A UNIQUE BRIDGE SYSTEM

By

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ABSTRACT

This thesis examines several remarkable bridges designed by Santiago Calatrava, a Spanish architect-engineer. In those bridges, Calatrava exploits the phenomenon of torsion of the deck to create a certain longitudinal asymmetry. This asymmetry enables the designer to include original features like a big balcony one side of the bridge, "to emphasize the position of the bridge in relationship to the city around it, or the direction of the water, or even the position of the sun. It permits to sensitize the bridge itself, as a phenomenon set into the surrounding landscape" (Conversation with Students, Calatrava).

Actually an inclined arch stabilized by steel arms or hangers generates the sufficient torsion defying equilibrium rules. But those structures cannot be considered as classical arch structures. They cannot be classified as usual bridges: they are unique.

This complex design is described through four relevant examples of bridges in which Calatrava gradually improved his technical design: the Lusitania Bridge, the La Devesa Footbridge, the Puerto Bridge and the Alameda Bridge.

Lastly his most recent design, even more technically advanced than the previous ones, is analyzed with respect to its structural concept, its conceptual design and its exclusive construction process.

Thesis Supervisor: Jerome J.Connor
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CHAPTER 1

INTRODUCTION

1 Introduction

In the eighteenth, nineteenth, and even the earliest twentieth century a lot of care was given to the bridge appearance, especially in Europe. The piles and the handrails were sculpted, the lighting judiciously chosen. They were esthetically pleasing but also very resistant to time. You can easily find in Europe intact bridge built four, five hundred years ago.

At that time architecture and engineering were very close. All the design was thought from an architectural view. "Architecture was not only all that you can took away from a bridge to leave the bridge standing" (Conversations with Students, Calatrava).

But Europe experienced an important population growth during the twentieth century. Many bridges had to be built. The only specificities required were efficiency for low cost. The aesthetic didn't matter so much. Now nothing has changed, economic criteria still govern bridges design.

It is very hard to design bridges that are functional and beautiful unless the architecture is an entire part of the design.

At the end of the eighties, a man had a bright idea. What about exploiting the torsional stiffness of the deck. Actually most of time the bridges are longitudinally symmetrical so the torsion is very limited. Furthermore by exploiting the torsional resistance of the roadway a certain asymmetry could be created in the bridge design. This could be originally used at an architectural level.

This man was Santiago Calatrava. His objective was to be an architect-engineer characterized by impressive creativity. He illustrated his talent in numerous bridges and buildings: Milwaukee Museum, Lyon Saint-Exupery train station, Trinity footbridge...
Santiago Calatrava is very interested in bridges for their power on urbanism. Indeed "when you want to regenerate a place, bridges introduce a very good reason to restructure the surrounding area and, in so doing, make more livable these parts in city that are rather lost" (Conversation with Students, Calatrava).
Moreover he is very dedicated to integrating bridges with the environment, the city. Calatrava is a perfectionist. For example he will refer to the history of the city by including details in the bridge design related to previous bridges, he will take into account the bridge reflection on water, the relationship between the design and the water flow, he will artificially illuminated in such a way as to emphasize its structural dynamic....

So Calatrava developed his smart idea of using torsional stiffness in the deck through the inclined arch principle. He experimented with this principle in different bridges in Spain.

His most relevant work is the Orleans Bridge in France, also called the European Bridge.

CHAPTER 2

EVOLUTION OF CALATRAVA BRIDGES

2 Evolution of Calatrava Bridges

2-1 Lusitania Bridge in Merida (Spain)

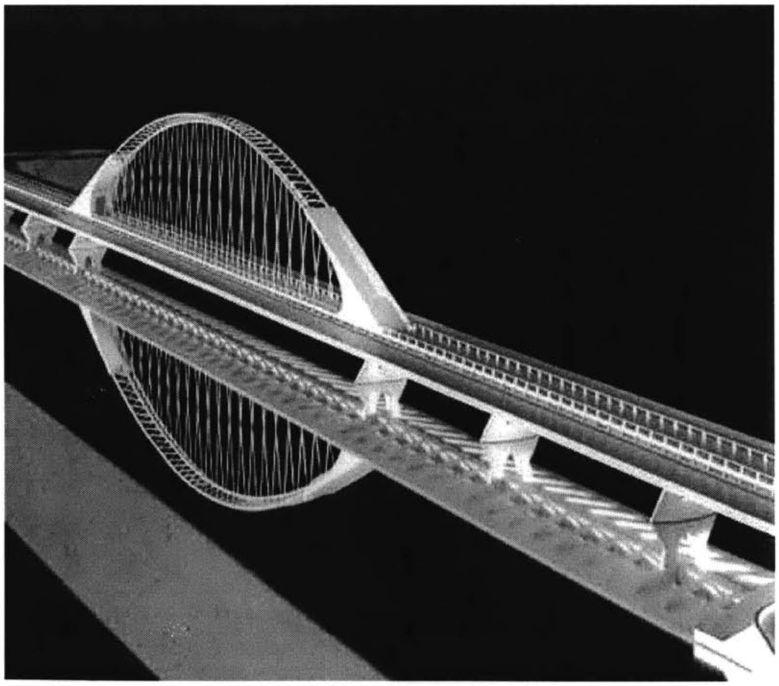

Figure 1: Model of Lusitania Bridge

2-1-1 Presentation

Figure 2: Central walkway of the Lusitania Bridge

This bridge was designed in 1988 and completed in 1991. The design is quite close to a classical arch bridge. The crossing is divided in three parts: the tied arch from which the roadbed is suspended, and two 138 meters parts simply supported by piers. The arch span reaches 189 meters giving to the bridge a total length of 465 meters.

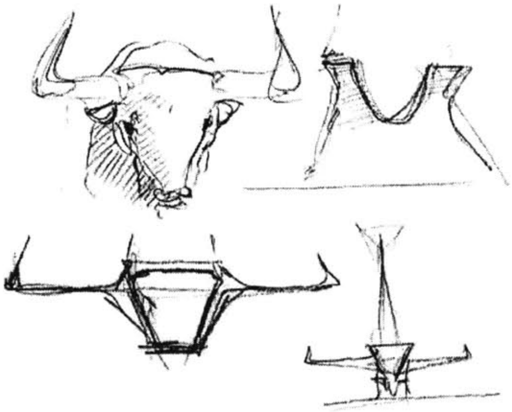

Figure 3: Calatrava's sketch for the Lusitania Bridge

A bull inspired the form of the bridge cross section.

2-1-2 Structural concept

A unique feature of the bridge is its absence of expansion joints as it was designed as an integral structure.

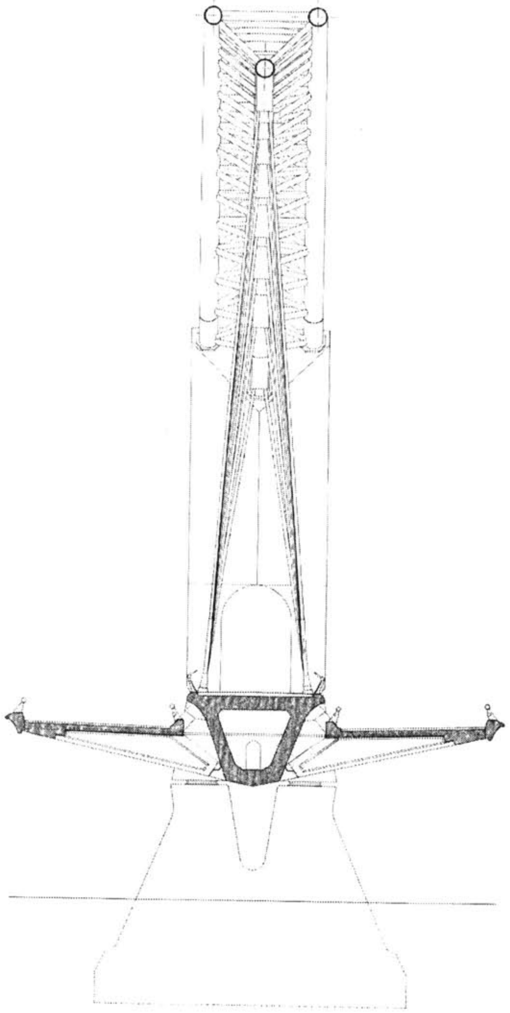

Figure 4: Cross section of the Lusitania Bridge

Just focusing on the center span, one will notice that the walkway is cast with the reinforced concrete box section. Twenty three steel rod pairs support this box girder that acts as a torque tube. Actually the 5.5 meter wide walkway separates two 7-meter cantilevered decks supporting the highway. Those pre-stressed concrete wings are post-tensioned to the box girder. The walkway elevated 1.5 meters above the divided highway offers a fantastic panoramic view.

Two twin piloti carry the weight of the 32 meter deep central arch. The arch is made up of a 5 by 2.5 meter triangulated section in tubular steel.

2-1-3 Criticism

Figure 5: View of the twin piloti and the concrete abutment of the Lusitania Bridge

One could criticize the use of concrete for the full span since a steel span would have reduced the dead load and avoided the ponderous appearance of the arched concrete abutments. Furthermore, other designs were possible for the concrete transition.

2-2 La Devesa Footbridge in Ripoll (Spain)

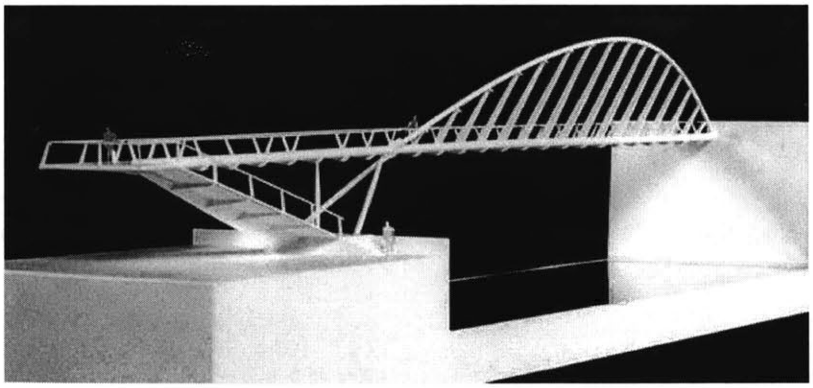

Figure 6: Model of the original project of La Devesa Footbridge with steel arch support

2-2-1 Presentation

This pedestrian bridge was built between 1989 and 1991. It was designed to cross the Ter River, which has the unusual feature of a 5 meters difference in height between the two banks of the river. This footbridge connects La Devesa with a railway station across the river. The height difference is handled by keeping the bridge's walkway at the higher bank's level until it is fully across the river, and then reversing direction with a stair that leads the pedestrian down to the lower bank's ground level.

It's the first bridge with an inclined arch constructed by Calatrava. One could say it is the direct application of the projects proposals of the Gentil Bridge in Paris in 1988 and the Miraflores Bridge in Cordoba (Spain) in 1989.
The bridge is quite small comparing to the previous with a total length of 65 meters.
The canted steel arch, spanning 44 meters, transmits the walkway loads to the existing retaining wall and to a new concrete pylon. The arch is only 6.4 meter deep.

2-2-2 Arms

Figure 7: View of the walkway of the La Devesa Footbridge

Steel arms have replaced the classical rods. Those arms reduce the movements of the arch out of its plane and prevent it from buckling. Calatrava handled the buckling through the arms that have stiffness. In the Merida Bridge, Calatrava was afraid of buckling and therefore made a huge arch

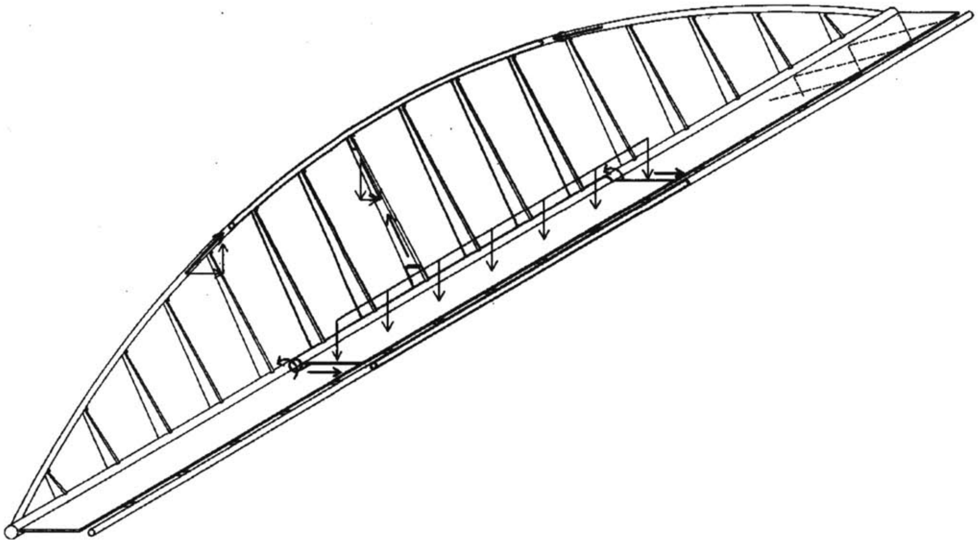

Figure 8: Project view explaining the global stability of the La Devesa Footbridge

The arch is not in a vertical plane, thus the arms have to resist vertical and horizontal force components. The 65 degrees angle of the arms was chosen in order to keep them loaded in pure tension. Consequently the "arch-shape" is loaded in its plane which ensures that the structure works as an arch-structure and not as a curved beam. The vertical force component in the arms comes from the walkway load. The horizontal component is developed by a cross truss structure located below the walkway. In fact this structure reduces lateral distortion towards the arch, thus creating this horizontal component.

