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Disponible en www.hormigonyacero.com
Hormigón y Acero 2019; 70(289): 81-94
https://doi.org/10.33586/hya.2019.2072

Arch and tied-arch steel bridges – some applications

Arcos de acero: aplicaciones

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Recibido el 21 de septiembre de 2018; aceptado el 14 de octubre de 2019

ABSTRACT

During 2000 years, the basic material to build a bridge was stone. The typical bridge was the semi-circular arch bridge. The first bridges made of metal were again arch bridges where the internal forces are essentially compression forces. The industrial revolution and the progress of the theoretical knowledge in the field of structural mechanics made it possible to design bridges with different shapes. Bridges with large spans were mostly suspended and yet arch bridges.

This paper presents some applications of steel arch bridges designed twenty years ago with, each time, the objective to obtain the most efficient structure, a slender structure, by using the last theoretical developments in the field of instability because an arch works essentially in compression. The examples of bridges were chosen with the aim to explain the reasoning for the design and, also, to show that, even for similar bridges, it is often possible to improve any detail.

KEYWORDS: Arch, tied-arch, steel, buckling, cables, construction.

RESUMEN

Durante 2000 años, el material básico para construir un puente fue la piedra. El típico puente era el de arco semicircular. Los primeros puentes de metal fueron de nuevo puentes de arco donde las fuerzas internas son esencialmente fuerzas de compresión. La revolución industrial y el avance de los conocimientos teóricos en el campo de la mecánica estructural hicieron posible el diseño de puentes de diferentes formas. Los puentes con grandes vanos eran colgantes y, todavía, puentes arco.

Este trabajo presenta algunas aplicaciones de puentes de arco de acero diseñados hace veinte años con el objetivo de obtener la estructura más eficiente, una estructura esbelta, utilizando los últimos desarrollos teóricos en el campo de la inestabilidad porque un arco funciona esencialmente en compresión.

Los ejemplos de puentes fueron elegidos con el objetivo de explicar el motivo del diseño y, también, para demostrar que, incluso para puentes similares, a menudo es posible mejorar cualquier detalle.

PALABRAS CLAVE: Arco de tablero superior, arco de tablero inferior, acero, pandeo, cables, construcción.

1. EVOLUTION OF THE BUILDING MATERIAL

The Iron Bridge over the Severn River (UK, 1779) (Figure 1) is the first metal bridge in the world. It is still used today for pedestrians. The structural behaviour of cast iron multiple arches bridges is similar to that of arch bridges in stone masonry. It develops only compression stresses, which made it possible to use cast iron, which is mostly resistant to compression.

Iron, replacing cast iron, is a stronger material than stone. Its tensile strength is low, but significantly higher than any other material available before the mass production of steel appeared. One of the first modern suspension bridges was the

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https://doi.org/10.33586/hya.2019.2072

Figure 1. Iron bridge – 60 m.

Menai suspension bridge (Figure 2) designed by Thomas Telford and completed in 1826. The 176 m span of this structure marked an important milestone in bridge construction.

Iron was also used to build arch bridges, by means of trusses to create the arches. A good example are the two major viaducts of Gustave Eiffel: the bridge Maria Pia in Porto (1877) and the viaduct of Garabit (1884) (Figure 3).

Steel, with its mechanical characteristics far superior to those of iron, gradually replaced iron in all types of structures and allowed reducing their weight. Taking both tension and compression, steel made it possible to produce lattices whose overall stability was ensured by only normal forces. In order to optimize these lattices, their overall geometry followed the longitudinal bending moment distribution, as in the case of the Firth of Forth bridge (1890), or was arranged creating arches, like in the Eads bridge in the United States (1874) (Figure 5). The advantage of this lattice-based design was to make possible the construction of large structures with individual elements of limited size, easy to transport and assemble on site.

2.
EVOLUTION OF THE BUILDING MATERIAL

2.1 Typologies

From this time, the arch bridges were defined in different forms by arranging the deck either above the arch (a), under the arch (b) or at mid-height (c). The configuration b is called a tied-arch bridge (Figure 6).

The choice of one or the other configuration depends essentially on the obstacle to be crossed:

- the arch below the deck (a): mountainous areas
- the arch above the deck (b): areas without relief
- the deck at mid-height (c): intermediate situations

and the mechanical characteristics of the soil:

- for configurations (a) and (c), the critical aspect is the arch foundations, which require a soil with good mechanical properties to be able to take over important inclined compression forces
- the tied-arch bridge is self-stable: the compression of the bow is balanced by tension in the deck and there are only vertical reactions.

The span-length/arch-rise ratio is often in the range of 5-6. The deck is positioned at the level of the abutments. Its thickness is relatively limited because it is supported by the hangers (config. b and c) or by the columns (config. a) that can be considered as multiple supports whose inter-distance is small, about ten meters. Therefore there are bending moments acting between these supports. In the case of tied arch bridges, the deck will also be in tension.

2.2 Deck above or at mid-height of the arch

In the configurations (a) and (c), large horizontal compression forces must be taken up by the abutments. The arches being in compression present a potential risk of buckling, but this risk is reduced because of their connection with the deck. The arches are either fixed or articulated at their base. With three hinges (hinges at the base and at the keystone), the arch is a statically determinate structure.

The deck above the arch is supported by columns in compression, or in the case of mid-height decks, the parts of the decks under the arch will be suspended.

2.3 Arch above the deck

In this case, tied-arch or bow-string bridges as an analogy of the form of a bow with its stretched string. The arches are not held by the deck. They are generally connected in their upper part by a bracing structure, often composed by transverse beams, perpendicular to the arches. They ensure their transversal equilibrium, for example under the action of the

Figure 2. Menai suspension bridge - 176 m.

Figure 3. Viaduct of Garabit – 165 m.

wind and to avoid the risk of instability due to compression in the arches. The deck is suspended from the arches; the hangers are stressed in tension, which explains their lightness.

2.4 Construction

Whatever the configuration, the main difficulty for this type of bridges is its construction. The overall scheme is such that each element, the arch, the deck and the hangers (counter) are slender (length-to-height ratio). For each configuration, deck above or under the arch, the bending is limited between hangers (columns) and the bending stiffness of the deck is small. During construction, each one of these elements, deck and arch must be supported at regular distances to limit bending. Thus the deck cannot be put in place by launching. The arch is often assembled on temporary piers, for tied arch bridge, or is constructed, for example, using the cantilever method by stabilizing it with temporary bracing.

3. TIED ARCH BRIDGES

3.1 Interest of tied arch bridges

Tied arch bridges are particularly well-suited for crossing a depression in a flat landscape. The deck is stretched over its entire length and bent between its hangers. It therefore has a small superstructure depth

Figure 4. Firth of Forth bridge (1890) – 2 x 521 m.

