Design of the Térénez curved cable-stayed bridge

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Summary

A new bridge has been designed to replace an existing suspension bridge to cross the river Aulne at Térénez. It has been decided to erect a cable-stayed bridge with a main span 285 metres long; but due to the road alignment, it appeared that it has to be curved.

This paper explains how the design was conducted and how it is possible to control forces in this type of bridge.

Keywords: curved cable-stayed bridge

1. Introduction

The Térénez bridge is located on a road with is one of the two only ways which give access to the Crozon peninsula, and the shorter one for its connection to the North of the Finistère region. The existing bridge was destroyed by the German army, in 1944, during the second world war; it has been replaced with a suspension bridge, completed in 1951 with a main span 272 metres long.

Figure 1 - View of the site and the existing bridge

Its two towers in reinforced concrete are unfortunately suffering from a very severe alkali-reaction; major cracks developed and were recorded in the eighties, and they are still now developing. Their opening can reach 4 to 5 millimetres. Besides this major problem, the masonry of the piers, as well as the steel superstructure are not in very good condition. This is why the local authority –the Conseil Général du Finistère– decided in 1995 to built a new bridge.

The cracks in the towers have been injected in 1992, but it appeared also necessary to strengthen the bridge so that it can resist with the required safety until the erection of a new one. Detailed inspections are conducted at short intervals, masonries have been strengthened –for example by confining the upper part of the pier on the left bank–, and the cross beams of the towers have been strengthened by gluing TFC films (carbon fibres).

2. The site and the first project

The crossing point is very close to the river mouth, in a very natural area: almost no house is visible in the site, and the hilly river banks are covered by major forests. The quality of the site is such that it is highly protected by French and European rules.

The existing road has a very poor lay-out: when entering the Crozon peninsula, the road follows the right bank upstream, crosses the river Aulne and then follows the left bank downstream, so that it has two sharp bents, one at the entrance and the other one at the end of the bridge.

For this reason several other road alignments were analysed. But either the new bridge would have been very high –and thus in the same time very long and costly, and extremely intrusive in the site–, or very deep cuttings would have been necessary in the hills on both banks, destroying the splendid landscape. This is why it has been decided to maintain the road almost as it is, and to built a new bridge close to the existing one and at the same level.

The Sétra and the architect Charles Lavigne were in charge of developing the bridge design and after the analysis –and elimination– of some classical and non-classical structures, it was decided to build a cable-stayed bridge spanning the river almost from bank to bank.

Though some options were rather original, the bridge was designed with a straight alignment, still with two sharp bents, one at each bridge end; the curves were made slightly larger than in the existing road, by widening the side spans of the cable-stayed bridge in the inside of the curvature.

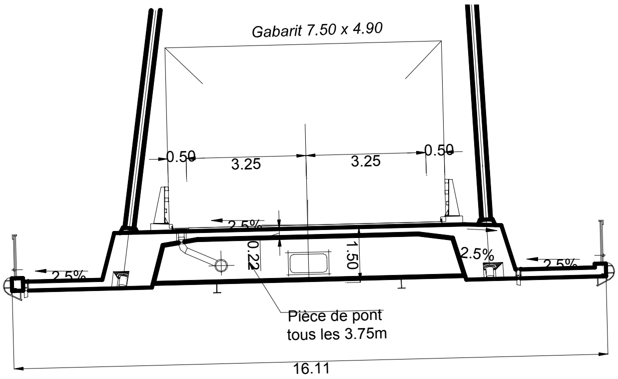


Figure 2 - Typical cross-section of the bridge

Two main decisions were made at this time: the bridge will be built in prestressed concrete, and the cross section will be of the same type as for the Bourgogne Bridge at Chalon-sur-Saône (Burgundy Bridge), called the inverted plate: the cross section is made of two longitudinal, almost rectangular ribs, connected by the upper slab and multiple floor beams; the roadways are supported by this intermediate upper slab, and the sidewalks are outside the stay cables, on cantilevered slabs at the lower level.

Such cross-section has the inertia of a slender box-girder with all the practical advantages of an open cross-section.

3. The final project

In 2000, the owner, the Sétra and the architect invited Michel Virlogeux to join the team. Almost immediately he suggested designing a curved cable-stayed bridge for a flexible road alignment and for a better inscription of the bridge in the site. He proposed a radius of 200 metres in the side spans, and a longer one of 1000 metres in the main span which was very rapidly reduced to 800 metres, with the same main span length as in the first project (285 metres).

