ARCH BRIDGES IN SOUTH AMERICA

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SUMMARY

This paper intends to present arch bridges that stood out in South America, by its span up to 290 m, by its architecture, by the constructive method, or by any relevant innovation. They are 5 bridges constructed from 1934 to 2013. Between them one is in Mexico, Latin America, but was especially included by its qualities and similarity to others performed 50 or even 70 years before.

Keywords: *Bridges, arch, concrete, falsework, suspender, hydrology, provisional.*

1. LUSSANVIRA BRIDGE – NOVO ORIENTE-PEREIRA BARRETO [1]

The Lussanvira Bridge was located in vicinity Pereira Barreto over the Tiete River. Unfortunately it was submerged with the filling of the Lake of Three Brothers Hydraulic Power Plant, opened in February of 1991 with the waterway Tiete-Paraná.

The bridge was built in 1934 by Companhia Construtora Nacional (Wayss & Freytag in Brazil) with its own design.

The largest arch in the world at the time was the La Caille Bridge, designed by Albert Caquot and built from 1925 to 1928, spanning 140 m. The second was the bridge over the Seine river in Saint Pierre de Vauvray, designed by Freyssinet in 1923 (132 m). The Lussanvira Bridge, 130 m span, would be the 3rd in the world.

Lussanvira is road bridge 5.7 m wide, suspended by steel ties each 5.2 m to two arches of hollow reinforced concrete section.

The arches are slightly inclined, being the distance between their centers variable from 3.9 m at mid span to 10 m at the supports. This geometry improves bracing and stability of the arches without creating obstruction to the traffic of vehicles (4 m template required at the time).

The arches have a rectangular cellular section 1.2 m wide with variable height from 1.6 to 2.2 m. The walls thickness is 25 cm.

The deck has two beams 20 × 60 cm, 2.5 m apart, which support the slab with variable thickness from 18 cm at mid span to 14 at the edge parapet.

The deck is hanging from the arches by means of special steel ties with, 5 cm thick, without involvement of concrete. Every 5.2 m the ties dive into cross beams that support the deck and give the ties the correct slope. These cross beams 22 × 110 cm, are 50 cm higher than the stringers beams. The deck seems to really float and was built for free longitudinal expansion, having pendulums in one extremity.

The reinforcement detailing was carefully studied. Large hooks fix the ties to the cross beams and include stirrups to prevent the opening of these hook, as well as to confine the anchorage area.

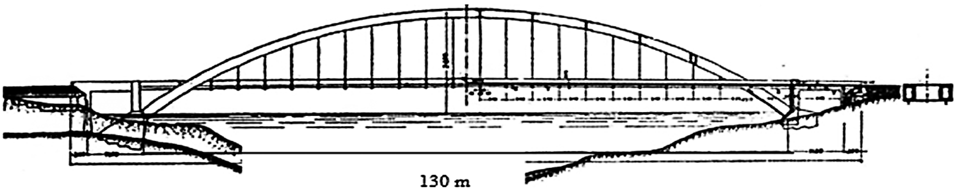

Fig. 1. Bridge longitudinal view.

1.1. Falsework

The falsework of this bridge is its main innovation, composing an original construction procedure. Two huge timber towers were built, 50 m height, one in each side, spanning 142 m, with two side spans for the cables anchorage.