2-2-3 Pipe

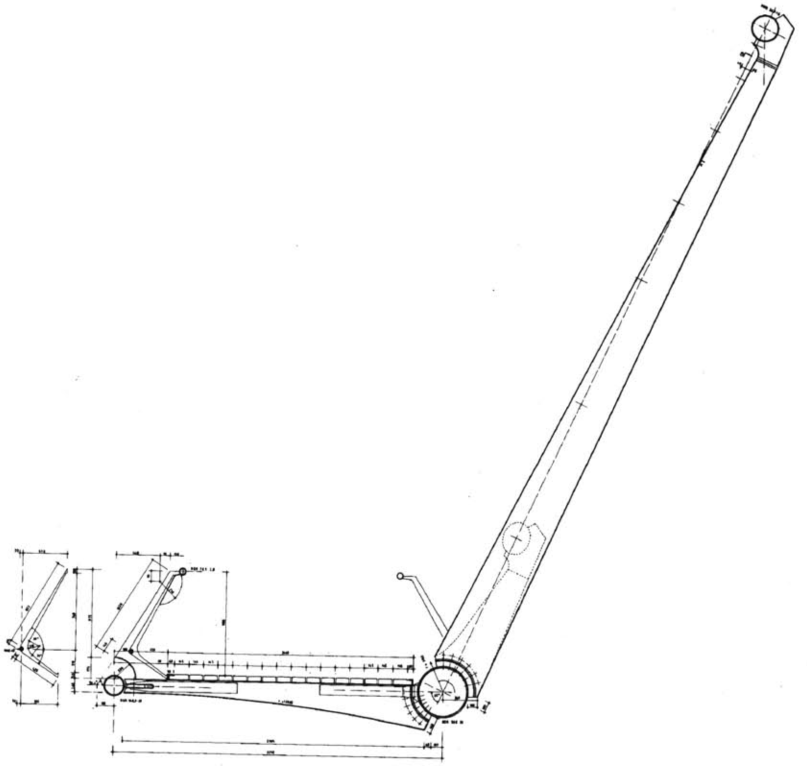

Figure 9: Mid-span section showing maximum depth of arch of the La Devesa Footbridge

The pipe is located at the base of the arch.

However whereas the bridge can appear reassuring by its solidly proportioned structure, one could wonder how it can stay in static equilibrium with such an inclined arch on one side of the bridge. Indeed the weight of the walkway and the arms are not centered under the arch like in a classical arch bridge. The secret lies in a large pipe at the base of the arch. This very stiff pipe carries the load through torsional action to the retaining wall and to the pylon under small deformation.

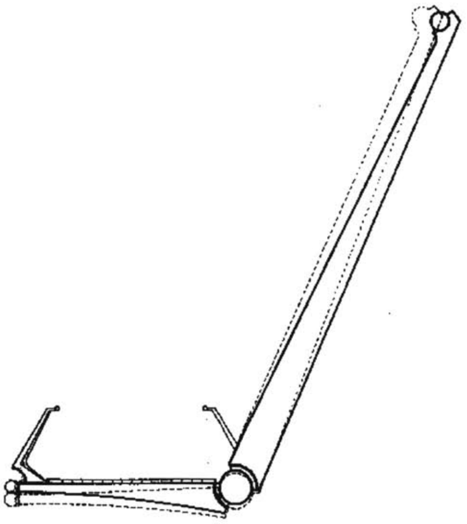

Figure 10: Global rotation of the La Devesa Footbridge with walkway loads

The walkway load tends to move the arch to a vertical position. Furthermore it tends to stiffen it and provide further protection from buckling.

2-2-4 Design comment

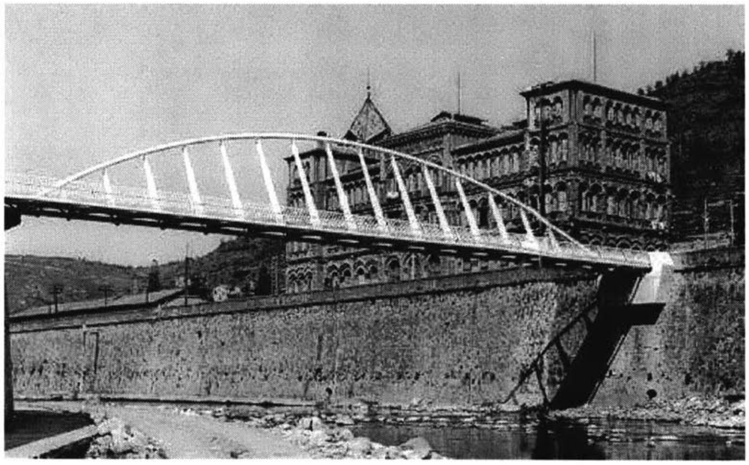

Figure 11: Overview showing the appendage on the right part of the La Devesa Footbridge

Note the ugly concrete appendage added at the retaining wall. Construction authorities wanted to move the pylon. This action would have resulted in increasing the span and forcing a redesign the bridge. To express his impatience, Calatrava added this crude corbel...

2-3 Puerto Bridge in Ondárroa (Spain)

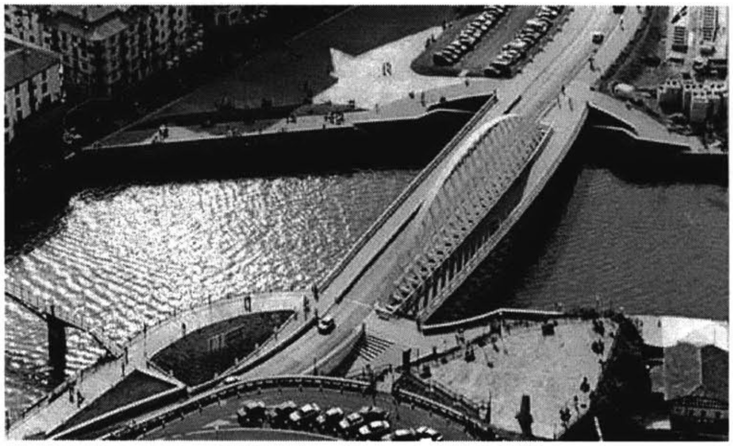

Figure 12: Overview of the Ondarroa Harbor with the Puerto Bridge

2-3-1 Presentation

The Puerto Bridge located not far from Bilbao was completed in six years between 1989 and 1995. The Puerto Bridge was commissioned to relieve traffic within the congested harbor area of the town of Ondárroa. The maximum span corresponds to the total length: 71.5 meters. The overall deck width varies between 20.91 and 23.7 meters at mid-span. The main deck reaches 11 meter wide.

Figure 13: The Puerto Bridge

The Puerto Bridge is constituted by an asymmetric arch, which separates the box girder carriage deck from the curved pedestrian deck. This box girder supports a pedestrian way and a motorway so it carries real traffic load unlike the La Devesa Footbridge.

2-3-2 Conceptual design

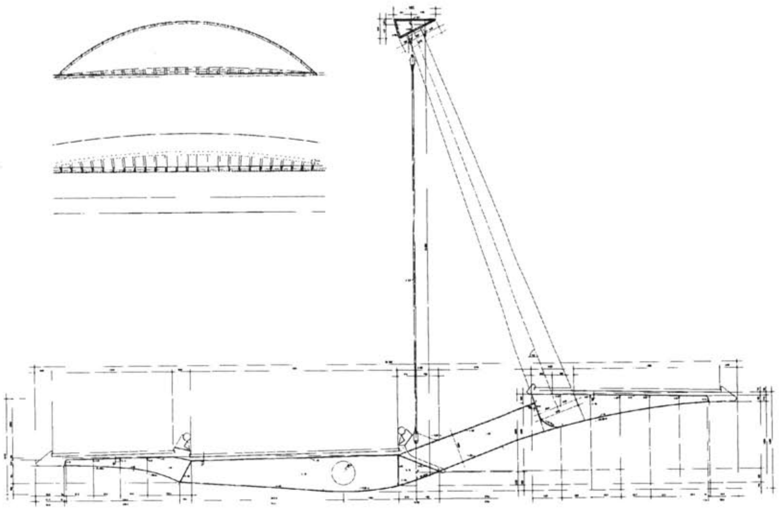

Figure 14: Puerto Bridge cross section

In this bridge, the constant-width arch appears like a further investigation into the inclined arched principle.

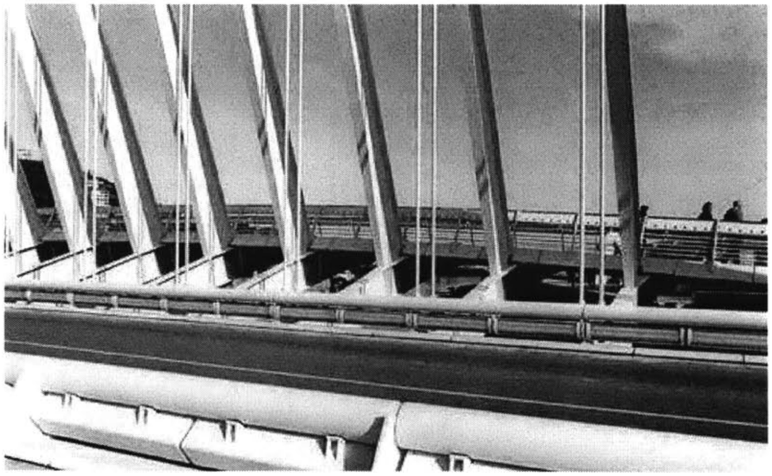

Figure 15: Arms and cables of the Puerto Bridge

However it just works like a classical arch with the suspension cables. The arms support the cantilevered curved deck. Those arms placed every 2.86 meters give the crisp aerial outlines of the 15-meter deep arch.

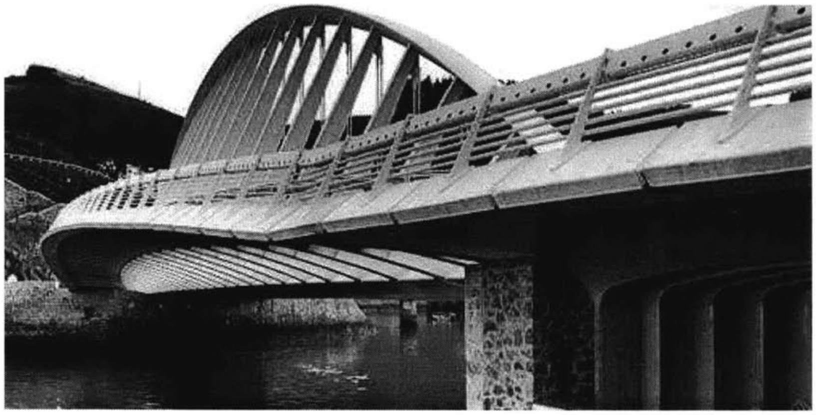

Figure 16: Curved cantilevered pedestrian deck of the Puerto Bridge

The arms angle was chosen like in the La Devesa Footbridge taking into account the vertical and horizontal component created by the truss. All the main deck is very stiff so it can resist against the torsion created by the asymmetric position of the arch. The curved cantilevered deck reduces this torsion that is finally transmitted to the ground support through the main deck. Consequently the lateral box replaces in a way the pipe of the La Devesa Footbridge.

Figure 17: Separation between the main deck and the cantilevered pedestrian deck

Moreover the pedestrian deck is given major importance by separating it from the roadway. This walkway, acting like a balcony, offers a superb view on the seaport.

2-4 Alameda Bridge in Valencia (Spain)

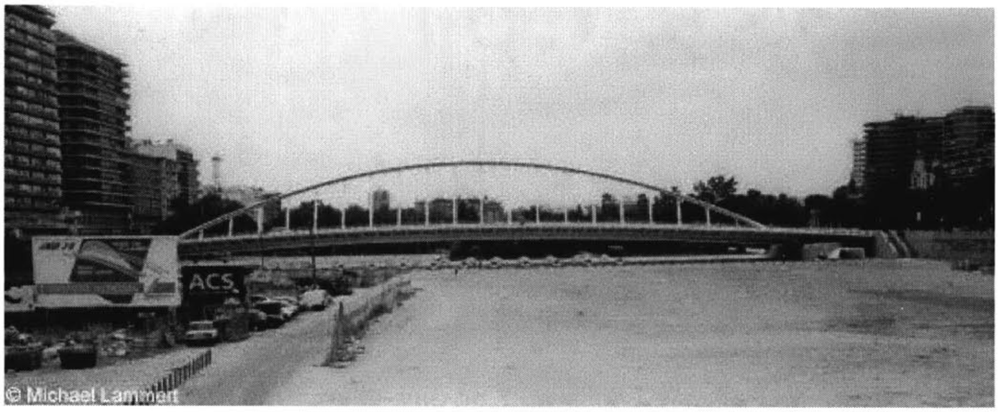

Figure 18: Overview of the Alameda Bridge

2-4-1 Presentation

The Alameda Bridge was constructed between 1991and 1993. Simultaneously another project was carried out: the metro station.