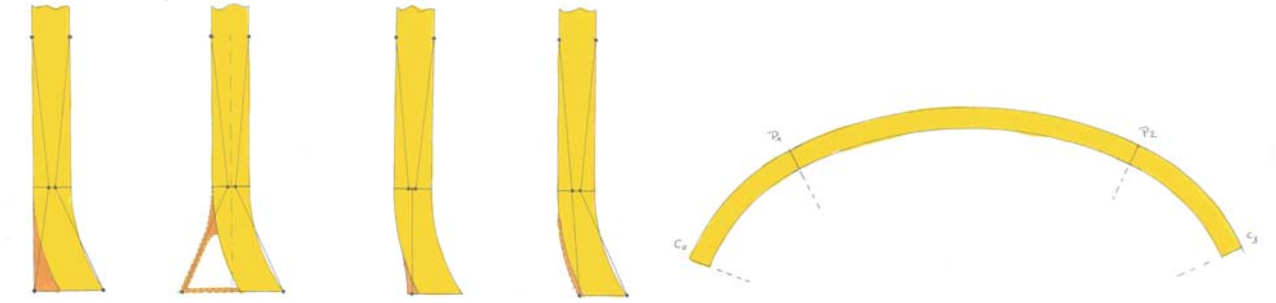


Figure 3 - Side span design – Analysis of possible options for curved side-spans, and the final option of a curved cable-stayed bridge

Immediately with this proposal came a very preliminary evaluation of bending forces in the deck –the ribbed slab in prestressed concrete– produced by the curvature: the horizontal effect of stay cables produces a compressive force at a large distance from the deck center line, which has to be balanced by prestressing forces in the opposite rib (the “outside” rib).

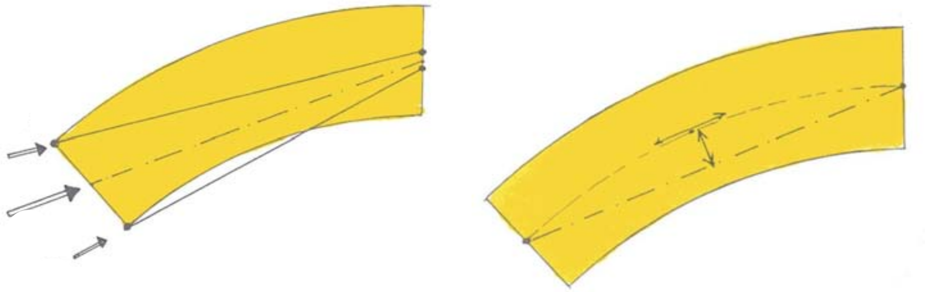
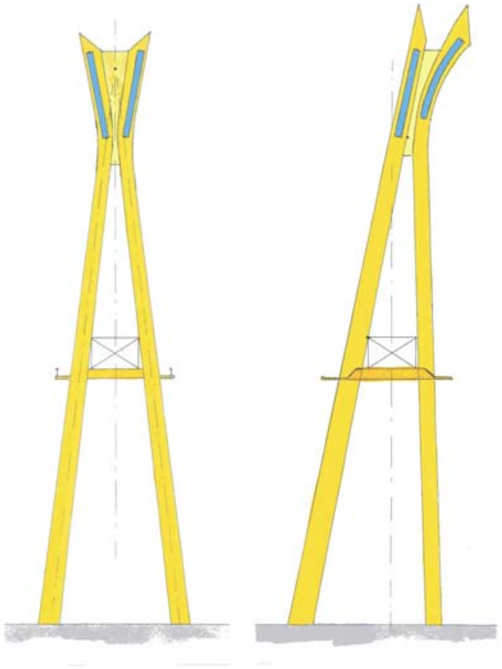


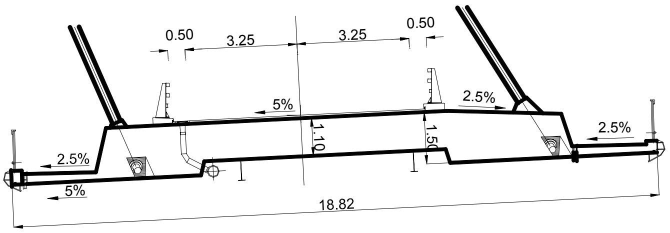
Figure 4 – Eccentricity of the compressive forces produced by stay cables in the deck

The development of the project, in close cooperation between the Sétra, the architect and the consultant, and under the supervision of the local technical service, took much time and efforts. It would be very gratifying to detail the final project and to give the impression that it has been developed in a very Cartesian way, from intelligent structural analyses, but this has not been the case. We tried to successively solve the different problems and discovered, step after step, news problems which we had underestimated or not even foreseen; and it is more honest to follow our hazardous way to find a solution which is, at the end, almost perfect, and which we could have reached more directly with more experience or thinking.