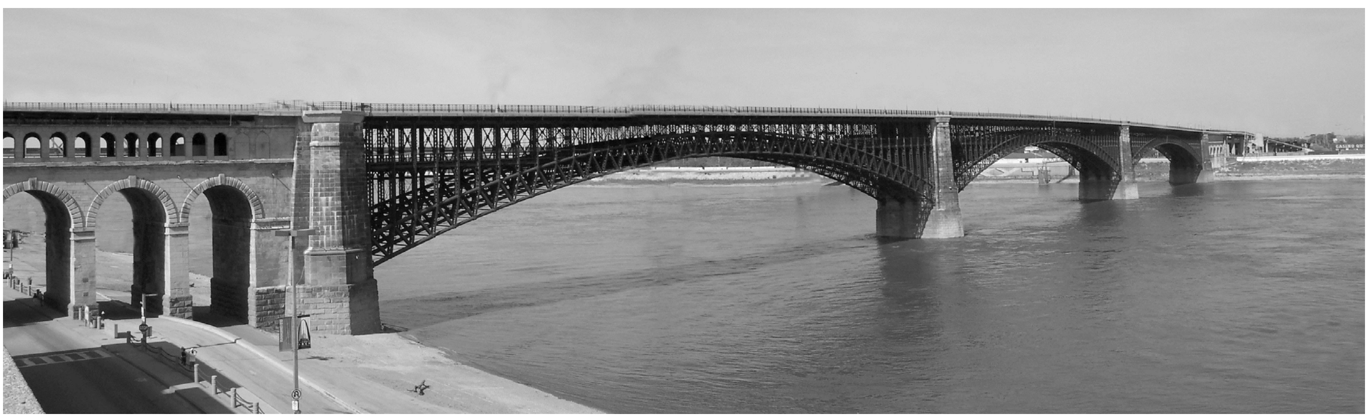

Figure 5. Eads Bridge (1874) – 3 x 158,5 m.

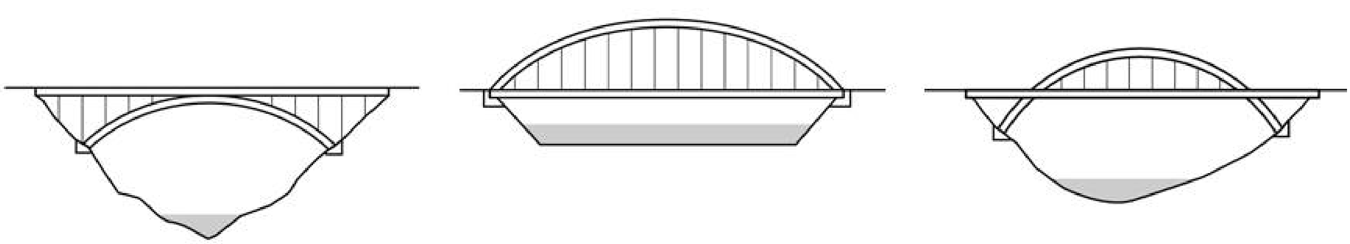

Figure 6. Different configurations of arch bridges .

- The vertical clearance under the deck is easy to guarantee
- The access ramps have a shorter length than for a beam bridge with a larger deck depth (Figure 8)

The deck is suspended at one or two arches arranged in vertical or inclined planes.

Bowstring bridges are internally, statically indeterminate systems and externally, determinate systems. They are supported by simple bearings (Figure 7).

3.2 Tied arch bridges over the Albert Canal

The Albert Canal, which connects the river Port of Liege with the seaport of Antwerp (Belgium), has been recently widened to allow traffic of pushed convoys with four barges and a total capacity of 9000 tons. This decision has required the replacement of the existing bridges by new structures with a much longer span length (roughly 165 m instead of 95 m). The topography where the bridges had to be erected is relatively flat. In that case, relatively few bridge typologies could be considered: girder bridges, cable-stayed bridges or bowstring arch bridges. The depth of the deck of a beam bridge is greater than for the other two types of bridges; it then requires longer access roads to get the required clearance under the bridge (Figure 8).

It explains the choice of cable-stayed bridges such as Lixhe, Lanaye and Wandre, whereas the case of tied arch bridges

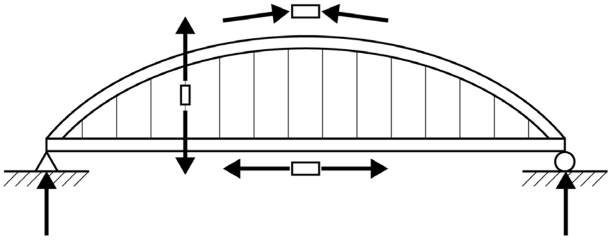

Figure 7. Internal forces.

could be supported by examples such as Haccourt, Hermalle, Marexhe and Misaucy (Figure 9).

In northern Belgium, a flat country, there are numerous examples of tied arch bridges. They are concrete bridges. The arches are braced over a great length and the hangers are vertical. The system of deck, arch and hangers works like a Vierendeel beam. For new bridges, the goals were to obtain slender structures, easier to build, with no (minimum) interruption of the river boats traffic. Designed in the same period, they gave an opportunity to try to optimize each structure, to adapt each one to the local configurations and to take advantage of the latest theoretical developments in the field of instability. Even though their main span-length is almost the same, each bridge is different (Tab. 1).

TABLA 1
Main Characteristics Of The Tied Arch Bridges Over The Albert Canal.

Location	Main span length (m)	Width length (m)	Arches	Bracing shape	Bracing location α=X/L
Haccourt (B)	139.5	20.90	2, parallel	/	/
Hermalle (B)	138.1	15.60	2, inclined	1 transversal top beam	0.5
Marexhe (B)	100.18	18.30	2, parallel	2 transversal beams	0.25/0.75
Milsaucy (B)	145.0	15.50	2, parallel	2 St. Andrew's crosses	0.20/0.80

The hangers are locked coil cables. Cross cables have been preferred to vertical and parallel ones for two reasons: to ensure a better distribution of the traffic loads to the arches (Figure 10) and to obtain a truss-like behaviour of the system of deck, arches and hanger. But, with this arrangement, it must be admitted that it also has some disadvantages: all cables are not in the same plane and, when the arches are inclined, as for the Hermalle bridge, the view of the suspension system is not clear (Figure 8).

3.3 *Behaviour of the arches*

The arches are in compression. It is necessary to verify their stability. Often, the instability in the plane of the arch is not preponderant, as the first buckling mode appears transversal to the arches plane. For this mode, the arch can be considered as a beam with compression stresses, restrained by the deck at each end. However, in contrast with a simple compressed column for which the ratio of the first two critical loads is about 4.0, in the case of tied-arch bridges, this ratio is around 1.0. The origin of this result is the stabilizing effect of the stretched hangers. The transversal instability of the arches is equivalent to a compressed beam on elastic foundation. The rigidity of this 'foundation' is equal to the tensile forces in the hanger divided by its length. (Figure 11). Based on several scientific papers and researches at the University of Liège, the stabilizing effect of the tension hangers has been considered to better explain this behaviour and also to optimize the rigidity and the location of the transversal bracing between arches [1-7].