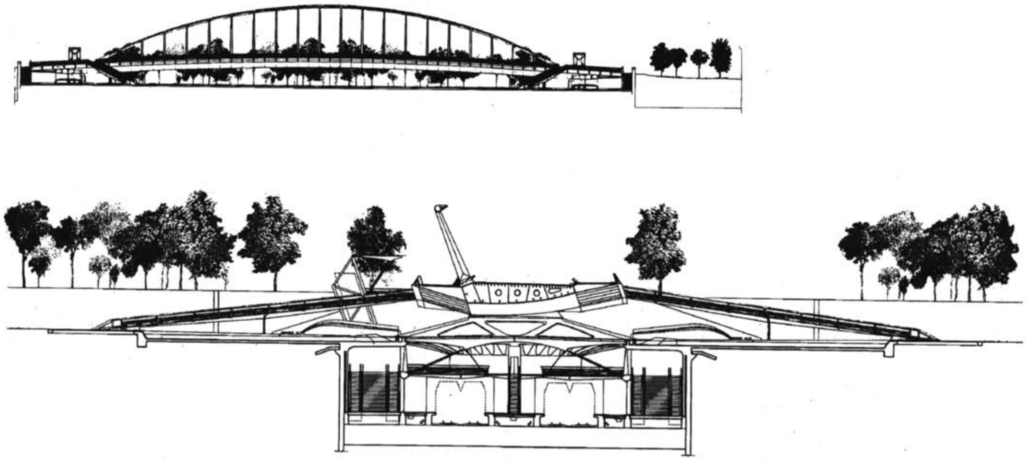

Figure 19: Longitudinal view and cross section of the entire complex

Note that the roof of the metro entrance is used as arch support.

This project is independent of Calatrava's work. This underground station is aligned on the longitudinal axis of the Alameda Bridge. As a consequence, to avoid obstruction on the site, the bridge was assembled to one side, and then moved into its final position on a system of rails and jacks.

2-4-2 Structural concept

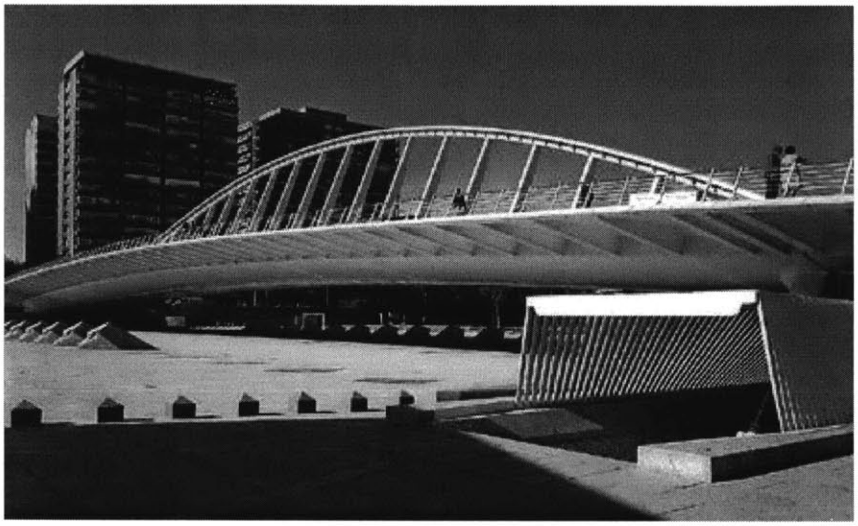

Figure 20: Overview of the Alameda Bridge with the metro entrance on the right

The Alameda bridge has got a design close to the La Devesa footbridge and the Puerto Bridge but on a different scale: the 26 meter wide deck spans 130 meters! The deck is slightly curved on its longitudinal axis.

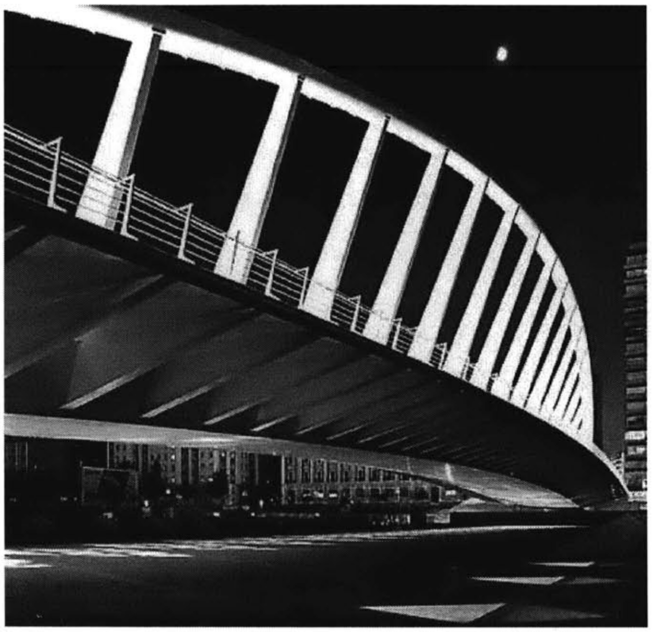

Figure 21: Night view of the Alameda Bridge

Like a number of other Calatrava bridge projects, the bridge employs a 70 degree inclined arch. As a reminder, the La Devesa Footbridge uses 65-degree angle arch. Furthermore this arch rises some 14 meters above the road surface at its apogee.

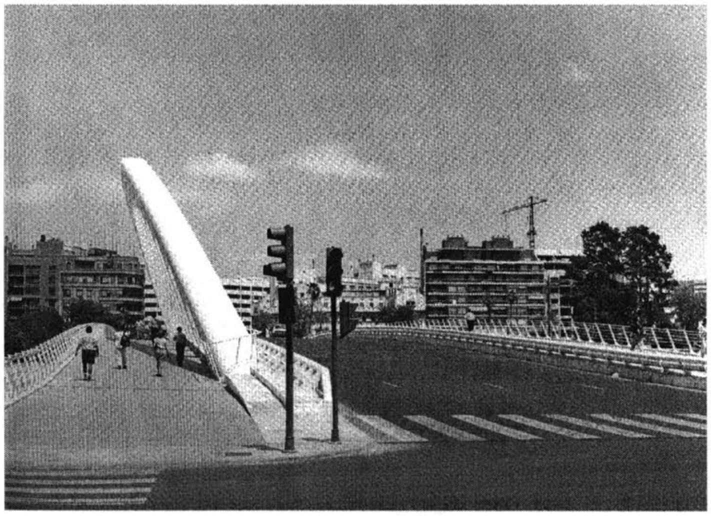

Figure 22: View of the walkway and traffic lanes of the Alameda Bridge

Two traffic lanes and two walkways like in the Puerto Bridge constitute the bridge. The two walkways are cantilevered off to each side of the main vehicle deck. Four cells that provide a very important torsional stiffness constitute the main deck.

The stability of the tube-made arch is still ensured by tension arms placed at regular intervals of 5.84 meters.

CHAPTER 3

ORLEANS BRIDGE

3 Orleans Bridge

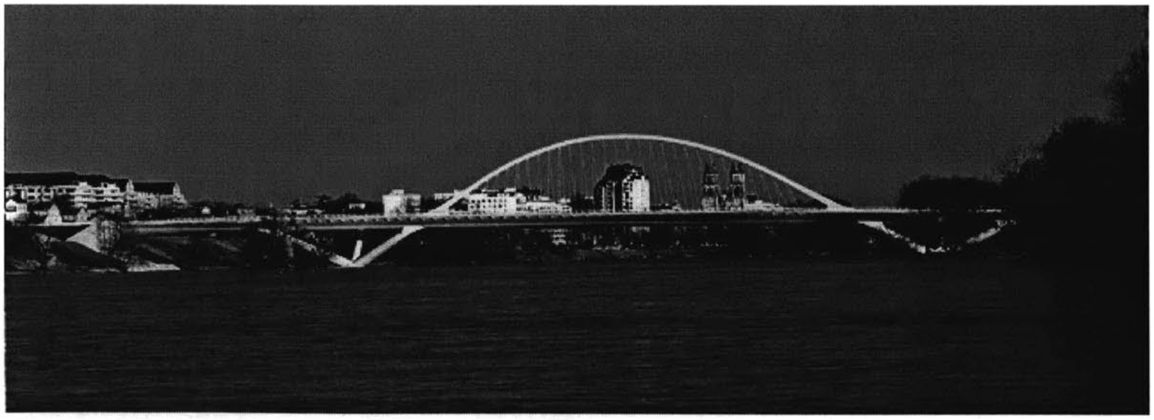

Figure 23: Overview of the Orleans Bridge

3-1 Presentation of the Bridge

3-1-1 Why a bridge in Orleans?

Over the past two decades, Orleans has experienced one of the highest population growths in France. Major traffic problems were observed at the level of the Loire River. To relieve traffic over the three other heavily congested bridges, Orleans organized a bridge design competition at the end of 1996. Orleans desired an original and beautiful bridge.

This bridge located at the South of Orleans would link the village of Saint-Jean de la Ruelle with that of Saint-Privé-Saint-Mesmin.

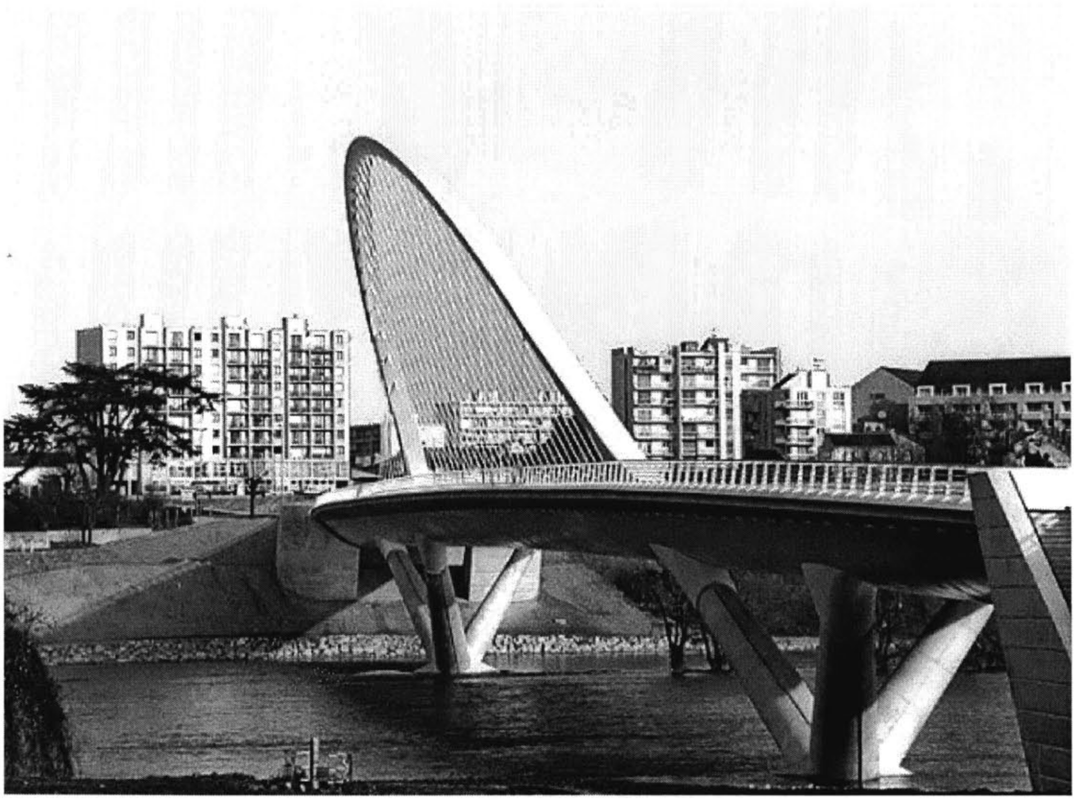

Figure 24: Orleans Bridge arch

Three projects were presented: two classical arch designs while the last one offered an inclined arch. This unusual design was preferred; it was Calatrava's concept.

3-1-2 Why Calatrava?

Calatrava bridge was chosen for its numerous architectural qualities and its integration in the environment.