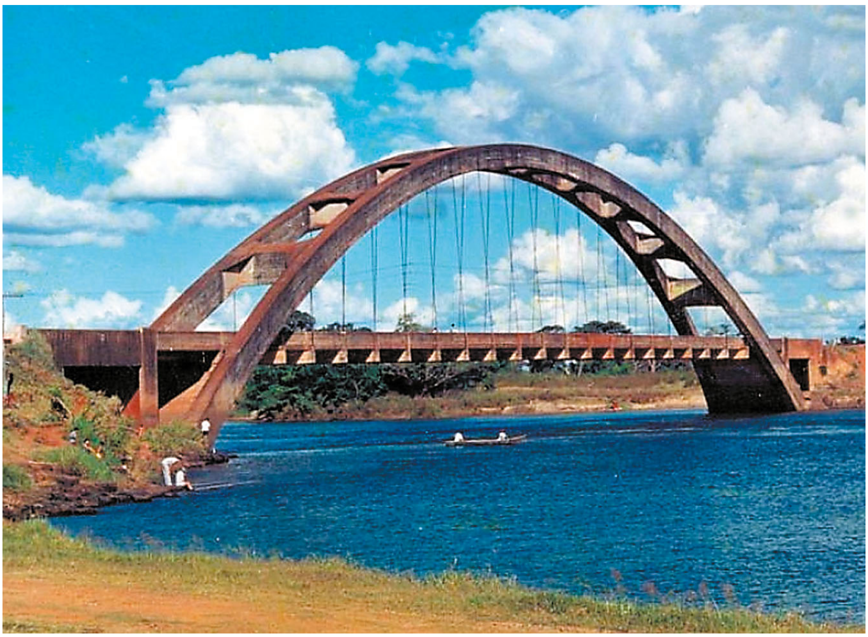

Fig. 2. Bridge view at the end of construction.

As the concrete arch has a 24 m arrow, it was left to the suspended cables no more than another 24 m arrow, but reversed. The falsework, made of a timber trusses, are hung on the cables by means of ties spaced of 4 m. It results a falsework built from auxiliary suspended cables.

These cables came from the Railway São Paulo – Santos, specifically from the inclined planes, already out of use. The maximum concentrated load on the top of the towers was of 214 tf.

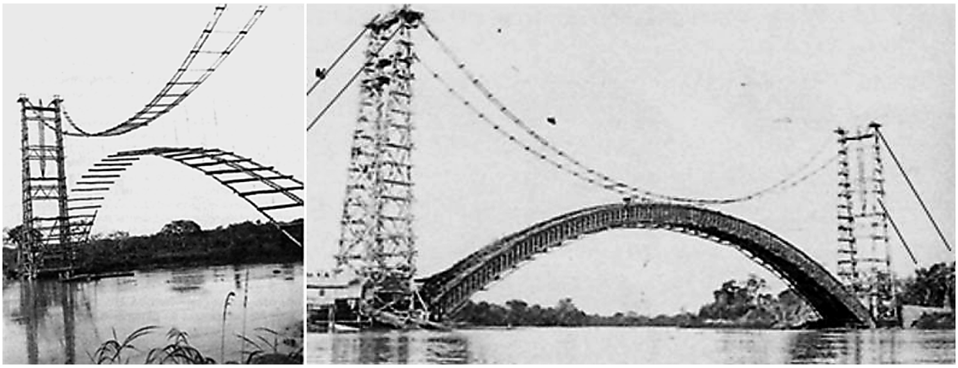

Fig. 3. *Suspension cable and template for falsework (left), Suspension cable and falsework (right).*

It was made a careful calculation and detailing of the funicular cable, the falsework, the towers, the scaffolding and the executive process. It seemed that the main work was the falsework.

Again we find in the La Caille Bridge, of already mentioned, the possible inspiration for the design of this falsework.

2. PROGRESO BRIDGE – JALISCO-MEXICO [2]

Since 1930, the population of San Sebastian Del Oeste, Jalisco, Mexico, ordered the construction of a bridge to span the deep canyon in the middle of the Sierra Madre Occidental connecting the capital, Guadalajara, to the port of Vallarta in the Pacific. After 75 years the bridge was opened to traffic. The bridge reduces the travel time in 1 hour and a half.

The Government of Jalisco launched a Bid won by the Consortium of COCONAL and Cautin Construction.

After a long discussion of alternatives to the official solution, it was decided to build an arch bridge, supported on the banks of the Canyon.

Although this bridge is not in South America, it was chosen for this presentation because it is close, in Latin America, and especially because it applies the same technique used on Lussanvira Bridge, 72 years before.

This information is important, as even after all this time the solution of building falsework from suspended cables remains competitive in cases like this, although many techniques and equipment were created throughout this period. In fact Progress Bridge went a little further away, as used the cables to transport falsework segments and stabilized the part already assembled with stay cables like in Friendship Bridge that will be the next bridge to be described. In Lussanvira Bridge, transportation and stabilization used suspended cables.

Fig. 4. Overview of the Progress Bridge.

Fig. 5. Segments transporting and fixing (left) and Closing segment (right).

More than that, suspended cables, in addition to transport falsework segments, were used carrying materials such as forms, reinforcements, concrete, etc. The masts were 25 m high and 25 m from the Canyon banks.