For a preliminary design, it can be considered that the buckling length of the compression arch is equal to 0.35 L*, with L*, the developed arch length. The first instability mode shape is the same one as for the second buckling mode of a compression beam fully restrained at each support (Figure 12). Based on a parametric analysis of the arch bracing, a simple design method, [7], has been suggested which allows a satisfactory accurate assessment of the critical out-of-plane buckling load of arches. This method simply consists of evaluating

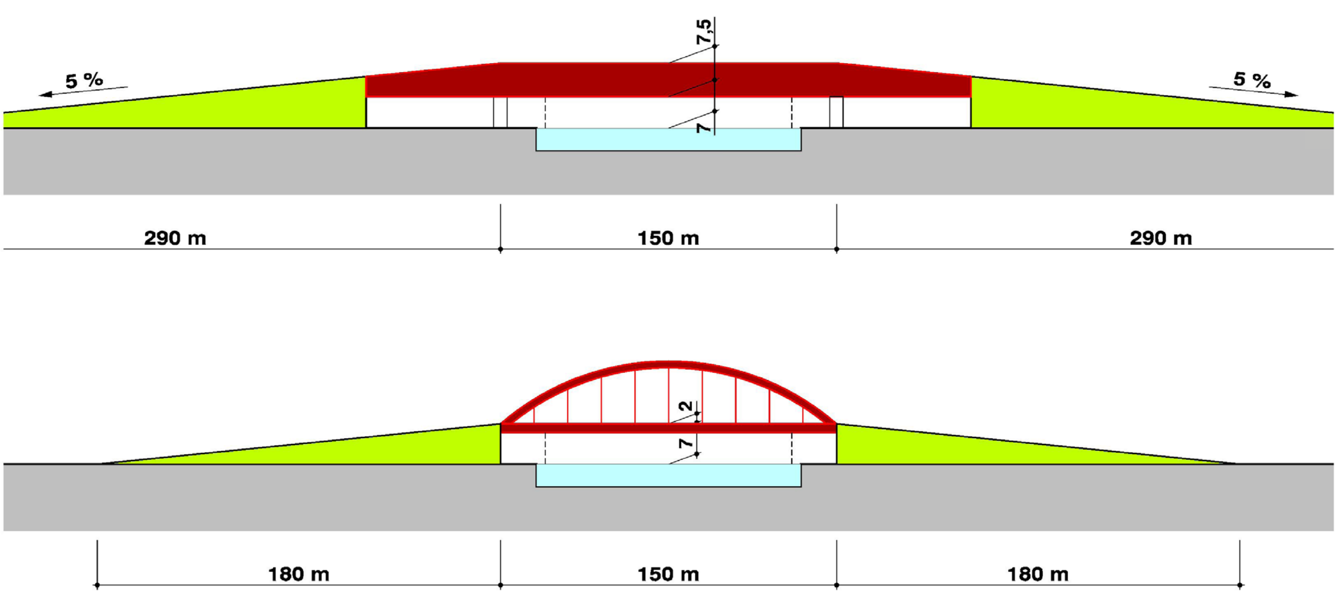

Figure 8. Approach spans combined with the two types of bridges.

Hermalle Bridge

Milsaucy bridge

Haccourt bridge

Marexhe bridge

Figure 9. Tied arch bridges on the Albert Canal.

analytically the instability of the set of bracing and arches submitted to compression in the arches transversally supported by an elastic foundation. This simple approach compared to the numerical values obtained by a finite element software shows that the understanding of the instability phenomenon appears to be correct.

Figure 13 shows the value the first critical transversal mode of the arches versus the location of the transversal bracing. The assumptions are: elastic constitutive law (Euler assumption) bracing beams with hollow cross section, only two bracing beams arranged symmetrically. It can be seen that the effect of the bracing beams is optimum with a location of 0.21 L* or 0.41 L*, with L*.

Taking into account the plasticity and the second-order effects, the gain is lower but the optimal location of the bracing is the same (Figure 14).

The efficiency of the bracing is clear but it is also possible to ensure the stability without it. For the four bridges on the Albert Canal (Figure 9), four solutions to ensure the transversal stability have been used, namely:

- Hermalle bridge: inclined arches ‘connected’ at the their crowns
- Marexhe bridge: two transversal beams
- Milsaucy bridge: two cross beams
- Haccourt bridge: without bracing.

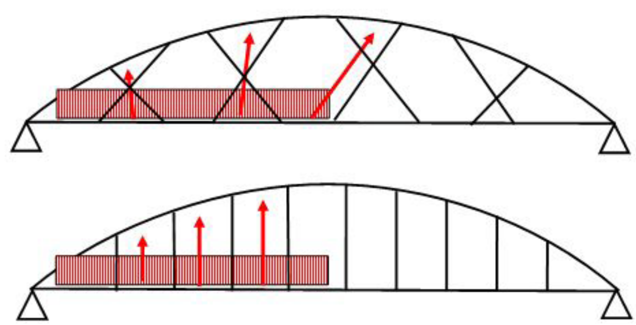

Figure 10. Inclined - vertical hangers and traffic loads.

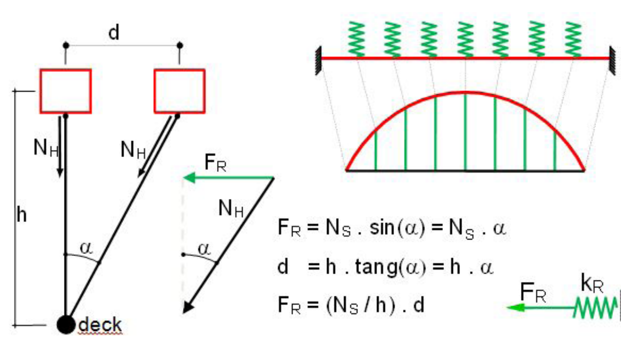

Figure 11. Elastic foundation induced by tension hangers.

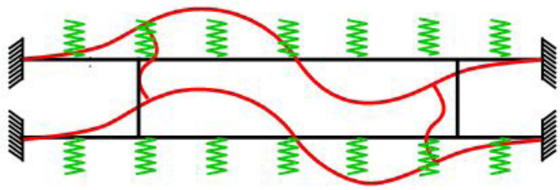

Figure 12. Model to analyze the arches buckling.

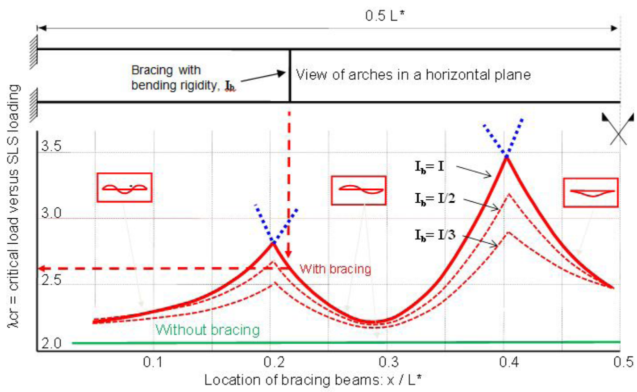

Figure 13. Buckling load versus the location of bracing.