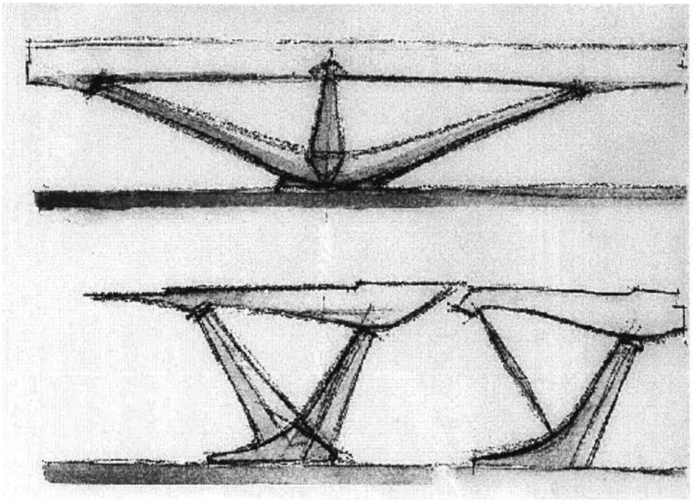

Figure 25: Calatrava sketch of the Orleans Bridge tripods

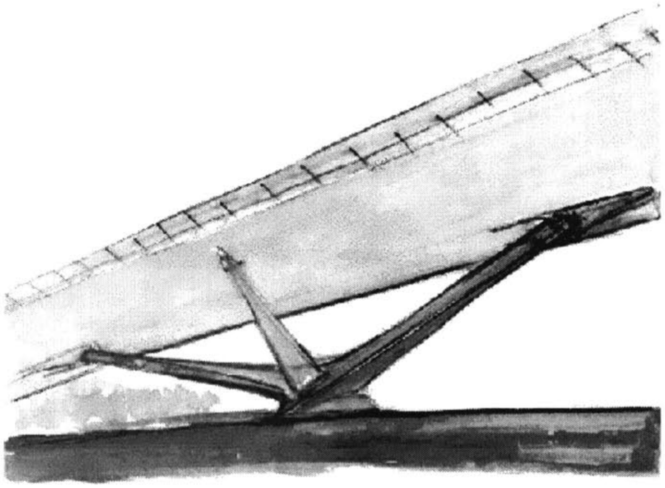

Figure 26: Calatrava sketch of the Orleans Bridge tripods

For example, look at the piles and notice that they were reduced to a strict minimum. This choice is not dictated by the soil instability along the Loire River. Indeed Calatrava main aim was to conserve the flow, the bed, and the reflection of the Loire. The existing natural sandbanks appeared to be the best location for the piles in order to minimize their environment impact. Two concrete tripods consisting of three inclined branches support the central arch span. The tripods, which represent three thin fingers of a hand, are visualized as the natural extension of the arch. As a consequence, one observes from the bank a perfect oval on the water, the reflection of the arch.

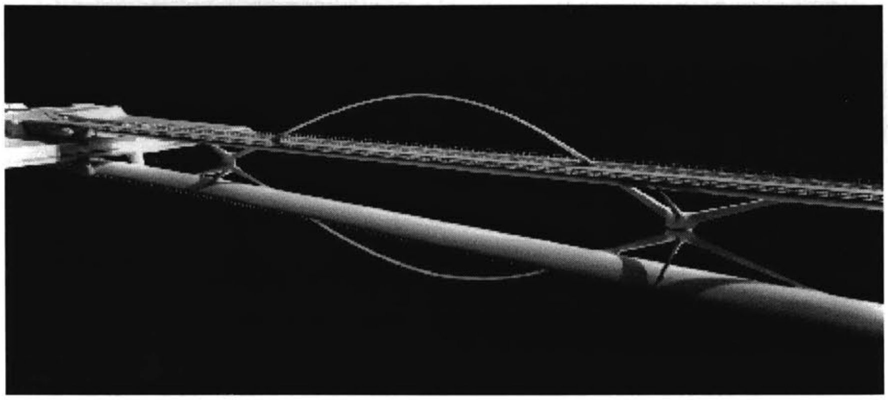

Figure 27: Model of the Orleans Bridge

Note the arch reflection on water

During the night, an ingenious light system integrated in the deck and the piles reinforces the appeal of the bridge, which is painted entirely in white. For Calatrava, lighting is an essential element of the bridge.

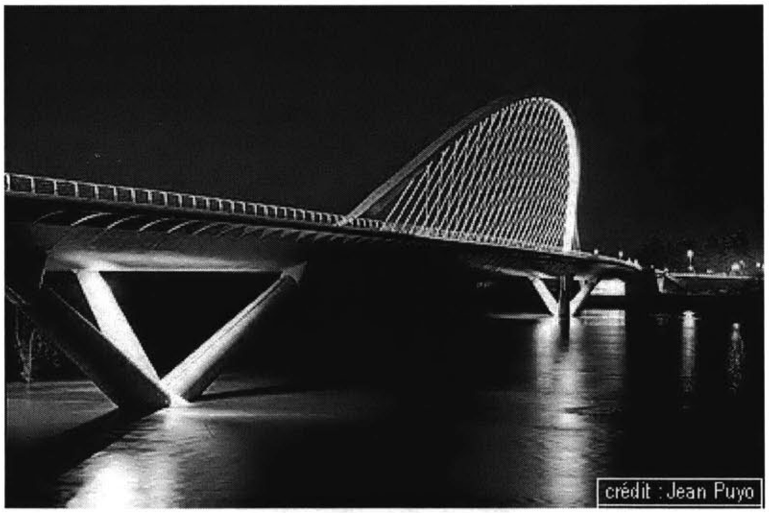

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Figure 28: Night view of the Orleans Bridge

This inclined arch gives vitality to the bridge symbolizing the entrance to Orleans. Four traffic lanes, cyclist and pedestrian paths on both side of the bridge constitute the deck. As in most of Calatrava bridges, the deck is not a simple single horizontal surface; it has been built up in terraces like in a theater so that people can enjoy the fantastic view offered: motorists, cyclists, pedestrians.

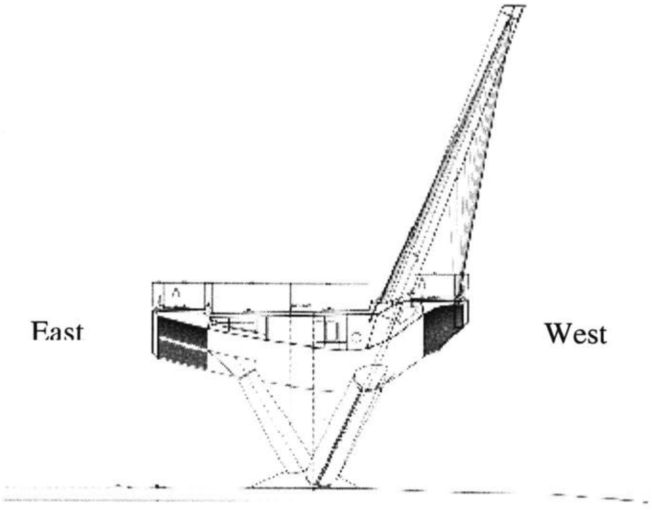

Figure 29: Cross section of the Orleans Bridge

All those details are just an overview of Calatrava's perfectionism. For those innovative ideas, Calatrava was declared winner of the competition.

3-1-3 Overview of the bridge:

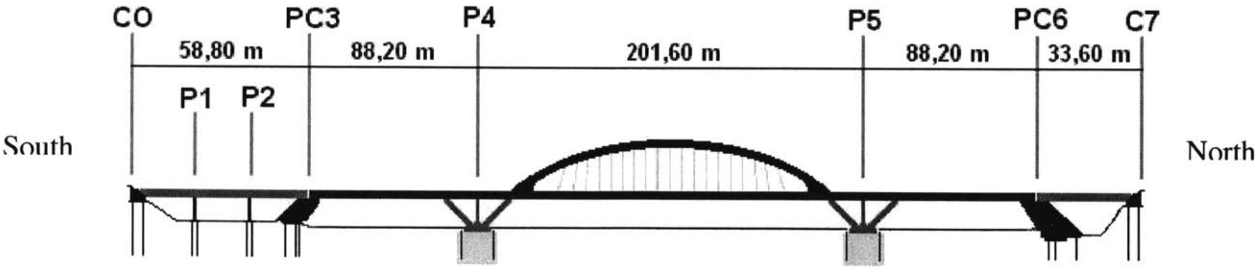

Figure 30: Longitudinal View of the Orleans Bridge

The arch, which is extremely slender, is located at one side of the bridge deck, between the traffic and pedestrian lanes. This planar arch, as tall as a building of 8 floors, lies at an inclination of 68 degrees and spans 201.6 meters! As a reminder the Alameda Bridge in Valencia spans 130 meters.

The spans between the intersection points of the branches of the tripods and abutments reach both 88.2 meters. Those 3 spans constitute the central arch bridge with a final length of 378 meters. This part of the bridge is entirely made of steel.

Two small concrete bridges at the embankments of respectively 33.6 and 58.8 meters complete the central arch bridge. This gives a total length of 470 meters.

One can distinguish two different slopes along the longitudinal axis of the deck: 2.046% and 0.500%.

Figure 31: Orleans Bridge roadway

The deck is 25.74 meter wide at mid-span and is composed of four traffic lanes of 13 meter wide, two cycle paths of 2 meters each, and two walkways of 1.5 meters.

Unlike the previous bridges presented, the bridge is suspended by two series of 28 cables placed in a reversed V-form. Those cables are placed at regular intervals of approximately 4.2m along the elevated walkway. The elevated walkway and the arch are located on the western side, the downstream side of the bridge.

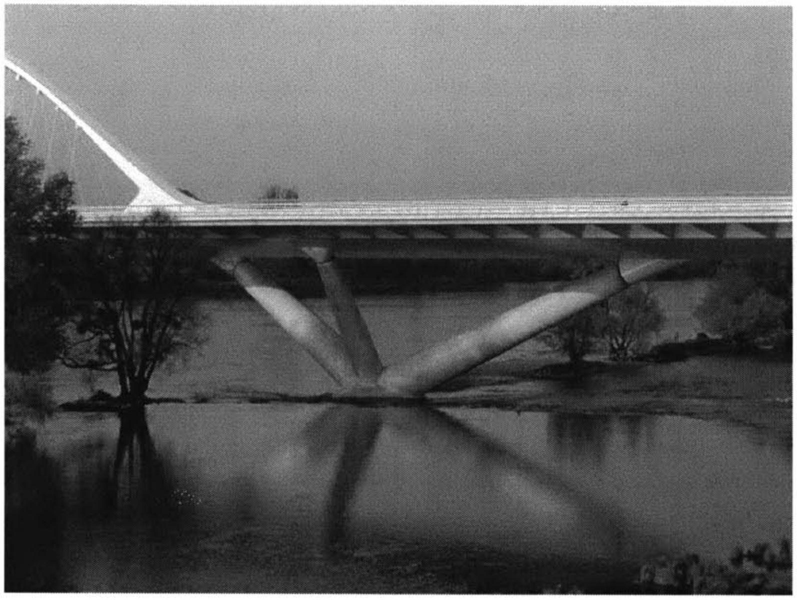

Figure 32: Orleans Bridge tripod

Both tripods consist of one branch or "finger" in the visual continuation of the arch, another in the same plane supporting the 88.2 meters spans, while the third branch is in the orthogonal direction of this plan.

3-2 Conceptual design

At a first glance, one could wonder how this bridge defying the gravity laws does not collapse! Is it the novel expression of the state of equilibrium?

3-2-1 Deck

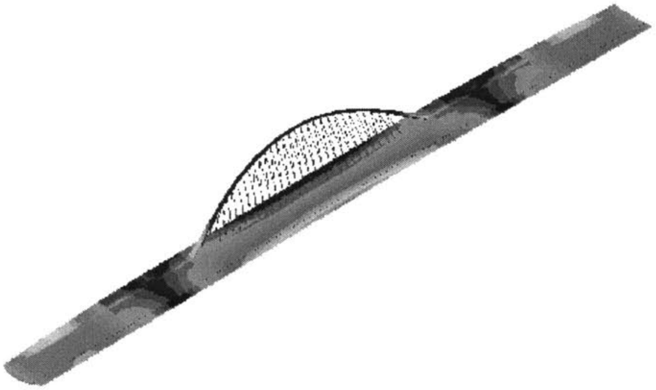

Figure 33: Static analysis of the Orleans bridge

Simplifying the complex design, the roadway which supports the structure acts as a horizontal beam between the tripods, delivering gravity loads to the cables and developing the necessary components of force required to load the two series of cables purely within the desired plane. Actually the beam prevents lateral distortion creating this horizontal component while the vertical component comes from the weight of the roadway. Thus the beam acts as a perforated torsion box to resist rotation of the arch into a position of equilibrium as a resultant of the horizontal and vertical forces. It's like a system of weight and counterweight.

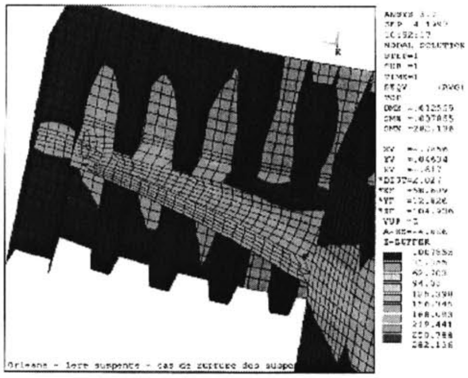

Figure 34: Static analysis of the cantilevered walkway of the Orleans Bridge

The hangers regularly placed along the deck not only stabilize the arch but also longitudinally distribute the torsion (created by the arch inclination) all along the deck. The torsional stiffness of the box girder is very important.