In May 2005, work began with the execution of footings in the bank slopes and improvements to its stability with injected ties.

At the same time they set up the towers and suspended cables. As each falsework segment was positioned, stay cables were installed to stabilize it.

There were two begging segments, one each side, 24 typical ones and a final closing segment (key stone). Each one weighted between 15 and 20 ton.

Installed the closing segment, the formwork might be installed, as well as the reinforcement that weighed 355 ton. Finally the concrete cellular section was casted with 2300 m^3.

Once the arch was ready, the columns were executed and the deck formwork, supported on the arch and the columns. The deck consists of single-cell cast place in 5 phases: thickening of the arch in the central section and each of the two spans each side.

The prestressing was also performed in 5 stages, reducing the total shortening of the bridge.

Once the deck was completed, provisional structures have been dismantled what was done using the cables still available. The first step was to loosen the screws of the closing segment, freeing it. The two halves of the falsework were disassembled in the reverse order of the assembly by removing segments by segment.

As shown in Fig. 6, the total length of the bridge is 194 m, 137 m of arch span and a deck 10.5 m wide as shown also in Fig. 6.

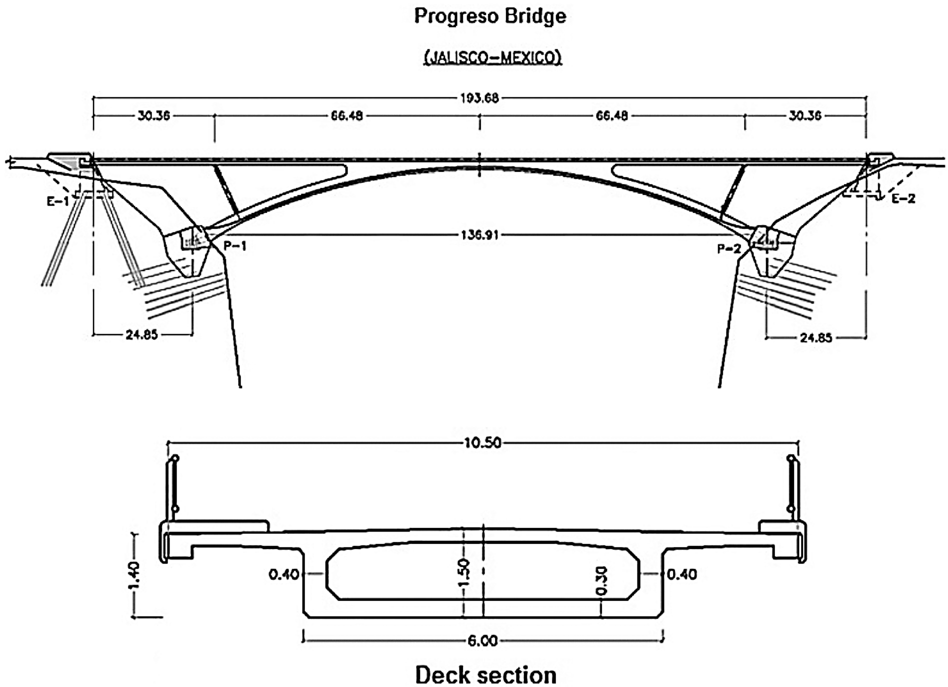

Fig. 6. Lateral view of the bridge (top), cross section (bottom).

3. FRIENDSHIP BRIDGE [1]

The Friendship Bridge connects Foz do Iguaçu, in Brazil, to Ciudad Del Este, in Paraguay, giving passage to the BR 277 road that leads to the Port of Paranaguá. The bridge was built as part of the Brazil-Paraguay Agreement that would give Paraguay access to the Port of Paranaguá.

The Friendship Bridge is a fixed arch with superior deck spanning 290 m, a world record in 1962, at the end of construction.

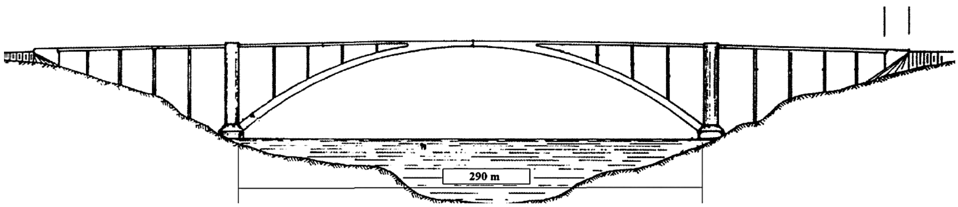

Fig. 7. *Lateral view of Friendship Bridge.*

However, as the highway was delayed and its inauguration took place only in 1965, it was surpassed by Parramatta Bridge in Gladesville, Sydney, Australia, 305 m span.