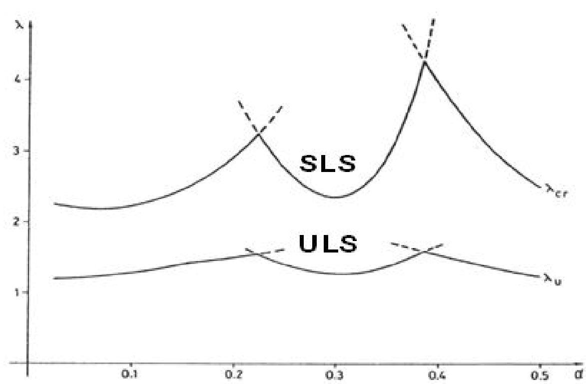

Figure 14. SLS, ULS safety factor respect the location of the bracing.

The deck of the Haccourt bridge is larger. A bracing with transversal beams was also possible but the dimensions of the beam's cross-section would be too great, not only to ensure the stability of the arches, but also to support its own dead load. The solution was to suppress the bracing and to increase the bending rigidity of each arch. But, it is clear that, in that case, the hollow cross section of the arches must be larger to obtain the same safety. The comparison can be made between the dimensions of the arches' cross-section of the Marexhe and Haccourt bridges (Figure 15) but the global slenderness of the structure was maintained.

For the Hermalle bridge (Figure 16), with inclined arches, during their transversal displacements, each arch leans against the other; this behaviour adds a rigidity effect to the stabilizing effects of the strechted hangers. To incline the arches seemed to be an elegant solution; the stability is increased. However, after several years of its opening, and despite a comfortable road clearance, the trucks were diverted the left of the traffic lanes when entering the bridge. Apparently, the trucks drivers are afraid to hit the arches. Perhaps, it would be interesting to increase the distance between the arch bases but, in this case, the deck width would also be increased.

The main stresses in the arches are in compressive and the plate buckling must be verified. Thirty years ago, it was typical to ensure the plate stability by adding numerous stiffeners. Moreover the loss of efficiency under compression stresses is also typical for the webs. For the upper and bottom flanges, a supplementary loss of efficiency appears due to the curvature of the plates (Figure 17). Under planar compression stresses, S1 and S2, transversal forces, TS, appear. In the projects designed by the Belgian administration, each plate was stiffened with a few T profiles along the whole length of the arches (Figure 17).

Based on researches carried out at the University of Liege, [8-9], it has been proposed, for the final design, to suppress each stiffener in order to limit the final cost. Of course the double loss of efficiency due to the plate buckling and to the transversal forces, TS, has been taken into account. It was more interesting to increase the plate thickness than to weld stiffeners obtaining a lower cost. Nonlinear simulations have been made with a finite element program to verify these assumptions.

3.4 *Erection methods*

After the brittle collapse of some steel bridges in Belgium between 1938 and 1940, the welding of steel elements on site was prohibited until the mid-1990's. Therefore the final connections of the arches for the new tied arche bridge on the Albert Canal were made with bolts (Figure 9.).

Two of these tied arch bridges were erected with temporary steel piers to assemble the deck and the arches: Milsaucy and Marexhe bridges. The two other structures, Hermalle and Haccourt bridges, were assembled on the ground and after that, transported on flat boats and installed on their final position.

3.5 *Evolutions of the design*

3.5.1 *Chanxhe and Chaudfontaine tied-arch bridges*

After the design of the tied-arch bridges over the Albert Canal, some other bridges with the same typology have been imagined and designed. The stability of the compression was well-known and understood; we could focus on other details of the structure. Two tied-arch bridges, with a span length around 50 m, have been designed in Chanxhe and Chaudfontaine (B) (Figures18-19).

The hangers are vertical and there is no bracing. With a ratio between the span length, L, and arch rise, f, equal to L/6, the road clearance would be difficult to be respected with a transversal bracing. Moreover, its suppression gives the impression of lightness.

A red colour has been adopted for the arches and the hangers for the Chanxhe bridge. For the Chaudfontaine bridge, the same red colour has been chosen for the arches and the deck and the white colour, for the hangers. This choice highlights the structural lines of the bridge.

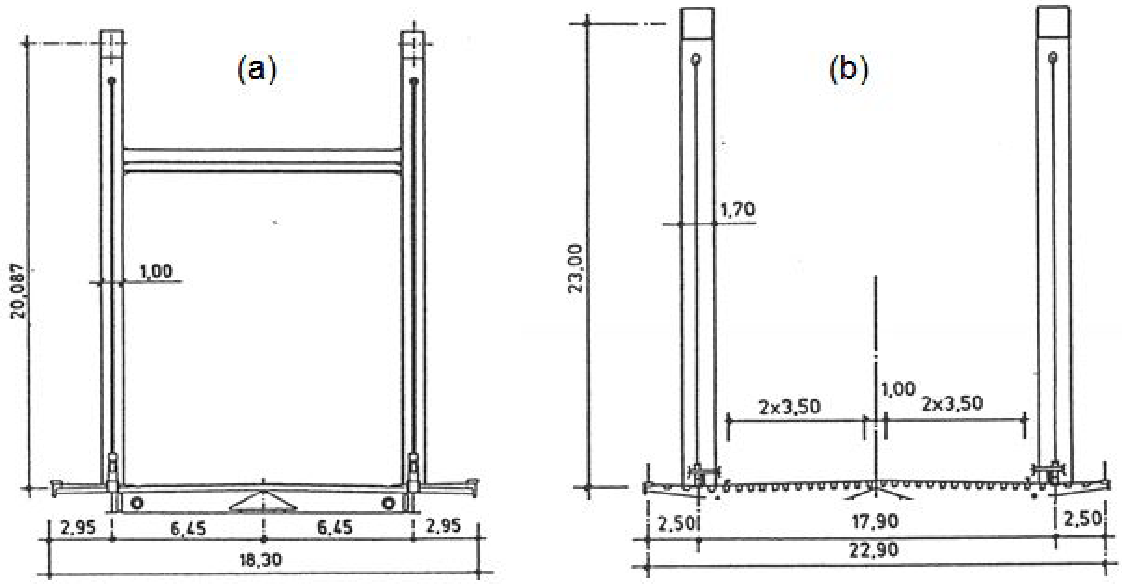

Figure 15. Marexhe (a) and Haccourt (b) bridges.