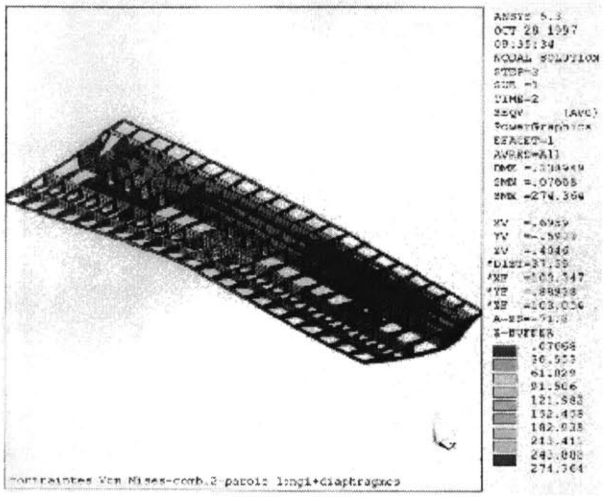

Figure 35: Static analysis of the Orleans Bridge deck

But the first function of the arch is to ensure the longitudinal bending resistance of the bridge by limiting the vertical deflection. In this particular bridge, the vertical loads create bending in a horizontal plane as a result of the inclined load transfer from the hangers and bring about horizontal deflection. As a consequence, all the resulting deformations into the deck had to be taken into account using pre-camber. The geometric compensations found are the following: a vertical pre-camber at mid-span respectively of 6 and 30 centimeters for east and west sides, a horizontal pre-camber at mid span of 23 centimeters, a torsional pre-camber and a shortening of the bridge deck.

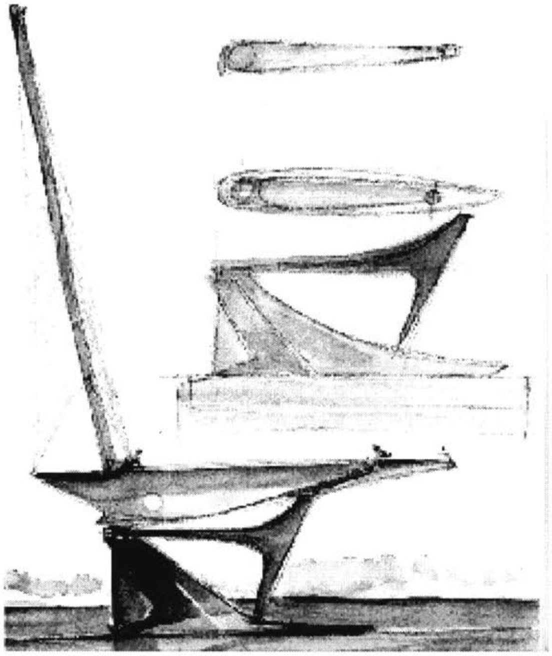

Figure 36: Calatrava sketch of the cross section of the Orleans Bridge

Note that actually the cross section represents a boat.

The asymmetrical deck shaped like a wing was designed with the help of the Danish Maritime Institute. Thus wind tunnel tests were carried out to obtain the best design. Finally the deck chosen has its curved bottom flange in a form of a wing or more probably a ship's hull. Indeed in that case the arch could represent the mast of the boat as clearly illustrated in the sketch above from Calatrava.

3-2-2 Arch

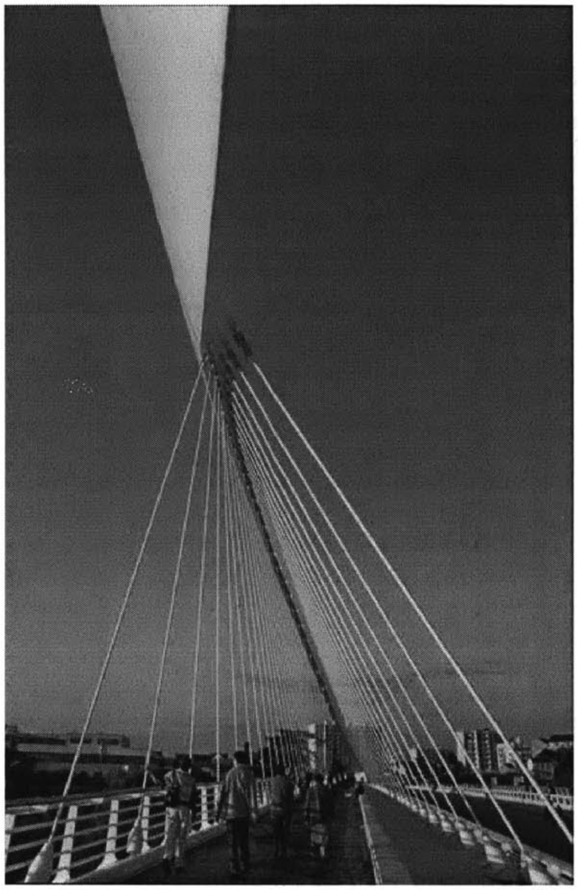

Figure 37: View of the elevated walkway and the arch of the Orleans Bridge

In the design phase, a first order analysis was carried out to determine the buckling modes of the arch. Afterwards, a second order analysis was made using the real buckling mode. Actually, when the bridge is used by people, the gravity loading displace the arch to a more vertical position, slightly stiffening it and providing further protection from buckling.

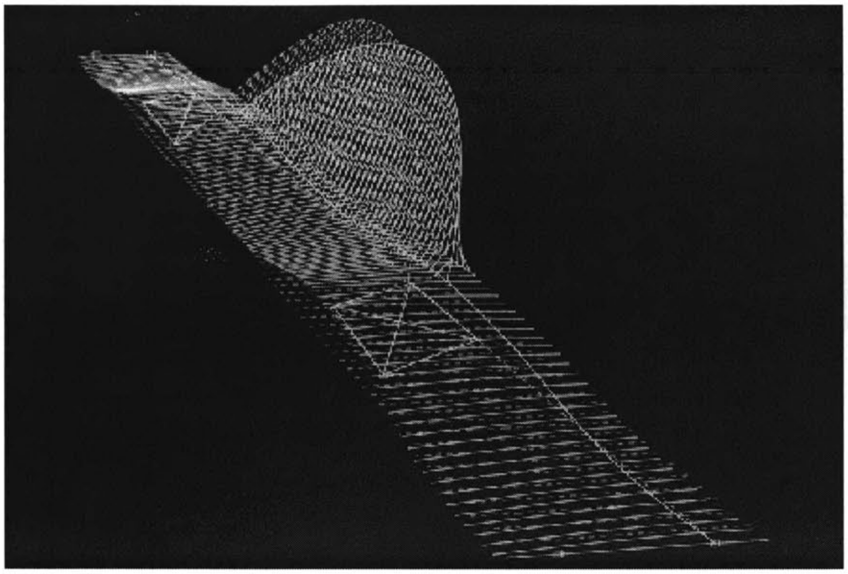

Figure 38: Static analysis of the Orleans Bridge carried out with Pythagore

The structural team for the static and dynamic analysis used the software Pythagore.

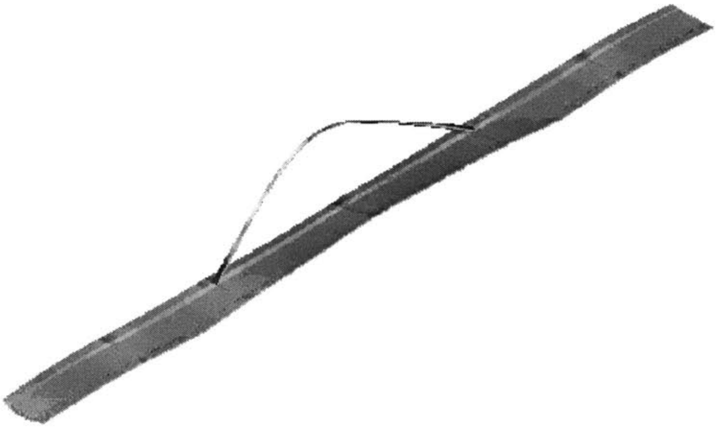

Figure 39: Static analysis of the Orleans Bridge during its construction

Note that the hangers are not attached

During the construction period, when the arch was not attached to the deck by the hangers, the bridge acted as a real bowstring. Thus a tensile force into the deck balanced the compressive forces in the arch. At that moment temporary piles supported the bridge. Once the connection with the two tripods was carried out, the bridge behaved like a real arch bridge. Consequently now the compressive arch forces are directly transmitted to the tripod and the foundations. This is not the case for the thermal actions.

For each construction phase a static analysis was performed out to determine the stability of the structure.

3-2-3 Hangers

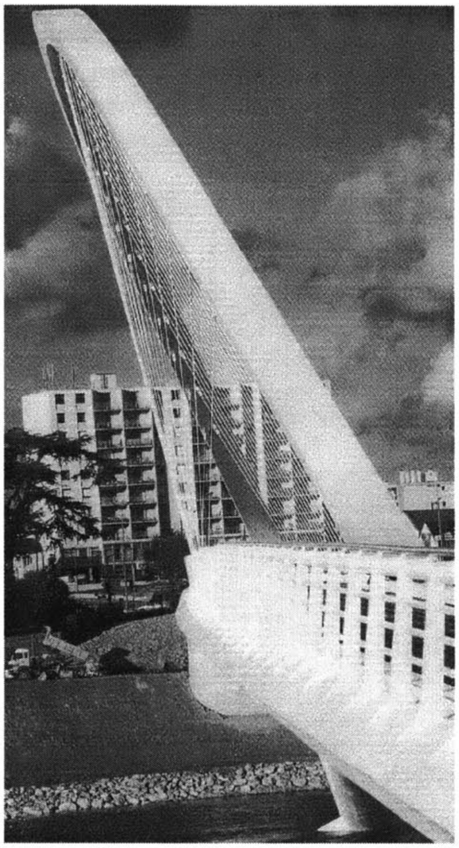

Figure 40: Hangers of the Orleans Bridge
Note the masses attached to the cables

A dynamic analysis of the bridge revealed that under wind loading, for certain modes, the harmonic frequencies of the arch and the hangers are very close. Consequently under wind loading, the arch and the hangers can be simultaneously excited by certain vibration modes. Furthermore all those vibrations create fatigue into the hangers. Especially concerned, the connections with tie rods undergo the very important number of stress cycles.

So it was decided to create specific dampers to reduce all those vibrations. Actually the best solution found consisted in equipping the hangers with simple masses. The tricky part was to determine the optimal location and weight of the masses.

3-2-4 Tripods

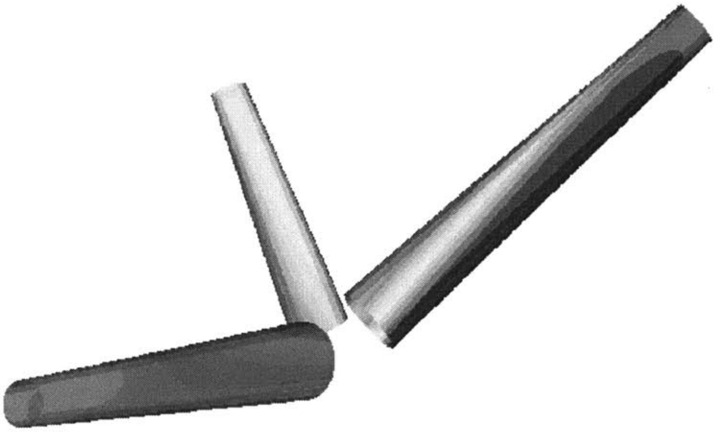

Figure 41: Static analysis of the northern tripod of the Orleans bridge

The right tripod supports the arch, the left tripod supports the 88.2 meters span

The two branches of the tripods in visual continuation with the arch only receive compressive forces from the arch.

The other branches in the same plan support the 88.2-meter spans of the central arch bridge entirely made of steel.

The two last branches perpendicular to this plan resist to the torsion transferred by the asymmetrical deck.

Figure 42: View of the tripod base of the Orleans Bridge

The form of this highly asymmetrical deck leads to important differences in the location of the center of gravity of the resistant section, the center of gravity of the permanent loads, and the shear center. This is why during the static analysis of the bridge, the arch inclination was chosen to have the resultant of the permanent loads passing through the point of intersection of the branches of the tripods. As a consequence, the bending moments were reduced at a maximum at that intersection point.

3-3 Structural concept

3-3-1 Deck

The box girder has a depth of 3.25 meters. Its width reaches 25.4 meters at mid-span and varies in order to create space between the roadway and the elevated walkway.

Moreover the steel box girder with the orthotropic deck is directly in contact with the carriageway. Panels have been cantilevered on both sides. They will support the cycle and pedestrian paths.