3.1. Choice of the crossing

The choice of the crossing location was set after exhaustive hydrological studies of the Paraná River during a period of 20 years. In addition bathymetric surveys were carried out covering a width of 140 m along the crossing, a job quite painful at the time in face of the flow and speed of the River. There was even an accident with deaths during this work (Tasso C. Rodrigues the engineer responsible for the survey was one of the dead).

Tasso and his team were able to obtain important data for the design. The area of the drainage basin upstream of the bridge is of 870,000 km^2, greater than the Iberian Peninsula. The stretch of the River between Seven Falls and Iguaçu Falls is 300 m wide and 180 km long. The cross section of the River can be divided into three parts, two lateral steps 75 m wide and a central stretch 150 m wide. The depth on the sides is not very large, reaching 9 m. The central stretch however is a deep channel that reaches 71 m in the flood season, but never gets down to 28 m.

The bed of the River and its banks consist of basalt and siltstone of high resistance. The flow speed of the River varies from 2 to 3 m/s. There are two floods every year, one in the end and another in the middle of the year, related to the rains in the huge basin, accelerated by the long narrow channel.

The preset condition for the design of the bridge was that navigation could not be stopped and an 18 m navigation clearance should be provided from the water highest level, reached in the 1905 flood.

The preliminary studies suggested an arc spanning 290 m with a 53 m arrow. For comparison of arch bridges geometry Spangenberg created a parameter measuring the relationship between the square of the span and the arrow (l2/f) that he named "degree of audacity" (Kühnheitszahl). In the case of the Friendship Bridge this number is 1.587 m, considered a very high value. Until 1950, the highest degree of audacity was Jonneiere Bridge 95 m span (Rémond et Cancy, degree of audacity 712). One of the highest degrees of slenderness, till 1953, was the new Conflans-Find'Oise Bridge, 101 m span and degree of audacity of 1060. Other notable values are Plougastel Bridge, with 1 .221, and Sando Bridge, with 1.809.

3.2. The Design

The design of Friendship Bridge was carried out by Paulo José Rodrigues Leite, from Polytechnic School of Sao Paulo, at that time not yet incorporated into the USP.

The Friendship Bridge has the total length of 552.4 m, being 303 m of arch measured between pylon axis and 2 × 108.7 m of two access viaducts, the remainder being completed by abutments. Fig. 7. shows the general scheme of the bridge.

The arch has a cross section with three cells. Fig. 8. shows the section which has a maximum wall thickness of 81 cm at pylons. At mid span, the top slab is 60 cm thick. The sections supporting the columns have a diaphragm almost closing the entire section.

The pylons are enormous, with a box section of 9.6 by 22.6 m with four diaphragms along the height and rounded corners. This design is due to the fact that the arch stays submerged 40 m in the flood season. So, in flood, the arch as well as the pylons are subjected to large hydrodynamic loads of current that are transmitted to the foundations of the pylons. In addition the deck helps leading horizontal forces to the top of the pylons. But there is the thrust of Archimedes problem yet.

