremely weak by itself tending to fall. They oppose their own weakness in the other and thus two weaknesses become a single strength*”.

We know of no steel arch built using this construction procedure before concrete bridges. It was first used in 1943 to build the wooden arches of the centering of the Longeray sur le Rhône Viaduct with three concrete arches of a 69 m span. It was also used to build the wooden arch of the centering of the Saboya Bridge, also over the Rhône, of an 80 m span, built shortly after.



F-14. Semi-arches rotation in the Bolueta 1 Bridge



F-15. Storms River Bridge

The first engineer to use a procedure similar to the free rotating of the semi-arches in a concrete bridge was Ricardo Morandi in the Torrente Lussia Footbridge in Italy, of a 70 m span, completed in 1953. In this footbridge he built the semi-arches supported on the riverbanks and he then rotated them until supporting them against a central tower that was removed once the arch was closed.

The procedure of building the arches with prefabricated semi-arches was applied by Carlos Fernández Casado in various bridges. The Mérida Bridge over the Gadiana River, built in 1955, has eight 60 m spans built using prefabricated semi-rings that were raised first on the abutments and then by using a central tower until closing them at the



F-16. Argentobel Bridge

m span arch. The semi-arches were built in a quasi-vertical position over the abutments and were then rotated simultaneously until closing them at the keystone without using a provisional tower.

The same procedure was used in 1987 to build the Argentobel Bridge in Germany of a 145 m span. This is the largest bridge built using this procedure.

Four bridges were built in Japan one after another, each one of greater span than the previous one:

The first one, the Uchinokura Bridge has a 37 m span and was completed in 1988.

The second one, the Senpiro Bridge of a 60 m span was finished in 1993.

The third one, the Sanganme Bridge, has a 90 m span and was over in 1999.

The fourth one, the Kobaru Bridge of a 135 m span was finished in 2002. This is an asymmetrical arch and it was built with two asymmetrical arches.

We used this procedure to build two bridges for the Bilbao Underground over the Nervión River of 63 and 58 m spans respectively. They are located very close to each other and were built successively.

We adopted the system of rotated semi-arches instead of building the semi-arches using the free cable-stayed cantilevers because the means required to perform the rotation for the span of these arches are less and, although the arches are not the same, all the auxiliary assembly means can be used for both bridges.

The semi-arches are built in a quasi-vertical position over the abutments by means of a climbing formwork in the same way as when the piers of a

keystone. Once the rings were placed, the vaults were

completed fixing the formworks on the rings that were included in the final arches. We can

say that these were arches built using a concrete scaffolding truss. In the bridge over the spillway of the Cubillas Reservoir a spandrel arch of a 50 m span was built in 1954. In the bridge over the Cuadal River in Mieres, another spandrel arch of a 70m span, built in 1968, the initial semi-rings of the arches were built on the abutments and on a provisional tower until closing the arch at the keystone and the spandrels were then concreted over them.

In 1954 Morandi used the system of rotation until closure at the keystone for the first time to build the Storms River Bridge in South Africa. This was a 100



F-17. Kobaru Bridge



F-18. The Bolueta Bridge semi-arches

bridge are built. The initial position of the semi-arches must be as vertical as possible in order to make their construction easier. Since they are supported on hinges their position may be varied during construction in order to place the climbing formwork remains in a vertical position while concreting each segment, which reduces the cost of the formwork. This procedure has been used in some bridges built by means of this construction method.

It is convenient for the stability of the whole that the vertical of the centre of gravity of the semi-arch remains initially outside the

arch span in order to use the overturning moment to support the semi-arch on the extrados. Since the semi-arches are supported at the foot on provisional hinges used to perform the rotation, in order to assure their stability during construction they had to be provisionally blocked. In the Bilbao bridges the blocking was performed using concrete diaphragms in the extrados of the semi-arches built-in into the foundations of the arches. The diaphragms were fixed to the semi-arches by prestressing bars. In bridges in which the position of the semi-arches varies during concreting, the blockage is performed by means of jacks fixed to the end of the already built part of the deck. These jacks are later used to begin to move the semi-arches.

As we have said, in order to perform the rotation of the semi-arches we had to place hinges at the feet that allowed rotation. After that we also had to place a hinge in the keystone in order to allow the completion of the initial three-hinged arch. There were various problems to be borne in mind in the design of the provisional hinges:

In the first place, there is the problem of stability during rotation. In the Bilbao Bridges this problem made us arrange two hinges per each half-ring, made with complete gusset plates, joined by a stud over which the rotation was performed. The gusset plates assure the transverse stability against wind thrust during rotation because they are able to resist the tensions in the hinge.



F-19. The rotating hinges

Secondly, they must allow corrections in the plan and in the elevation of the position of the semi-arches once they are rotated in order to make sure the final directrix is correct. This is achieved by placing horizontal jacks between the hinges in the arch feet, and the foundations. The hinges are supported upon Teflon so that they can move. The possible tension that can appear in them due to transverse wind effect is resisted by means of special gusset plates fixed to the foundations, which secure the hinges at the foot and allow them to move.



F-20. Bolueta 1 Bridge

The back jacks are also used to retrieve the pieces forming the provisional hinges, once the concreting of the first stage of the hinge blocking is completed. It is only then that the jacks are unloaded and all the pieces can be removed.

The keystone hinges are similar to those placed at the feet. They need to be able to move in all directions so that the studs can be fixed. Jacks are also needed on one of the sides to allow the

unloading of the hinges once the concreting of the first stage of the hinge blocking is completed, and to allow the removal of the pieces forming the hinge.

In order to begin the rotation we had to launch the arch using jacks fixed to one end of the already built deck while on the other side they were attached to the arches. This is because, as we have seen, the semi-arches in their initial position are overturned towards the exterior of the arch. These jacks allowed us to move the semi-arches until the vertical axis of their gravity centre was within the arch span, which allowed them to be rotated using their own



F-21. Bolueta 2 Bridge

weight held by the stay. In some bridges these jacks have been replaced by tensioning from the opposite abutment. From the moment when the vertical axis was placed within the arch span the operation consisted of gradually unloading the backstays by double-effect jacks until the semi-arches met at the keystone. Thus, the initial arch was three-hinged.

At one end, the back stays were fixed on bipods that held the double-effect jacks which gradually released the stays. At the other, they were fixed on

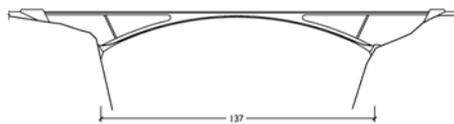
intermediate points of the semi-arches. The bipods were placed away from the arch and were fixed to the ground by a micropiles foundation and an active anchor foundation.

The rotation of the two rings on the riverbanks was performed simultaneously. Once the rotation was over, it was necessary to correct the position of the semi-arches in the plan. This was carried out by moving the hinges at the feet, by means of the horizontal jacks until the semi-arches were fully aligned.

The blocking of the keystone and foot hinges was performed in two stages. The area between the two provisional hinges was concreted first. These hinges were then removed and the concreting was completed.

Once the arches were built-in at the keystone and the feet, the deck was completed using a centering supported on the arches until the bridges were finished.

We are currently building a bridge applying this procedure. It is the 137 m span arch San Sebastian Bridge in the Mexican State of Jalisco, an area of high seismic risk.



F-22. San Sebastián Bridge