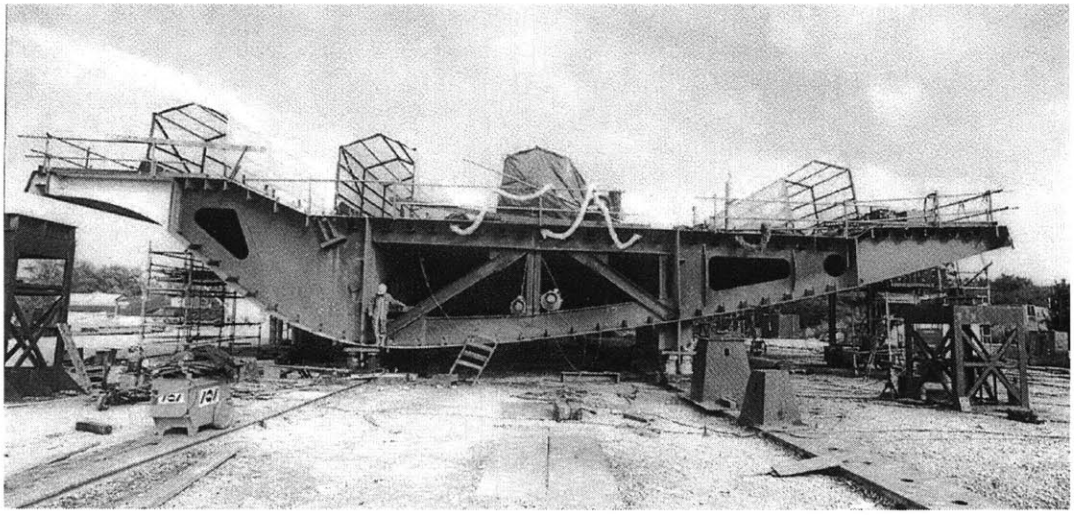

Figure 43: Cross section of the Orleans Bridge deck

Besides the box girder is reinforced with trapezoidal stiffeners at the top flange and flat plates at the bottom flange. Their trapezoidal stiffeners have a constant thickness of 1.4 centimeters whereas the flat plates thickness oscillates between 1.4 and 2.4 centimeters.

Diaphragms are placed every 4.2 meters either out of the flat plate at the supports or in the form of a K-brace. This K-brace is made with UPN 300 profiles. Furthermore three cells constitute the box girder. So the different units are transportable by trucks from the north of Belgium and the East of France where they were made.

Depending on the material thickness, steel grades S355J2G3, S355N, S355NL were used. To protect them from corrosion a three-coat paint system was selected in addition of a dehydration system for the interior.

The exterior elements of the deck are painted in white. An original detail: the balustrades follow the cables inclination.

3-3-2 Arch

Figure 44: Orleans Bridge arch

The arch is 25 meter deep. The cross section of the slender arch is a trapezium of 1.65 meters height with two bases of 0.55 and 1.40 meters. The top flange of the arch is always horizontal. S460M and S460ML high-grade steel were used to diminish the plate thickness to only 4.8 centimeters.

Like for the deck, every 4.2 meters where hangers are connected, diaphragms have been installed.

3-3-3 Hangers

Figure 45: Orleans Bridge cables

Placed every 4.2 meters in a reversed V-form, the cables have respectively a diameter of 5.5 centimeters for the connections in the plane of the arch and 3.6 for the connections to the downstream (exterior) side of the elevated walkway.

Figure 46: Connection of the cables to the arch in the Orleans Bridge

They are joined to the arch via a traditional pinhole connection and to the deck via tie rods. Plates fixed in the box girder maintain those tie rods. Those plates are machined in a bicylindrical form to reduce the "parasitic moments" in the rods and the cable acting like hinges.

Also, the connections at the level of the deck are protected from corrosion with conical shells.

3-3-4 Tripods

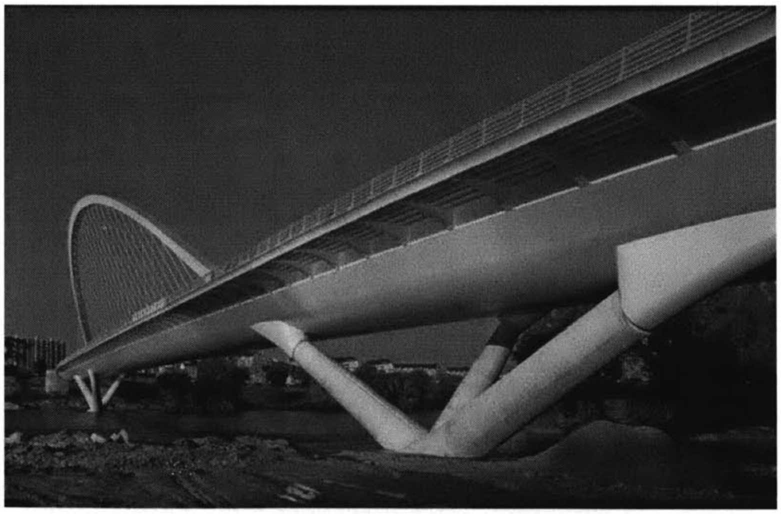

Figure 47: Southern tripod of the Orleans Bridge

The tripods were built with white concrete B40. The bridge is not symmetrical as the two levels at the end of the deck are quite different. As a consequence the tripod P4 located at the south is smaller than P5. The longest branch of the tripods is about 26 meter long. Furthermore the branches in visual continuation with the arch are inclined of 20 degrees to the horizontal.

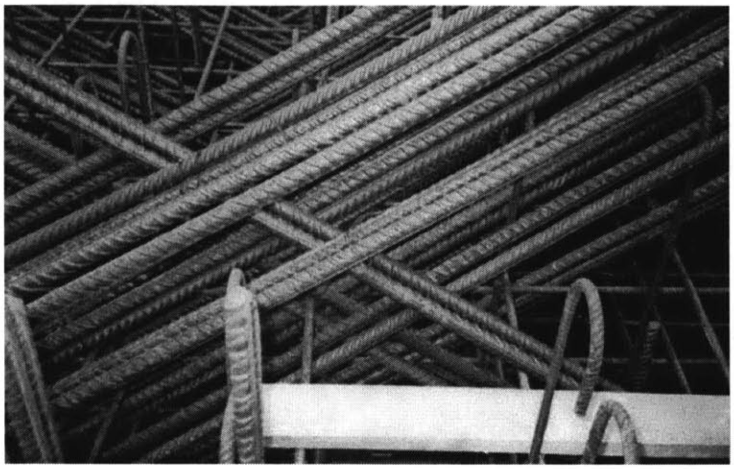

Figure 48: Reinforcing bars located in the base of the Orleans Bridge tripod

Note the high density of bars

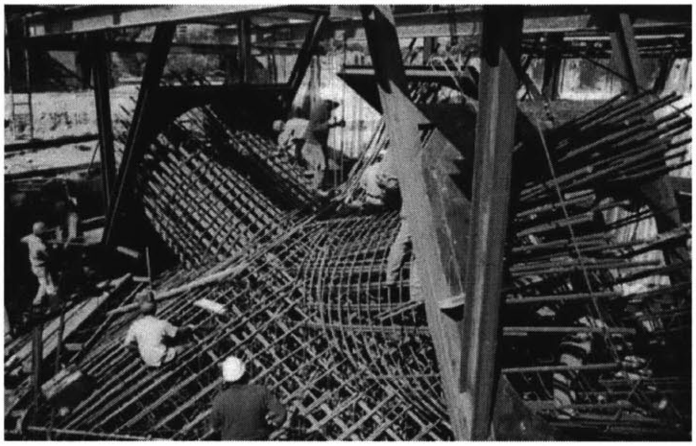

Figure 49: Tripod reinforcement in the Orleans Bridge

A profiled slab enables a good draining of the water. The cross section of the branches is elliptical. Those branches are connected to the deck with pot bearing which can be injected in order to counteract the creep. Indeed the creep can bring about an eventual shortening of the branches.

3-4 Construction of the bridge

3-4-1 Introduction

Figure 50: Overview of the site before the construction of the Orleans Bridge

The bridge construction lasted two years: between July of 1998 and July of 2000.

The complex construction was virtually carried out with three-dimensional CAD models to ensure a better erection on site.

122 road transports were completed from the workshops located in France and Belgium to the site. Actually the Loire River is not navigable so the road was the only way to transport the elements of the bridge to the site. Consequently the deck for example was divided in 108 different elements in order to be transportable.

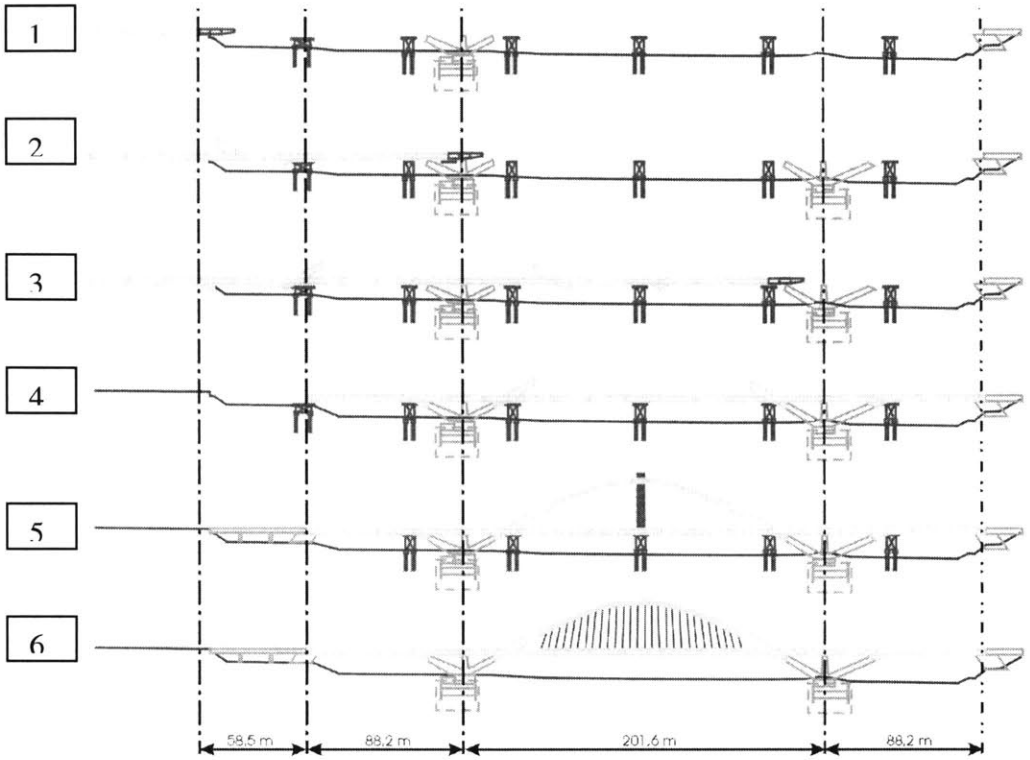

Figure 51: Construction phases of the Orleans Bridge

For the erection of the arch steel bridge with the span of 378 meters, two main phases can be distinguished: the erection of the deck (phases 1-2-3-4 of the figure above), the erection of the arch (phases 5-6 of the figure above).

3-4-2 Erection of the deck

3-4-2-1 Division of the elements

The deck was divided in 18 main parts, each with a length of 21 meters. The cross section was divided further in 6 elements. Thus the biggest part transported was 130 tons with a length of 21 meters, a width of 6.5 meters and a height of 4.5 meters.

3-4-2-2 Assembly site

Figure 52: Assembly site of the Orleans Bridge located on the southern riverbank

The bridge was launched from the southern riverbank where was located the assembly site. The assembly site was 77 meter long and was able to weld and paint up to three elements of 21 meters.

So every three weeks, the deck was launched 21 meters. Hence 17 phases were realized to complete the deck erection with the help of two 120-200 tons mobile cranes.

3-4-2-3 Launching nose

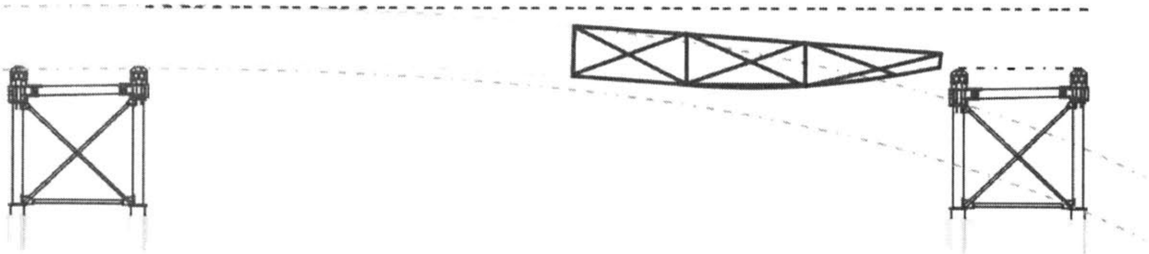

Figure 53: Launching nose system

As the bridge is pre-cambered, it was launched in a curve (in the longitudinal view) and was equipped with a 20 meter long launching nose. Therefore the deflection of the cantilevered part could be reduced.