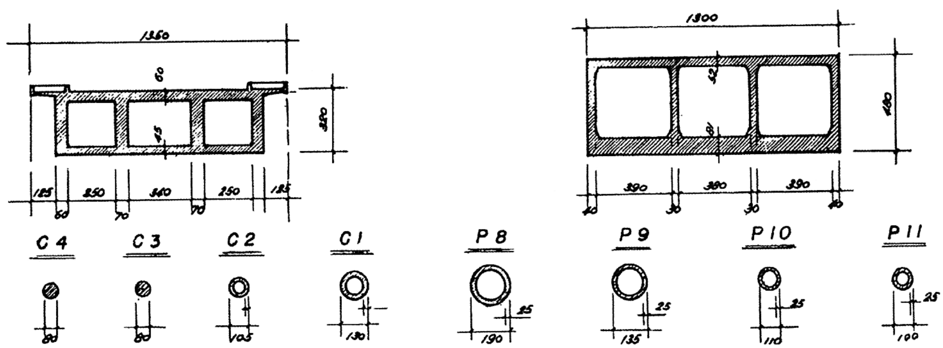

Fig. 8. *Cross section and columns from mid span (left) to the support (right).*

To prevent the thrust of Archimedes, the water can penetrate the cells of the arch, as well as the pylons, by its rear. This balanced a large part of the thrust of Archimedes, approximately 40 tf/m. This thrust would unbalance the line pressure of the arch. At mid span, breaths give output to the air, allowing water to enter the box.

3.3. Construction

A consortium of two firms was awarded the construction in a public bid: Construtora Rabello S. A. (Builder of the Dawn Palace, in Brasilia) and the Society of Earthworks and Large Structures Ltd -Sotege.

The construction of the abutments has undergone a large number of difficulties and delays caused by several floods.

In January 1958, the construction of cofferdams on both banks has already initiated. These caissons had cylindrical shape of 40 m diameter, 11 m high and 60 cm thick, but incomplete (242 degrees), closed and anchored in rock. On January 23, early works were interrupted until May, when the river level started to lower. In May, the caisson of the Paraguayan side was completed. From May until August 16 it was not possible to start the construction of falsework's auxiliary blocks, due to the high level of the water. In this period, it was only possible to work inside the cofferdams. Only on August 16 the construction of auxiliary blocks could be initiated, but September 8 the level of the river rose again stopping the works until July 7 1959. Soon the River dropped; the services were attacked with all energy, getting those blocks ready on July 25, after 10 months interruption.

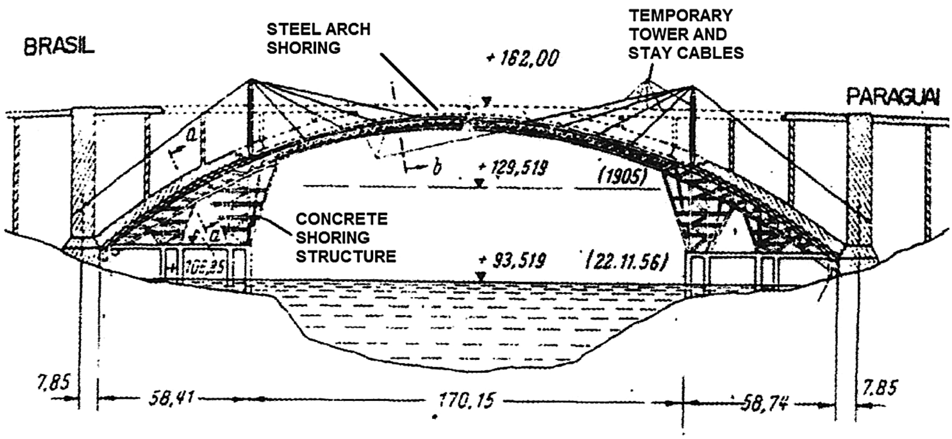

Fig. 9. Scheme of the concrete falsework on the banks and metallic one at the center.

Fig. 9 also shows the central stretch of the steel arch falsework. On July 20, the first 100 tons of steel structure were already delivered on site. The work of assembling trusses was prolonged until December 12, 1959.

3.4. The Falsework

The most important item of the whole design was the falsework with degree of audacity 1.638. Its conception and design were crucial to make the work worthwhile. Any falsework supported on the bottom of the River was out of question, not only due to its depth but also due to the strength of the current.

After much discussion and analysis of alternatives, it was the engineer Sergio Marques de Souza, with his vast experience acquired also working in other projects with Emilio Baumgart, who conceived the falsework system adopted. This solution made it not only technically, but also economically feasible. His idea consisted of the following:

- in the shallow stretch of the river falsework would be designed with a fan shape concrete structure, that would allow to cast 75 m of the arch, each side;
- in the central section, where it was not possible to reach the bottom of the River, it would be used a steel arch, built in cantilever (technic learned from Baumgart) using provisional stays until closing. See Fig. 9.

Providing a steel arch to support the weight of the whole concrete arch would be very expensive. It was then that the final idea appeared widely used today, to design the falsework to resist only a part of the weight of the main arch, the vertical walls of the cells. See Fig. 10.