4. Design steps

4.1. We started with the definition of a geometry such that stay cables do not interfere with road traffic. Among different preliminary ideas, we selected two principles: the tower has the shape of an inverted V with a wide head, allowing for the installation of the stay cable anchorages at a distance, transversally, from the tower vertical axis; and the ribs at the side-span ends (close to abutments) are widened, up to 2.00 metres, to avoid geometric interference.



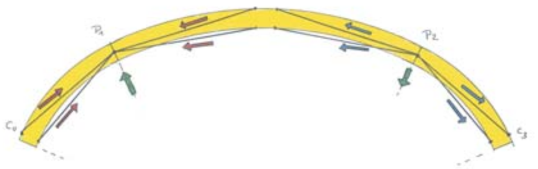


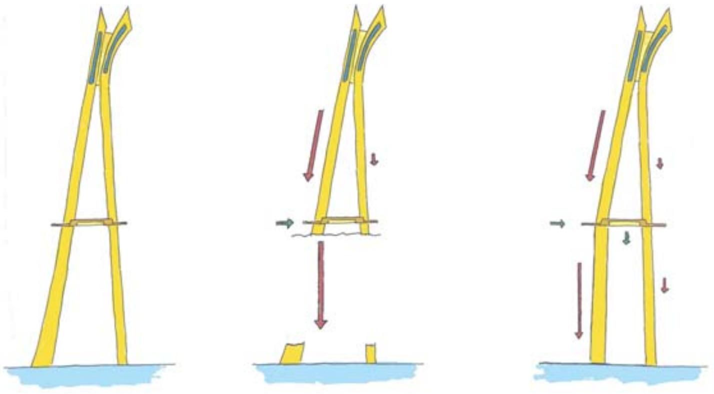
▲ *Figure 6 - Massive slab cross-section in the side span, with a widened outside rib and inclined stay cables*

◀ *Figure 5 - V-shaped tower, and design of an asymmetrical tower*

4.2. Then, in a second step and in order to reduce the size of the tower head, we have designed an asymmetrical tower, with one of the two steel anchorage block curved for a greater efficiency. We could note that the largest part of loads is then passing in the “inside” leg (about 90%), the leg which is in the inside of the road curve.

4.3. We were rather satisfied by this principle when the first computations by Jérôme Petitjean evidenced very important bending moments in the tower legs below the deck. In fact this is clear evidence: the load corresponds to the weight of the curved cantilevers suspended to the tower; and due to the curvature, the centre of gravity of these two cantilevers is in the inside of the curve. Practically, it is at the connection of the inside leg with the deck; and thus produces high bending moments in the frame created by the two tower legs and the cross-beam connecting the deck.





On the left part of the drawing: forces produced in the deck by the action of stay cables. On the right part: forces produced on the tower by stay cables.

Figure 7 - Flow of forces in deck and tower, and necessary evolution of the tower shape

4.4. Then we tried different options: changing the shape of the legs below the deck, so that the “inside” leg may carry a high vertical load, giving the tower the “golfer” shape, with an angle between high and low parts of the tower legs. Finally, since practically all loads pass in the inside leg of the tower above the deck, Michel Virlogeux proposed to have only one leg above, inclined exactly in the direction of loads, and to design the lower part of the tower with the shape of an inverted V below this “inside” leg, in fact below the centre of gravity of the cantilevers supported by the tower.

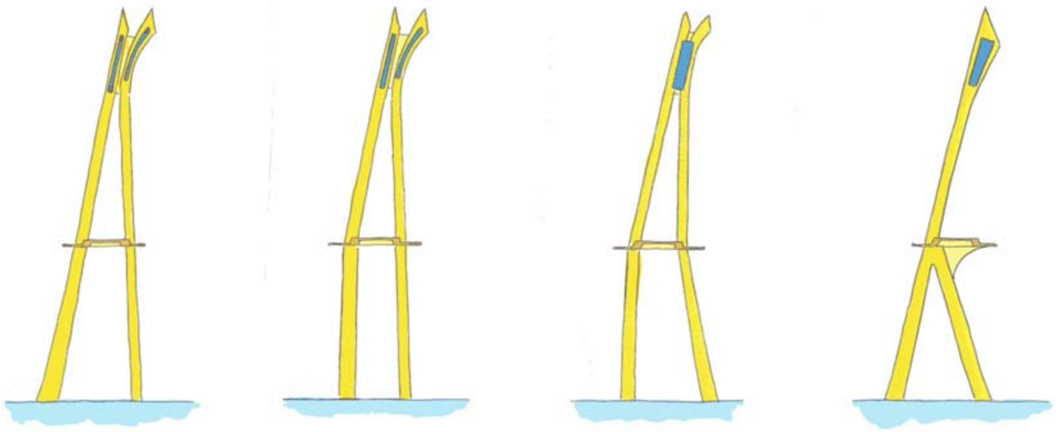


Figure 8 - Evolution of the tower design

4.5. Computations developed by Jérôme Petitjean confirmed the efficiency of the system, and the architect worked intensely on shapes to express the structural concept and the flow of forces.