Figure 54: Launching nose of the Orleans Bridge

Moreover he bottom flange of the launching nose was pre-cambered by 1.25 meters.

3-4-2-4 Erection towers

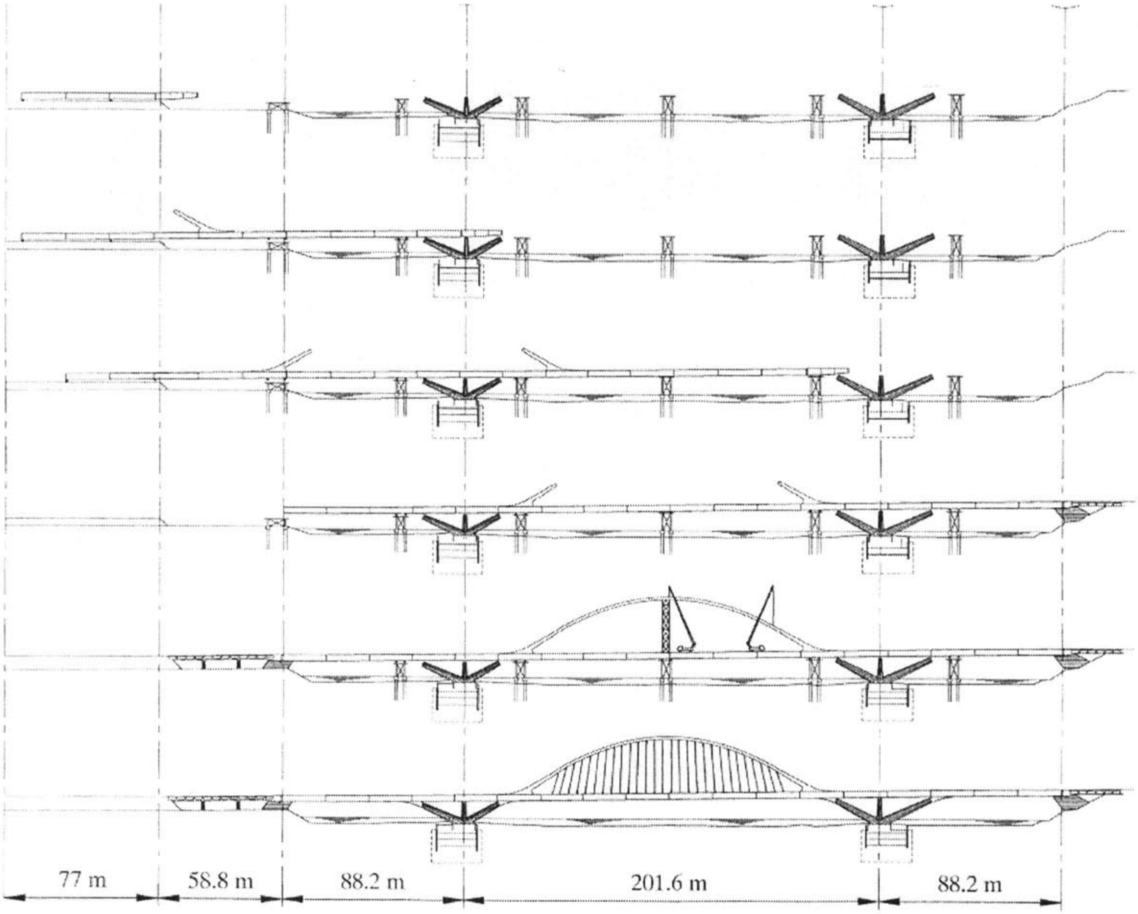

Figure 55: Location of the erection towers during the Orleans Bridge construction

Six temporary erection towers were constructed at different locations: at each abutment, at mid-span and at both sides of the tripods.

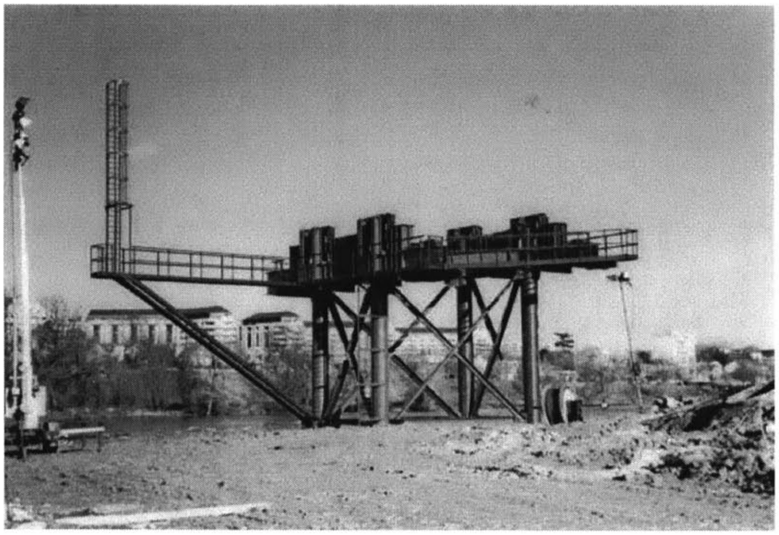

Figure 56: Erection tower of the Orleans Bridge

They were made of four S460 piles with two longitudinal girders on the top where special structures call balances were added.

Those balances had the ability to adapt to the inclination of the deck. Actually this inclination is not constant during the launching. They were able to support a maximum pressure of 3 kilo Newton/ square centimeters. 72 spherical springs were present to ensure an optimal distribution of the stresses created by the deck over the balance.

Two hydraulic jacks were installed on the balance to correct an eventual settlement and to adjust the vertical pre-camber of the deck.

3-4-2-5 Launching system

Figure 57: Concrete rails supporting the Orleans Bridge launching system

At the level of the assembly site, the bridge was fixed to four supports. Those supports were able to slide on concrete rails thanks to neoprene bearings made of a stainless steel/PTFE interface. Hence the friction coefficient only oscillated between one and four per cent.

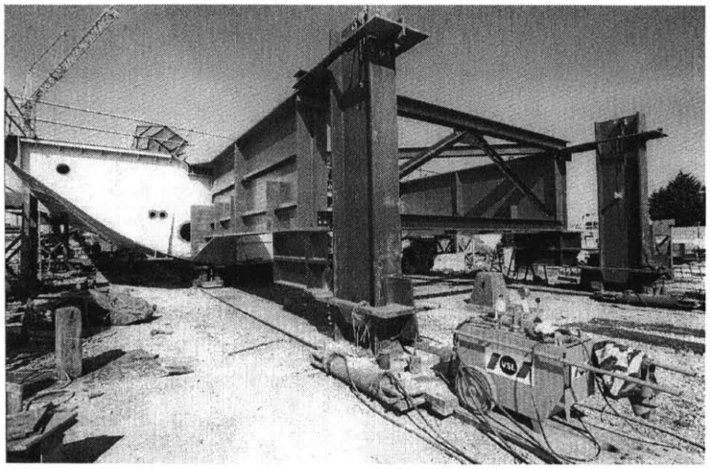

Figure 58: Launching system of the Orleans bridge deck

Four hydraulic jacks with a stroke of 80 centimeters and a capacity of 75 tons each were connected to the end of the deck by means of a yoke. The advantage of this yoke was its ability to allow vertical deflections.

The bridge was pushed over 378 meters with this launching system. But the steel bridge had to leave the assembly zone bypassing over the area of the concrete bridge to reach its final locations. Those last 58 meters were completed using the launching system as a pulling device not as a pushing device with the help of high strength strands. A launching nose of 5 meters was placed at the southern part of the deck so that he smoothly left the assembly area.

3-4-3 Erection of the arch

3-4-3-1 Assembling of the arch elements

Figure 59: Arch elements on the Orleans Bridge deck

Figure 60: 400 tons mobile crane lifting an arch element of the Orleans Bridge

The arch elements were assembled on site to obtain two larger units each of 55 meters length and 120 tons. Placed on the deck, those units were launched with it up to its final location and finally lifted thanks to two 400 tons mobile cranes. Those mobiles cranes were located on the deck itself.

3-4-3-2 Weld of the stubs

The stubs ensure the contact between the six branches of the tripods and the deck. Those six stubs were brought in their final location and two were welded with the arch.

3-4-3-3 Erection of the hangers

After the erection of the arch, the 28 hangers connected in the plane of the arch were tensioned with 42 tons in each cable. So the erection tower at mid span was dismantled, as it was useless. Consequently a big part of the horizontal pre-camber suddenly disappeared.
Afterward the 28 hangers located on the edge of the elevated walkway were connected but without any tension.
At that moment behaved like a bowstring where the deck was the tensioned tie (1100 tons of tension).

3-4-3-4 Installation of the six pot bearings

Finally the six pot bearings were set in place and grouted after an accurate geometrical survey. By grouting simultaneously those six pot bearings in the early morning with a quick hardening mortar, the thermal expansion of the bridge was reduced.
The erection towers around the tripods were taken apart. At last the compression arch forces were transmitted to the pods and the foundations. At that time, another part of the horizontal pre-camber disappeared.

3-4-3-5 Comments on bearings at the abutments

As explained before the vertical loads on this unique bridge create transversal deflection. Thus the transverse loads created could affect them. This is why the bearings at the abutments were completed after the construction of the bridge. However the variable loads and the creep effects if the concrete tripods will still provoke some transverse bearing loads but their effect is reduced.

CHAPTER 4

CONCLUSION

4 Conclusion

Through the work of Calatrava, we can see that “ there is a kind of progression with Merida, where the arch is centered above the roadway deck, which is the element that provides torsional resistance. Case number two is Ripoll, which was for me a kind of experiment to control the system of the inclined arch in a span of 70 meters, or 230 feet, making it feasible at a very low cost and with a deck that is only something like 3 meters, or 10 feet wide. Case number three is Ondárroa, in which there is a significant traffic load, and case number four is Valencia, with four lanes of traffic. Orleans is number five, with a major span, four lanes of traffic, and pedestrians on both sides”(Conversations with Students, Calatrava).

This last case, the Orleans Bridge, is original and very spectacular. It is still the biggest and the most advanced Calatrava bridge that uses an inclined arch. The tripod system for the piles never realized before, the complexity of the overall design, testify the work carried out. Those innovations required the latest design technologies, high performance materials like concrete B40, high-grade steel S460.

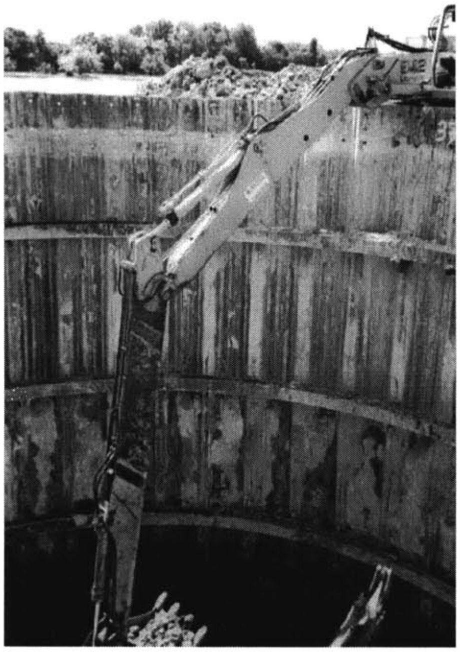

Figure 61: Tripod foundation of the Orleans Bridge

Furthermore the geotechnical characteristics were quite special. Indeed lots of voids, called Karsts were present in the limestone. Consequently injections and deep foundations under the tripods were performed. And I don't mention the consequences brought about by the numerous floods of the Loire River during the construction.

Figure 62: Floods of the Loire River during the Orleans Bridge construction

Finally 5380 tons of steel, 9800 cubic meters of concrete, 15 tons of paint have been necessary to complete this bridge in 24 months.

This explains the total cost of such a bridge: 30 millions of euros. But in contrast to those who precede him and many of his contemporaries, Calatrava does not consider efficiency and economy as design ideals, but instead necessary aspects of a design. The Alamillo Bridge both demonstrates Calatrava 's design ideals and distinguishes them from those of many other bridge designers. Calatrava treats his bridges as public places, civic icons and opportunities for structural inventions. Calatrava challenges the other contemporary designers but also foster all of us to re-examine the potential of the bridge infrastructure.