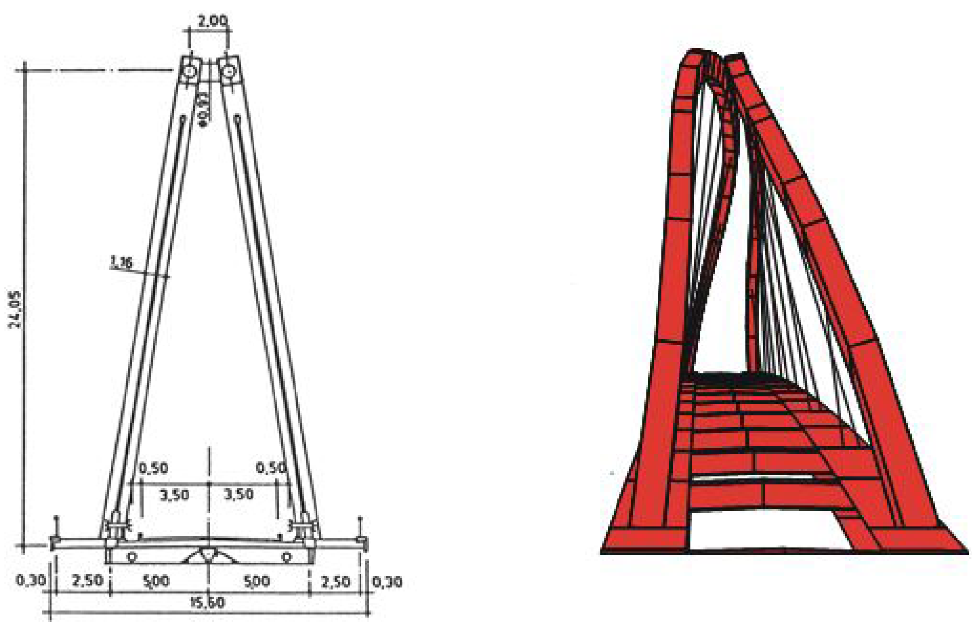

Figure 16. Hermalle Bridge – First buckling mode.

3.5.2 *Hoge Brug in Maastricht*

When it is possible to imagine tied-arch bridges with two arches without bracing, why not a tied-arch bridge with a single arch?

The Hoge Brug in Maastricht (Figure 20) is a footbridge and crosses over the river Maas in the centre of Maastricht (NL). It constitutes a link for pedestrians and cyclists between the new modern Ceramique district and the old city. With a 164 meters long main span without supports in the river, the bridge is perfectly integrated in its both modern and natural environment, but its elegance and its slenderness are also attractive. This impression of slenderness is due to the little dimensions of the structural elements (deck, arch, hangers) compared to their length, and is accentuated by the curve of the deck section, a box girder shaped as a sector of a circle. It is constituted by 5 inner boxes with a maximum height of 1.2 m.

The main span is suspended by 14 crossed cables fixed to a single central arch which its cross section has a variable geometry. So, at the haunches, the cross section of the arch is 1.2 m wide by 1.2 m high, and at its crown 2.4 m wide by 0.8 m high. In this way, the steel is distributed in a efficient way: a vertical rigidity at the basis to transmit the longitudinal moments to the deck and a transverse stiffness at the crown of the arch to ensure its stability. This geometry reinforces yet the impression of slenderness. The single plane of hangers, anchored in the middle of the deck serves as a separation between the flow of pedestrians and cyclists. The main bridge was built on pontoons near its final position and was placed by barge driven by cables.

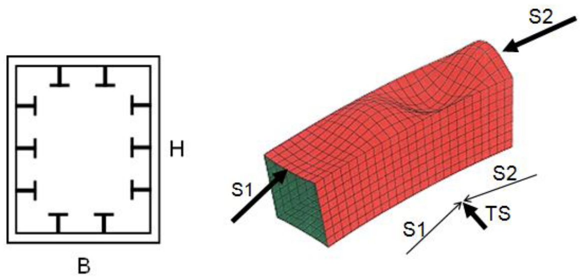

Figure 17. Arch flanges in compression.

Figure 18. Chaxhe bridge.

Figure 19. Chaudfontaine bridges.

3.5.3 *The Sado Viaduct*

The railway Sado Viaduct (Figure 21) is a bridge in the south of Portugal. It carries two rail tracks. To limit the number of piers in the river, the choice of a multiple tied-arch bridge was quickly been adopted: three successive tied-arch bridges with 160 m long main spans. For the pre-design, two solutions were examined: tied arch bridges with two inclined arches or one single vertical arch. Of course, for this comparison, the deck shape was different for the two solutions. With two longitudinal arches, the longitudinal rigidity is ensured by two longitudinal beams located, each one, below each railway track. A transversely eccentric vertical load is equilibrated by an alternated loading in each arch. For the case of single arch, the deck cross section must be a composite box girder, with a sufficient torsional rigidity to transmit the torsional moment to the supports.

Both solutions were confronted with objective criteria on the basis of two preliminary designs carried out in parallel. Finally, the choice was made and the second design was selected for different reasons. Firstly, the single central arch is more effective. Its critical buckling load is greater and the overall deflection of the structure is lower. The variation of stresses in the hangers of the inclined arches is greater, thus making its design more prone to fatigue issues. The solution with two arches increases the number of elements to be assembled. The estimated cost for the two arches solution proved to be 10% higher. All these conclusions led to the final choice of three bowstring girders with a single arch [13].

The steel hollow cross section of the arch has a hexagonal shape of whose height and the width are variable from the basis to the top. The width is increasing to ensure the transversal stability of the arch and the height is decreasing to have the maximum vertical bending rigidity at the connection with the deck. The ratio between the length of the span and the height of the arch is 5.40. The deck is suspended from the arch, every 8 meters, by vertical and cylindrical solid steel bars. Their diameter is 200 mm and they are made of S355 steel.

One particularity of the main bridge, composed by three tied arch bridges, is its continuity. Under the dead load, in spite of the continuity between the bridges, the bending moment between two bridges is almost null. Under the variable load, it is not the case. This scheme doubtlessly distorts the behaviour of a real tied arch. But the interest in providing continuity was double: to suppress the problem of the rail track movement at the extremity of each tied arch bridge but also to have a single bearing device at the top of the concrete piers.

Assembled on temporary steel frames upstream of the river, the total length of the three spans of the deck was erected by launching. For that, two steel temporary piers were installed in the river Sado between each final concrete pier. Temporary piers were also used to assemble the arches pre-fabricated in three elements. To suppress the bending moment in the deck, above the supports, due to the dead load, after the launching the internal bending moment in the deck due to the dead load after the launching, a vertical displacement of 1.3 m high has been imposed after the final launching. The instability of the arches was verified with finite element simulations. The first critical eigenvalues being not so high in comparison with the ULS load level (2.55 and 2.75 ULS), nonlinear elasto-plastic computations have been carried out with initial transversal deformed shape and several combinations of loading, dead load, wind and UIC loads, to ensure structural stability.