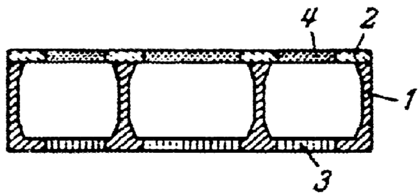

Fig. 10. *Steps of execution of the arch.*

After casting this first part it would be necessary to wait until the concrete has gained enough resistance to withstand its own weight. After that, 28 jacks (300 tf each) were installed at the closing section of this first part to open the provisional joint, relieving the falsework. This enables casting of the 2nd part that would be supported by bough falsework first part.

The idea was to completely relieve the falsework. This process was repeated for the execution of the third and the fourth parts of the arch.

Concluding part four a last operation with the jacks was executed, relieving the falsework and allowing casting the closure for removal of the jacks as well as disassembling falsework.

Fig. 11. *General view of the Friendship Bridge.*

In order to ensure that the relief of the falsework was adequate, it was decided to include in one extremity of the steel falsework another set of jacks to check the relief.

Elements to be highlighted on this falsework are the following:

- first execution of concrete arch with this methodology (later other arches in Europe were executed the same way);
- first large steel structure for a bridge with Brazilian design, manufacture and assembly (total weight of 1363 tons);
- greatest assembling in cantilever already made in Brazil – 78.65 m;
- 100 days of assembling with no serious accident.

The bridge was opened to traffic in 1965, with a pompous solemnity with the presence of two Presidents, Juscelino Kubitschek of Brazil and A. Stroessner of Paraguay.

4. THIRD BRIDGE OVER THE PARANOA LAKE – BRASILIA [3]

The third bridge of the Paranoa Lake is a singular work, either by its architecture, with three arches alternately skewed, 240 m span, or its implementation, especially the tensioning control of suspenders, in function of the temperature effects, since both the deck and the arches were made of steel. It was opened to traffic in 12/15/2002.

4.1. Description of the bridge

4.1.1. Arches

The bridge has three spans with skewed arch in relation to the deck, crossing from one side to the other. The arches are metallic, except at its ends, which are made of reinforced concrete. It has a trapezoidal cell cross section with variable dimensions along the length. The bottom width ranges from 5 to 6.5 m, the top width from 5 to 2 m and the height from 3 to 7 m.

4.1.2. Deck

The deck is suspended by pairs of stay cables (one at each side, with inverted slope) spaced 20 m along the longitudinal, 16 stays per arch. The deck is connected at each end to columns through bearing devices. Its section is a three cells steel section, overall width of 24 m and total length of 200 m. Between each pair of these three suspended decks there is a simply supported 40 m span. As the inclined suspenders, as well as inclined, use stay technology, this stretch came to be called Stayed Stretch! It is important to note that the deck is not continuous and consequently do not work as a tie. See Fig. 13.

4.1.3. Stay cables

The stays are composed of strands ϕ 15.7 mm CP – 177RB galvanized and coated by individual waxed sheath of HDPE. There are stays with 31 and 41 strands which are tensioned from the deck. In order to facilitate the control of cables tension, each one is endowed with a load cell in a strand.

Fig. 12. The three arches, Clubs, Central, and Shis, supported on columns P5 to P8 (always from left to right).

4.1.4. Foundation

Three supports (P6 the P8) has vertical and inclined piles (1:4 and 1:5), with ϕ 120 cm metallic tube 9.5 mm thick, filled with concrete. The cap is made of reinforced concrete with a height of 4.60 m.

The fourth support (P5) has vertical piers ϕ190 cm covered by a concrete cap with a height of 4.10 m.

Since the arches are not tied, these supports receive important horizontal forces, especially P5 and P8.