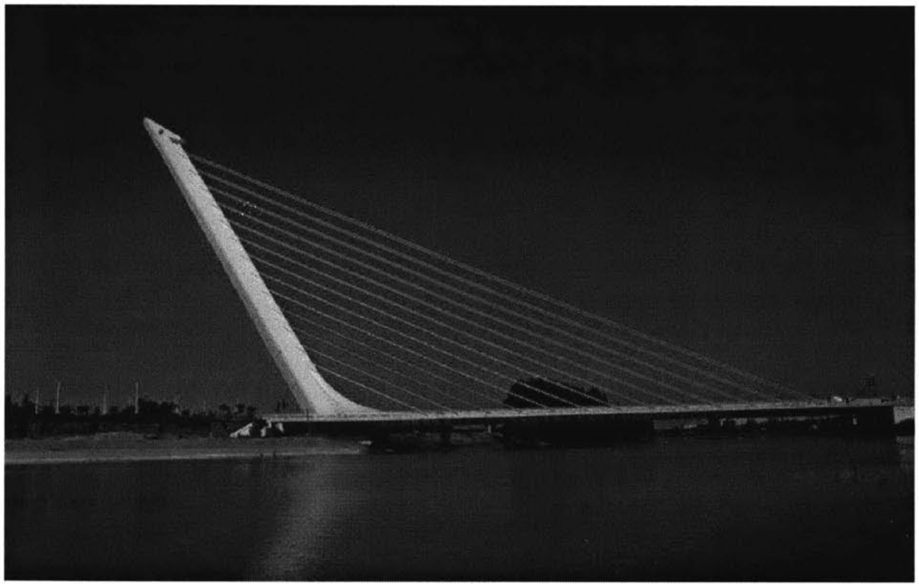

Figure 63: Alamillo Bridge spanning 200 meters with a 142 meters high mast

But what can explain there are so few bridges that can pretend to be as innovative as Calatrava's?

Firstly "the idea of the architect-engineer has been lost. Creativities is buried under equations or hemmed in by the walls of specialties" (Conversations with students, Calatrava). Most of structural and civil engineers have a very narrow, almost exclusively technical education. This education can be so specialized that an engineer may dedicate his career to the application of one material! Consequently this education limits their ability to face larger design issues. And the professional practice reinforces that problem instead of solving it. This today's ironic

situation is similar in Europe and the United States. Now an engineer with a broad background is more innovative, can generate a richer work in a particular field than a highly specialized engineer in that field.
This is why there are very few examples of persons trained like Calatrava. The French Marc Mimram is one of the rare people who can compete with Calatrava for bridge projects.

Secondly it is very hard to impose inventive designs through the competitive bidding process commonly used for big projects. People do not want to pay a lot of money for a unique structure. Inexpensive structures are preferred. Whereas this is true in the United States, the actual cultural climate in Europe foster people like Calatrava. Thus you can note the commission increase of innovative footbridges in England (whereas those are quite small projects).

Thirdly people have to trust the structural designer, which becomes not so easy now with complex structures. Calatrava had to face this problem when experienced contractors carefully scrutinized this famous Alamillo Bridge and finally rejected it as impractical. Actually this bridge was built and works well.
So another problem is raised. Those complex structures are checked and carried out with sophisticated softwares understood by only a handful of theoreticians. Can we trust so far those computer programs essential for this kind of structure?

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APPENDIX: CALATRAVA'S BIOGHRAPHY

Architect, artist, and engineer Santiago Calatrava was born on July 28, 1951, in the town of Benimamet, near Valencia, Spain. His background was eclectic. Calatrava is an aristocratic name, passed down from a medieval order of knights; and Benimamet is a town largely populated by Jewish converts to Catholicism. The family on both sides was engaged in the agricultural export business, which gave them an international outlook that was rare during the Franco dictatorship.

Calatrava attended primary and secondary school in Valencia. From the age of eight, he also attended the Arts and Crafts School, where he began his formal instruction in drawing and painting. When he was thirteen, his family took advantage of the recent opening of the borders and sent him to Paris as an exchange student. He later traveled and studied in Switzerland as well. Upon completing high school in Valencia, he went to Paris with the intention of enrolling in the Ecole des Beaux-Arts; but after he arrived in June 1968, he found his plan was unworkable. He returned to Valencia and enrolled in the Escuela Tecnica Superior de Arquitectura, a relatively new institution, where he earned a degree in architecture and took a post-graduate course in urbanism. While at the school, he also undertook independent projects with a group of fellow students, bringing out two books on the vernacular architecture of Valencia and Ibiza.

Attracted by the mathematical rigor of certain great works of historic architecture, and feeling that his training in Valencia had given him no clear direction, Calatrava decided to pursue post-graduate studies in civil engineering and enrolled in 1975 at the ETH (Federal Institute of Technology) in Zurich. He received his Ph.D. there in 1979. It was during this period that he met and married his wife, who was a law student in Zurich.

After completing his studies, Calatrava took a position as an assistant at the ETH and began to accept small engineering commissions, such as designing the roof for a library or the balcony of a private residence. He also began to enter competitions, believing this was his most likely way to secure commissions. His first winning competition proposal, in 1983, was for the design and construction of Stadelhofen Railway Station in Zurich, the city in which he established his office.

In 1984, Calatrava won the competition to design and build the Bach de Roda Bridge, commissioned for the Olympic Games in Barcelona. This was the beginning of the bridge projects that established his international reputation. Among the other notable bridges that followed were the Alamillo Bridge and viaduct, commissioned for the World's Fair in Seville (1987-92), Lusitania Bridge in Merida (1988-91), Ondarroa Bridge in Ondarroa, Spain (1989-95), Campo Volantin Footbridge in Bilbao (1990-97), and Alameda Bridge and underground station in Valencia (1991-95). The attendant growth of his practice led him to establish a second office, in Paris, in 1989.

During this phase of his career, Calatrava won a reputation for designing other large-scale public projects as well. These included the BCE Place mall in Toronto (1987-92), the railway station for the Lyon-Satolas Airport (1989-94), Sondica Airport in Bilbao (1990-2000), Tenerife Opera House in the Canary Islands (1991-2001), the City of Arts and Sciences in Valencia, where he established his third office (1991 -- ongoing), and the Oriente Railway Station in Lisbon (1993-98, commissioned for Expo '98). He also won the design competition to complete the Cathedral of St. John the Divine in New York City (1991), a project that has not been realized.

Exhibitions of Calatrava's work were first mounted in 1985, with a showing of nine sculptures at Jamileh Weber Gallery in Zurich. A new stage in recognition was marked by two solo exhibitions: a retrospective at the Royal Institute of British Architects, London, in 1992, and the exhibition Structure and Expression at The Museum of Modern Art, New York, in 1993. The latter exhibition included an installation in the museum's Sculpture Garden of *Shadow Machine*, a large-scale sculpture with undulating concrete "fingers." The most complete exhibition of his work yet mounted was *Santiago Calatrava: Artist, Architect, Engineer*, presented at the Palazzo Strozzi in Florence, Italy, from October 2000 through January 2001. A similar but smaller exhibition, *Poetics of Movement: The Architecture of Santiago Calatrava*, was mounted in Dallas at the new Meadows Museum in 2001.

Among Calatrava's major projects that were recently inaugurated or are coming to completion are the Science Museum at the City of Arts and Sciences in Valencia (November 2000); Sondica Airport in Bilbao (November 2000); Orléans Bridge in Orléans, France (November 2000); and his first building in the United States, the Milwaukee Art Museum, which opened to great acclaim in autumn 2001. The Tenerife Opera House is scheduled to open in 2002. The first phase of the Opera House of the City of Arts and Sciences in Valencia is scheduled for an autumn 2003 inauguration.

Scheduling is now in progress for another major Calatrava commission in the United States, the new Roman Catholic Christ the Light Cathedral of Oakland, California. Other current projects in the U.S. include a terminal for the people-mover system at the Dallas-Fort Worth International Airport; an ensemble of bridges and parkway for the Trinity River, in the heart of Dallas; and a bridge and esplanade for the expansion of Grant Park, on the lakefront in Chicago.

Among the honors and awards given to Santiago Calatrava are the Gold Medal of the Institute of Structural Engineers, London; Honorary Fellowship in the Royal Institute of British Architects; honorary membership in the Union of German Architects; membership in the Royal Academy of Fine Arts of San Carlos, Valencia; the City of Toronto Urban Design Award; designation as a Global Leader for Tomorrow by the World Economic Forum in Davos; the Creu Sant Jordi, Barcelona; the Gold Medal for Merit in the Fine Arts, Ministry of Culture, Granada; membership in Les Arts et Lettres, Paris; the Algur H. Meadows Award for Excellence in the Arts (Meadows School of the Arts, Southern Methodist University); and the Principe de Asturias Prize in Spain. He has received 11 doctoral honors throughout his career.

Born

- 1951, 28 July, Benimamet, Valencia, Spain.

Education

- 1968 Primary and secondary schooling in Valencia, Spain.
- 1968-1969 Attends Art School in Valencia, Spain.
- 1969-1974 Studies architecture at the "Escuela Tecnica Superior de Arquitectura de Valencia" qualifying as an architect, Spain.
- 1975 - 1979 attends and earns an engineering degree at the Federla Politechnic un Zürich, Switzerland.
- 1981 Doctorate in Technical Science of the Department of Architecture ETH Zurich, Switzerland.

Career

- 1981 Office in Zürich, Switzerland.
- 1985 Member of BSA (Union of Swiss Architects). Member of the International Academy of Architecture. Honorary Member of BDA (Union of German Architects).
- 1992 Member of the Real Academia de Bellas Artes de San Carlos, Valencia, Spain. Member of the European Academy, Cologne, Germany.
- 1993 Hon FRIBA Honorary Member of the Royal Institute of British Architects, London, England. Doctor Honoris Causa, Polytechnic University of Valencia, Spain.
- 1994 Doctor Honoris Causa, University of Seville, Spain. Doctor Honoris Causa of Letters in Environmental Studies, Heriot-Watt University, Edinburgh. Fellow Honoris Causae, The Royal Incorporation of Architects, Scotland. Honory Member of Colegio de Arquitectos de la ciudad de Mexico.
- 1995 Doctor Honoris Causa of Science, University College Salford, England. Doctor of Science Honoris Causa, University of Strathclyde, Glasgow. Doctor of Science Honoris Causa, University of Technology, Delft. Doctor Honoris Causa of Engineering, Milwaukee School of Engineering, Milwaukee, Wisconsin.
- 1998 Member of Les Arts et Lettres, Paris, France.
- 1999 Doctor Honoris Causa of Civil Engineering, Universisitá degli Stugi di Cassino, Italy. Doctor Honoris Causa of Technology, Lund University, Sweden. Honorary Member Causa of the Real Academia de Bellas Artes de San Fernando, Spain. Foreign Member of the Royal Swedish Academy of Engineering Sciences, IVA, Sweden.

Information

Principal works

- 1983 - 1985 Warenhaus Ernstings Coesfeld.
- 1984 - 1986 Commercial building, Bernstrasse-West, Suhr (AG), Switzerland.
- 1984 - 1988 Kantonsschule Wohlen Wohlen (AG), Switzerland.
- 1984 - 1990 Train Station Zurich-Stadelhofen, Zurich, Switzerland.
- **1984 - 1989 Train Station**, Bahnhofplatz, Lucerne, Switzerland.
- **1985 Post Office Building**, Bahnhofplatz, Lucerne, Switzerland.
- **1985 - 1987 Felip II Bridge,** Barcelona, Spain.
- 1986 - 1988 Cabaret-Theatre "Tabourettli", Spalenberg 12, Basel, Switzerland.
- 1986 - 1988 9. Oktober - Bridge Valencia, Spain.
- 1987 Blackbox AG, Zurich, Switzerland.
- 1987 1992 Alamillo Bridge, Sevilla.
- 1987 - 1996 Wohnanlage Buchen Würenlingen.
- 1988 - 1991 Lusitania – Bridge, Mérida.
- **1989 - 1992 Telephone Tower**, Barcelona, Spain.
- 1989 Beton-Pavillon Swissbau (Schweizer Baumesse) Basel.
- 1989 - 1994 TGV-Train station, Lyon.
- 1990 Bahnhof Spandau Berlin-Spandau.
- **1992 - 1993 Allan Lambert Galleria**, Toronto, Canada.
- **1992 - 1993 Heritage Square**, Toronto, Canada.
- 1994 - 1995 Kronprinzenbrücke Berlin-Tiergarten, Germany.
- 1994 - 1995 Oberbaumbrücke Berlin-Kreuzberg, Germany.
- 1994 Jahn - Sportpark Berlin-Prenzlauer Berg.
- 1994 Bundestag der Bundesrepublik Deutschland (ehem. Reichstag) Berlin-Tiergarten, Germany.
- 1997 Bahnhof Lissabon (Lisbon).

Work in progress

- Milwaukee, Valence, Liege.

Awards

- 1987 Auguste Perret UIA prize for applied technology in architecture.
- 1990 "Médaille d´Argent de la Recherche et de la Technique", Paris.
- 1991 European Glulam Award, (Glued laminated Timber Construction), Munich, Germany.
- 1992 Gold Metal, Institute of Structural Engineers, London, England.
- 1993 City of Toronto Urban Design Award, for the BCE Place Gallery, Toronto, Canada.
- 1995 Medalla de Oro al Mérito de las Bellas Artes, Ministry of Culture, Granada, Spain.
- 1995 European Award for Steel Structures, reconstruction of the "Kronprinzenbrücke", Berlin, Germany.

- 1999 Principe de ASTURIAS Award for the Arts.