4. CONVENTIONAL ARCH BRIDGES

4.1 *Eau-Rouge Viaduct*

The structure (Figure 22) is located between Francorchamps and Malmedy on the E42 motorway (Belgium) close to the border with Germany. The aggressiveness of the valley bottom soil, required a central span of 270 m to avoid the area of soil

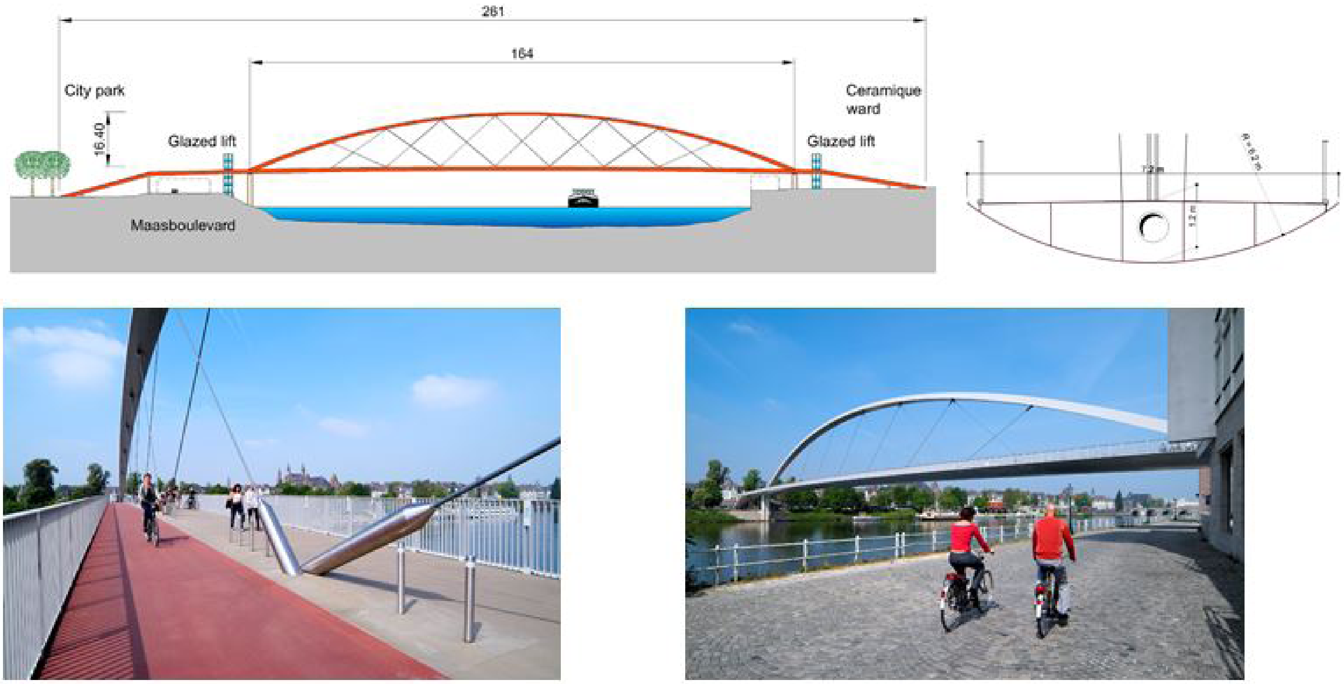

Figure 20. Hoge Brug in Maastricht (Netherlands).

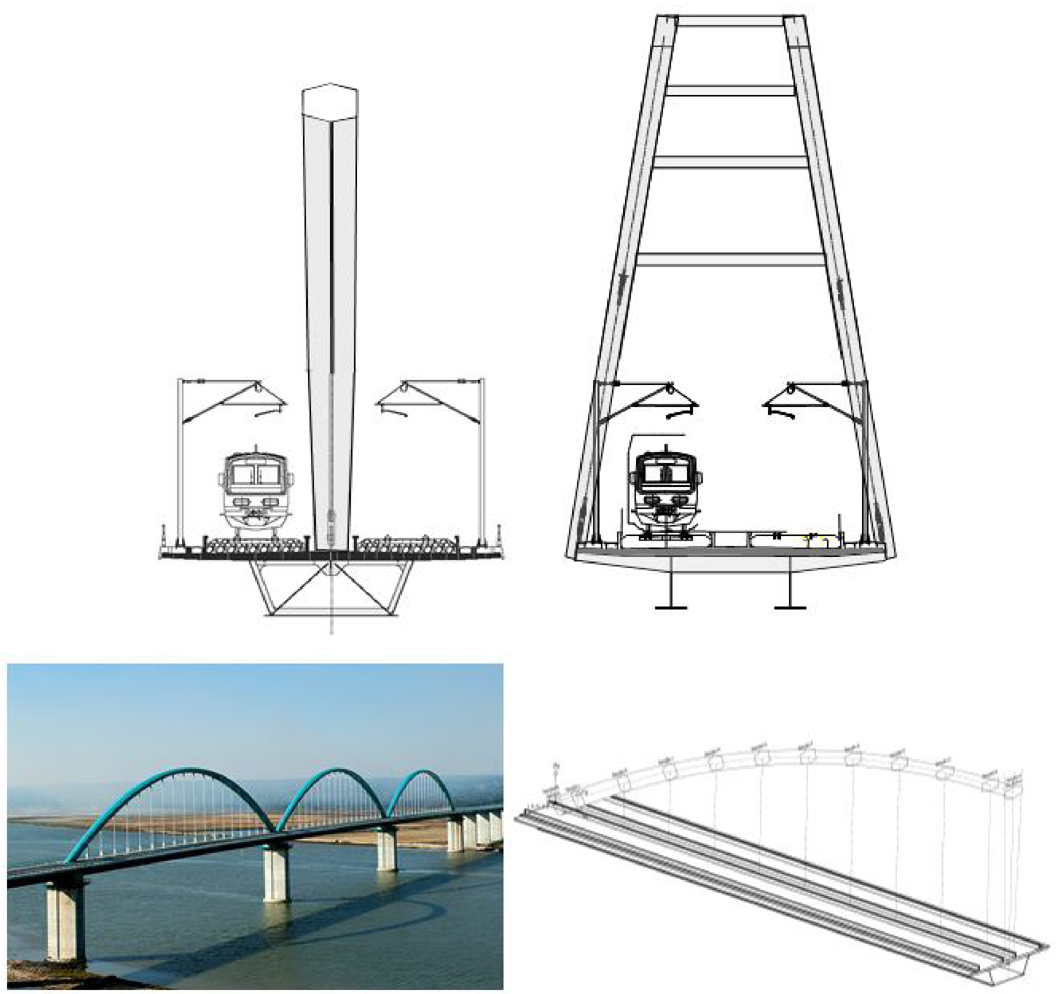

Figure 21. Sado Viaduct (Portugal).