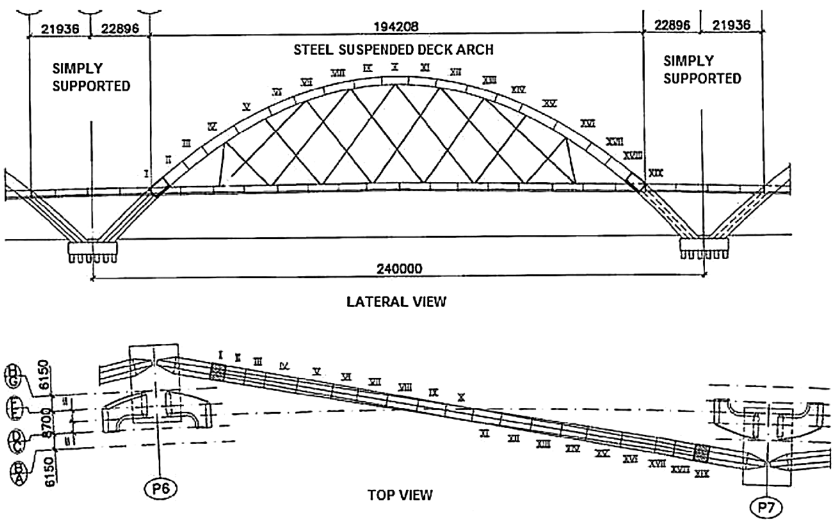

Fig. 13. Geometry of the bridge in plan and profile.

4.2. Execution of the bridge

The piles as well as the piers were executed using floats.

The piers were executed using a compressed air system. The piles were done with driven steel shirts, digging up the rock using Wirth, descending the reinforcing cage and then filling the shirt with concrete.

To make the implementation of the caps easier it was made a pre-cast peel serving as formwork for the remaining block.

The deck was assembled on site and launched to the final position over the supports, definitive and provisional. See Fig. 14.

The steel arches were assembled on a steel falsework supported by the deck. The segments were always welded in stages and at dawn in order to minimize the stresses due to the influence of ambient temperature and the ones generated by long welds.

After assembling the steel arches one could begin the tensioning of cables. To ensure the arch stability the cables were tensioned in 4 steps, where they were stretching to hit 20%, 60%, 80% and 100% of the final force.

4.3. Tensioning operation, monitoring and Back-analysis

The tensioning of the cables was made by iso-elongation, when you score and elongate all the strands from each cable with calculated elongation. This stretching is equal to the sum of the stretching of the cable itself plus the arch lowering and deck lifting, calculated for final force on the cable. See Fig. 14.

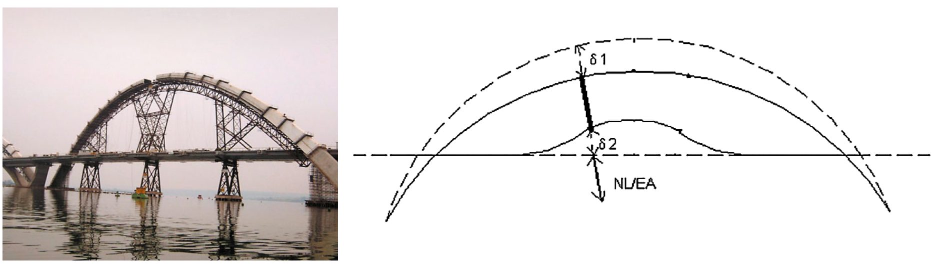

Fig. 14. *Assembling of the arch (left) and stretching of the cable (right).*

4.3.1. The monitoring objectives and back-analysis

Due to the complexity of the bridge for being suspended from the falsework, against the skewed arches, under great influence of variation of ambient temperature, it was decided to monitor all cables by installing load cells that provided its force at all stages. Thus it was possible to better control the phases of the work and the necessary adjustments of the forces and provide information for back-analysis with theoretical calculations.

4.3.2. Model

To calculate the forces and deformations of the structure, a model was developed using only bars with SAP2000 NonLinear Version 6.11 and for the analysis of the forces worksheets were created using Microsoft Excel 2000.

Even with an equivalent average stiffness for the cables (since the variations for different loads were small) nonlinearities were carefully considered as provisional support detachment, 2nd order effects in the arches, as well as, interaction of the 3 arches.

4.3.3. Back-analysis

To correct any differences between the theoretical model and the field measurements, static tests were carried out on site. The tests consisted of measuring the variation of forces in a cable for defined loads and compared with calculated results. If necessary, stiffness adjustments were made until the results were very close to the measured.

4.3.4. Tensioning of cables

The tension of the cables was made in the order set by the design, in order to obtain the final distribution. The forces in each step have been calculated in the model.

Since the temperature effects were high throughout the day, only changes of applied forces were measured.

Measurements of total forces were only made early in the morning, at sunrise, confirming with acceptable precision the intended values.