The "inside" sidewalk had for example to turn around the unique upper leg of the tower; the shape of the cross-beam supporting the deck at the tower level, on the outside of the curve, has been shaped for both efficiency and elegance…

Figure 9 - Final tower model ➤

4.6. More classical decisions were also made during this period.

An intermediate support was anticipated in the side spans, in order to make more efficient backstaying effects. In relation with the site topography, this led to the final distribution of spans: 33.70, 81.25, 285.00, 81.25 and 33.70 metres. Nevertheless, the structural depth of the cross-section was selected rather high – 1.50 metres – in order to resist easily the bending forces produced by traffic and wind loads.

In addition, to avoid uplift reactions on the intermediate supports and at the abutments, the cross-section weight is increased on a distance of about 40 metres from abutments by the constitution of a massive slab between the longitudinal ribs (see figure 6).

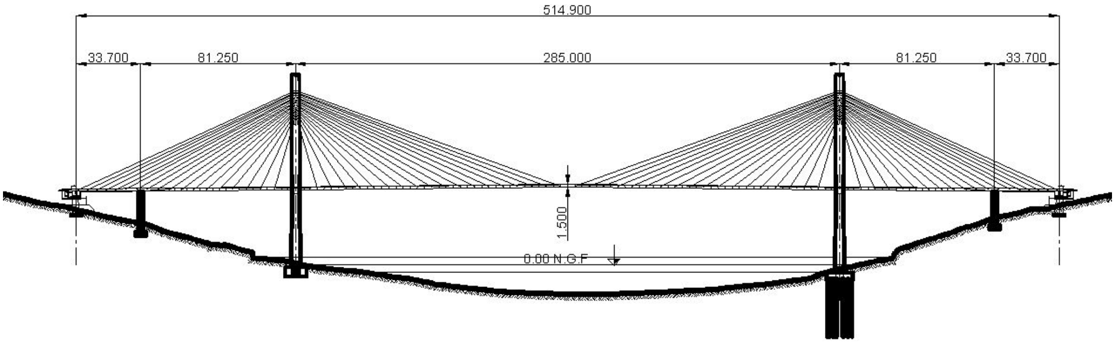


Figure 10 - Final project

5. Development of the design

5.1. As Jérôme Petitjean left the Sétra, his work was complemented and developed by Florent Imberty. He performed the analysis of construction steps, segment after segment, to evaluate bending forces in the deck and in the towers; this is of major importance because forces – which are very well balanced when the bridge is completed – are not balanced during construction; it is thus necessary to introduce prestressing forces in the tower (mainly in the inside member of the box-girder section), which are for a part temporary and for a part final.

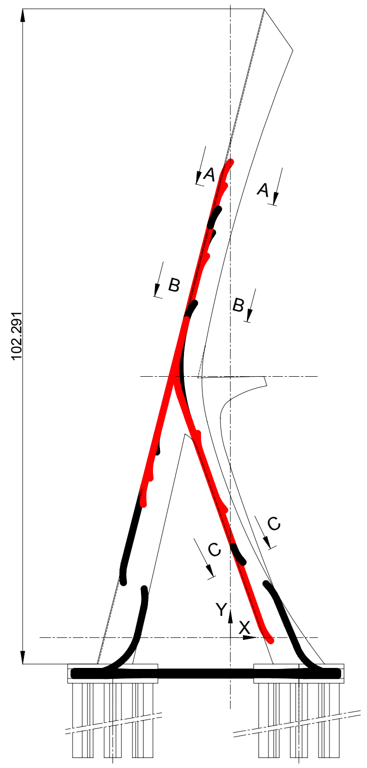


Figure 11 – Prestressing in towers

Figure 12 – Perspective view of the project

5.2. Bending forces in the deck appeared more important than expected, especially at the tower level due to the local displacement of the center line produced by the passage of the outside sidewalk around the tower. This called, as expected, for a non symmetrical distribution of prestressing tendons and for a local widening of the "outside" rib.

5.3. Finally, wind analyses – developed after a climatic analysis and wind tunnel tests performed by the CSTB – evidenced that the length of the cantilever has to be limited in the side spans before its connection with the part of the deck which is erected on scaffoldings.

6. Conclusion

Step by step the design of the Térénez Bridge passed from a rather classical design to a very impressive one, with a curved deck suspended on the outside from inclined towers. This concept has been highly appreciated by the owner and the local population. The call for tender is to be issued soon and we expect beginning construction next year.