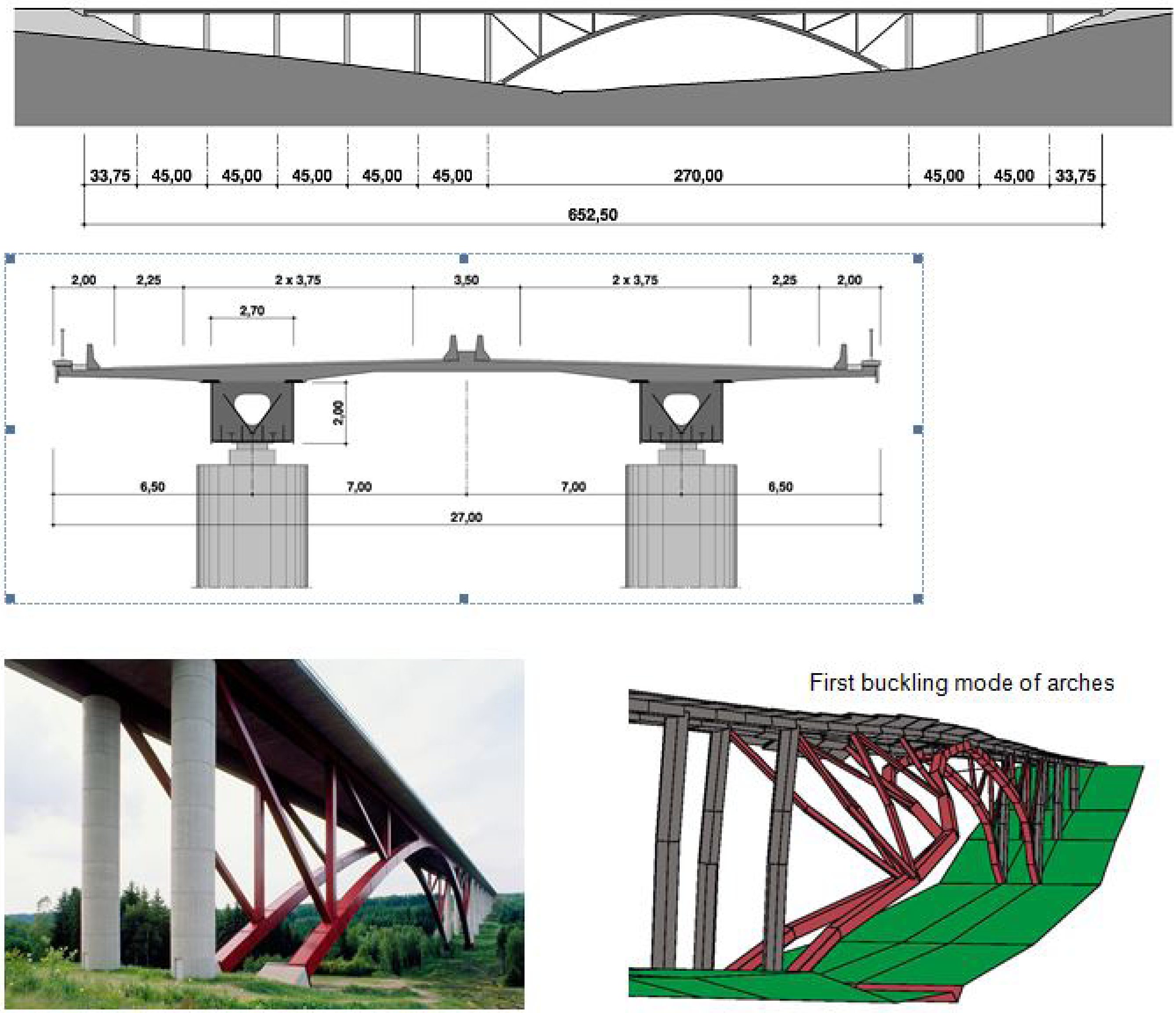

Figure 22. Eau-Rouge Viaduct.

with bad geotechnical properties. This central span is crossed with two arches made of steel hollow rectangular cross-sections spaced 14 m, supporting the composite deck with vertical members and diagonals. The approach spans are 258.75 m long on the north side and 123.75 m on the south side. The viaduct has a total length of 652.5 m. The composite steel-concrete deck is 27 m wide with two carriageways, each with two traffic lanes and one emergency stop lane.

The two steel arches have a parabolic shape of a minimum radius of 150 m and a rise of about 50.0 m. The two steel caissons are not interconnected by any bracing except during the assembly phases. At the top of the arch, the arch and the deck are combined to form a single box of variable depth (2.0 m up to 7.0 m).

The special character of the structure, its lightness, slenderness, and span length of the arch has led engineers to carry out a series of special simulations to verify:

- for the whole structure, its behaviour under the effect of an earthquake and its safety vis-a-vis the instability of the arches without transversal bracing. The first two instability load factor are equal to 4.84 and 5.09 versus the SLS loading (Figure 22.).
- for certain structural elements, the effects of the second order effect such as the vertical webs of the steel hollow caissons of the deck for which the phenomenon of web breathing for the common caisson deck-arch at the top of the arches would occured. [10].

The vertical webs of the steel caissons can be considered as restrained by the concrete slab. Then, when longitudinal stresses in the webs are close to the critical buckling stresses of the plate, transversal displacements appear and cause vertical stresses. So, there is a bi-dimensional stress state. Nonlinear computations with a finite element program have been made to evaluate the level of these stresses and an analytical model has been developed to give the opportunity to do a parametric study with the aim of better understanding the phenomenon, [12].

Figure 23. Arch bridge over the Ravine Fontaine.

This type of bridge, where the wish to simplify the structure is omnipresent, forces the engineer to use ever more advanced calculation methods. The software such as FINELG, [11], can better help understand the behaviour of the structure. But beyond a check, the interest also lies in the possibility of undertaking parametric studies that help guide the researcher in the development of a theory which should then result in design methods.

4.2 Bridge on the Ravine Fontaine

The arch bridge on the Ravine Fontaine (Figure 23) is a bridge on the road connection called "Route des Tamarins" in the West of the Reunion Island (F). It is one of four civil engineering works qualified as exceptional on this road because of their type, dimensions and/or location. The Tamarins road progresses on the sides of a volcano, approximately one km away from the coast and at an altitude close to 300 m. It must consequently cross innumerable ravines. The Ravine Fontaine has at the level of the road, an opening of 200 meters and a depth of 110 meters. The deck is 20.1 m width and carries 2 road lanes and an emergency lane in each direction [12].

As first approach, it was reasonable to consider that (Figure 24.):

- for a bridge whose reactions were vertical, the support zone must have been located 20 m back relative to the edge of the cliffs where a basalt layer sufficiently thick to allow the diffusion of the support reactions could be found.
- for a bridge with inclined reactions (arch type bridge), that it was necessary to consider the zone following the natural balancing slope as unstable, and that a support surface directly behind this zone was acceptable, as far as it was possible to find one or more basalt layers which were able to balance the horizontal component.

Reunion island is the seat of a very significant endemic flora of which many species are protected. In particular, certain birds

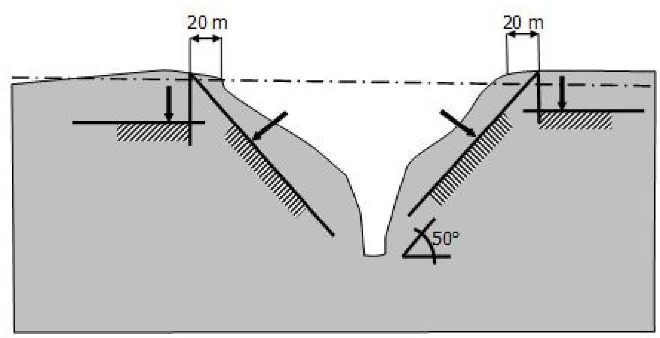

Figure 24. Ravine Fontaine profile and possible support zones.

such as the "puffins of the baillon" nest and reproduce in the cracks and fractures of the basalt layers. It was not possible to envisage a cable-stayed bridge that would have disrupted their flight. In consequence, the best choice was a bridge with a support structure below the deck: an arch bridge.