At the end of the tensioning operation it was found that the distribution of cable forces was reasonable, consistent with the back-analysis (minor deviations lower than 10%), but not with design values. Differences were caused by construction process and temperature effects.

In agreement with the designer it was decided to adjust the forces so that maximum and minimum values were respected in each cable, putting aside the search for design forces themselves, because in fact, the back-analysis model was more reliable than the design one.

5. BRIDGE OVER EL TERCERO RIVER – VILA MARIA – ARGENTINA [4]

This bridge is the first arch bridge Network type of Latin America. It was designed by Apia XXI and built by the Consortium Electroingenieria – Freyssinet and won an award of honorable mention of the Argentinian Association of Highways for technological contribution in 2013.

The bridge deck is suspended in 2 arches by 2 cable Network with radial distribution of suspenders, 24 per arch, uniformly spaced along the arches with inclination towards them practically constant, allowing a good optimization.

The arches win 120 m span and are braced on each other by bars.

It is a steel arch bridge with a square cell section 80 × 80 cm tied by the deck made of prestressed concrete, which balances the horizontal component of the arches thrust, and is suspended by the Network that applies essentially vertical forces to the deck. The arches win 120 m span with an 18 m arrow. The deck is made of a slab over 2 prefabricated beams, 1.05 m high, suspended by the Network. These beams are braced by also prefabricated cross beams 3.75 m high.

***Fig. 15.** Model of the bridge, showing the arches, bracing and network.*

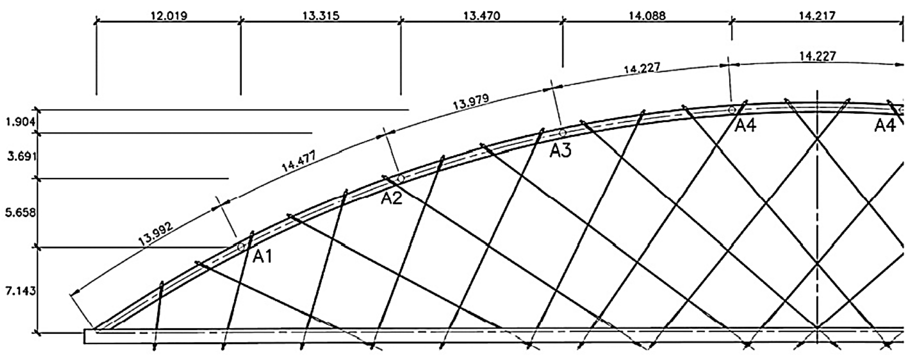

***Fig. 16.** Distribution of mesh cables, uniformly over the arches.*

Fig. 17. shows the carriageway 8.3 m wide, for 2 lanes and, on either side, 3 m are left to riders and 1.5 m for the suspenders and the arches near support.

The deck precast beams were mounted over a concrete pile falsework with spans of 15 m, made then continuous and prestressed. Later the deck slab is cast and also prestressed.

Once the deck is ready, the arches are mounted on a steel falsework over the deck, similar to the JK Bridge in Brasilia. Fig. 18. shows this executive phase.

The following are the suspenders and their tensioning with pre-established forces, able to relive the loads on falsework, but insufficient to raise the deck.

Since the longitudinal beams supports are spaced 15 m making them very stiff, tensioning operation is very easy because the tensioning of one cable does not affect significantly the forces on other ones already tensioned.

The execution finishes with the completely lighten the falsework, using the devices previewed supporting beams over concrete piles, and supplementary longitudinal beams prestressing.

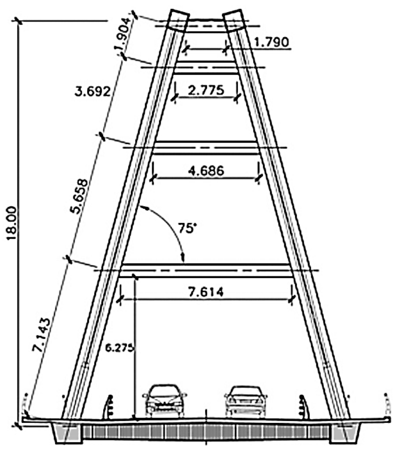

Fig. 17. Cross section.

Fig. 18. *Deck falsework and arches ready to start cable tensioning.*

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