The length of the structure is strictly limited to what is needed for carrying out the crossing, this is 200 m. It is easily understood that if the geotechnical conditions allow the construction of an arch bridge, this solution will be the most interesting, both from an aesthetical technical and economic point of view. Within this scope, various solutions were subject of a comparative analysis, but the form of an arch was finally retained, for the purity and expressivity of its line.

The principle of an arch bridge is such that it is principally subjected to an almost constant compression force. It is therefore logical to design a constant section. The design takes account of this principle. However, to benefit from the possibilities of restraining the arch in the foundations and in the basalt layers, the height of the section was increased at the basis, which also made it possible to decrease it in the central part and to give the impression of a large slenderness. Transversely, the arch is mainly subjected to wind forces (mean wind speed, 50 m/sec, in cyclone regions). It behaves

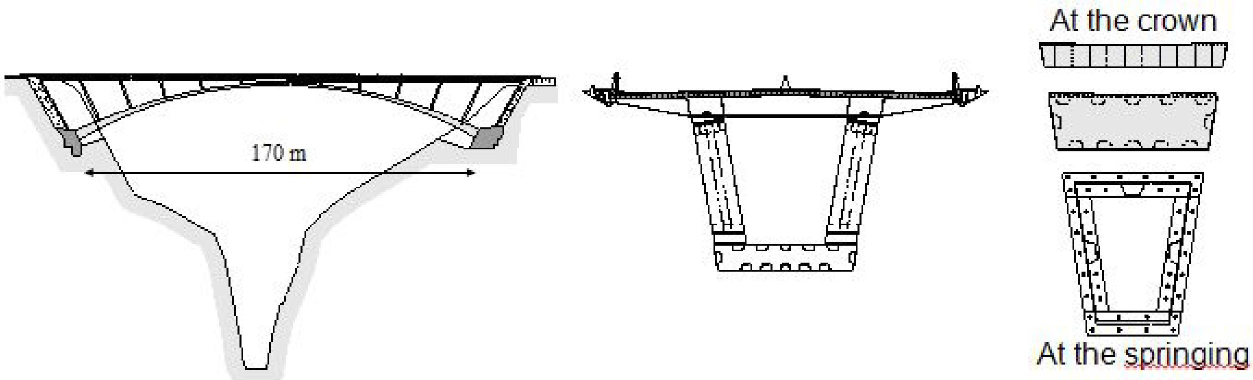

Figure 25. Bridge on Ravine Fontaine – Evolution of the arch transverse Cross section.

like a beam supported at its two ends, with a maximum bending moment in the central part. The width of its section develops proportionally to this bending moment. These principles have made it possible to fit the arch section between two inclined planes.

The geometry of the arch defined in such way was used as the basis for the geometrical construction of the columns and the deck. The deck is composed of two small caissons 2 meters high and 2 meters wide. These two small caissons are braced every 4 meters in order to support the reinforced concrete slabs. They are in addition supported by the radiating, inclined columns. The columns as well as the caissons of the deck fit in the planes of the arch.

The ratio f/L, arch height to span length, is usually guided by economic considerations and lies between 5 and 6 (see tied arch bridges on the Albert Canal). In addition to the general rule, other parameters had to be considered. The foundations must find a sufficiently rigid support on the basalt layers to take the compression of the arch. The abrupt face of the cliffs made the earthworks and the access to the bottom of the excavation particularly delicate. It was necessary to limit their depth to the minimum. But aesthetically, the economic ratio leads to a less dynamic aspect. This is why we made the choice to decrease the slenderness ratio to 1/7.5, which is a rise of 22.50 meters for a span of 170 meters.

The four sides of the box girder consist of stiffened steel panels (Figure 25). These panels were checked by means of Eurocode by taking into account the combined plate-column behavior.

Two by two and laid out every 16 meters, the columns transfer the loads coming from the deck onto the arch. They are provided with hinges at their two ends in order to be subjected only to normal forces. Indeed, under the effect of the asymmetrical forces (a longitudinally loaded half-bridge), the arch works exclusively in bending and significantly deforms, inducing significant relative rotations, particularly at the foot of the columns. An end restraint at this place would have imposed a bending moment in the columns incompatible with their resistance to fatigue. In order to ensure their functionality and to limit the maintenance works (inspection, replacement), the supports at the interface with the deck are carried out by means of steel grains on steel, and at the arch, by means of a welded plate (Figure 26.).

After execution of the earthworks, foundations and support abutments, the assembly of the metallic structure, with a total weight of 2000 tons, was erected by the cantilever method (Figure 27). Basic sections are manufactured in workshops in Italy before being conveyed by boat to Reunion Island. After assembly on site to create elements of a maximum weight of 100 tons, these assemblies were set up ones after the others by means of a derrick crane built explicitly for this work.

5. CONCLUSIONS

Although numerous arch and tied-arch bridges have already been designed around the world, it is yet possible to imagine innovative structures. But, the most important thing is perhaps to design aesthetic and elegant structures with the due respect to their environment.

The beliefs of Greisch's founder about appropriateness of design in relation to efficiency, economy and functionality have been expressed in a series of works which have established the reputation and the references of Bureau Greisch. René Greisch was engineer and architect. His interest in architecture has instilled the Greisch team with a spirit of research and innovation and has led to many collaboration ventures with architects. Collaboration between engineers and architects is important in order to create an atmosphere where the design team is constantly questioning and searching for new solutions, both formal and technical. The team spirit and the attitude of quest, the determination to work through collaboration and synergy, constant innovation and dynamism, invention combined with imagination must become the working methods and principles that must underpin the design of structures and bridges.

The bridges must be designed to serve the city with the respect of three well-known principles: the statics, the aesthetics and the politics. Then, there will be many chances that citizens will be proud of ''their" bridges. The hope is that the bridges presented in this paper respect this challenge.

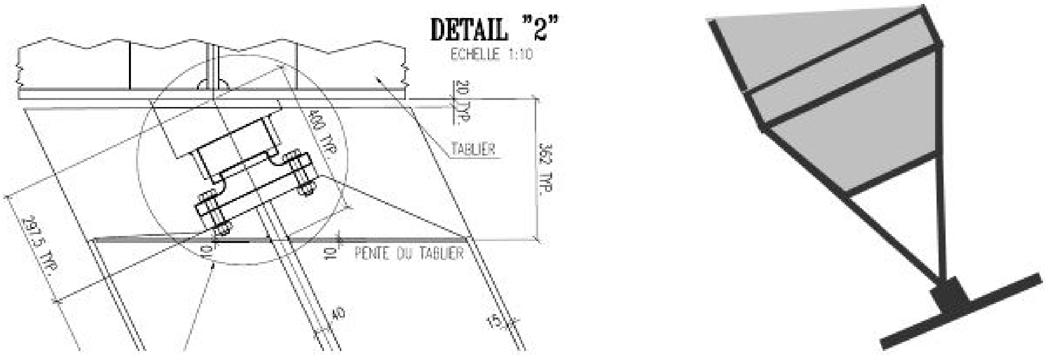

Figure 26. Interface between counters and the deck and the arch.

Figure 27. Erection stages of the steel structure.

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