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The Suspension Iron Bridge of the Early 19th Century Villa Borghese in Florence (Italy)

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Abstract: Between the 1825 and the 1828, Antonio Carcopino, an engineer, designed a suspension iron cable bridge: this fact shows the interest of the Borghese family for the technological innovations of the 18th and of 19th century.

Keywords: Suspended iron cable bridge, funicular polygon

Introduction – Villa Borghese in Quinto (Florence)

The Prince Camillo Borghese married Paolina Bonaparte, the sister of Napoleone. After the Emperor's death, in 1825 the Prince bought a Villa in Quinto in the suburbs of Florence, which he restored in Neoclassical style: Antonio Carcopino, an engineer, scholar of the Academy of Fine Arts of Florence, designed the villa and the garden (Fig. 1) between the 1825 and 1828. The plans (Fig. 2) are stored in the folders 115-122 of the Salviati's archive, currently under the care of the Scuola Normale Superiore in Pisa (Karwacka et al. 1993).

The garden was in the other side of the near road: so Carcopino built a iron cable suspension bridge to reach the garden from the mansion. According to our knowledge, this bridge is the oldest iron cable suspension bridge surviving of the period, together with the much longer one (1826-1832) on the river Garigliano (unfortunately destroyed and recently rebuilt) whose designer is the engineer Luigi Giura of the "Corpo borbonico di ponti e strade". Undoubtedly it testifies the interest of the family Bonaparte on the technical innovations following the period of the Illuminism.

Figure 1: The suspension bridge from the Quinto's road

Science and Technique in Tuscany between the 14th and 18th Century

Florence had been a top capital in the scientific research for more than four centuries since the 14th century. For example, in order to limit our interest to the bridge construction, let us remember the innovating shallow circular arches of the 14th century Ponte Vecchio and the 16th century arches of Ponte Santa Trinita, an inverted catenary according to Bargellini (Bargellini and Guarnieri 1978).

Let us also remember that in the 17th century the famous scientists Viviani and Torricelli founded in Florence, after Galileo's death, the first European scientific Academy, Accademia del Cimento,

that had its housing at the Archduke’s Palace. Beyond this, the naturalist Stensen, buried in the Florentine San Lorenzo church (1686), was the Granduke’s scientist.

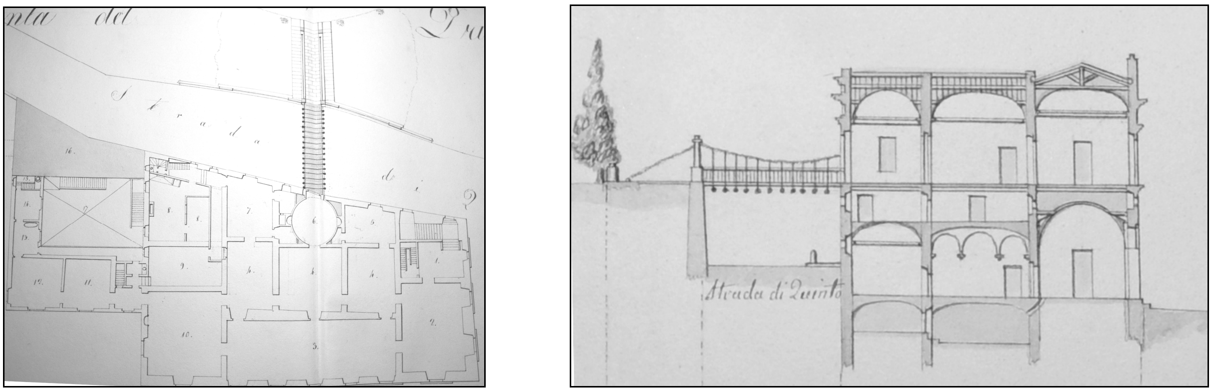

Figure 2: Plan of the first floor of the Villa and its section. Carcopino’s designs 1825-1828

Also in the 18th century Florence had an outstanding importance in the scientific scene of that time. Let us remember as, during the Lorena’s period, followed to the Medici, the Grand Duchy was penetrated by the Illuminist movement; in particular the Lorena took care of the territories of Tuscany, i.e. the drainages of the south and of the Arno valley and the building of main roads, as the Abetone’s one. Among the scientists of that time that cooperate with the Archduke we must remember the mathematicians Leonardo Ximenes (1716-1786) (Barsanti and Rombai 1987) and Giulio Mozzi (Mozzi 1763), who developed the theory of the “*Central Axis*” of a plane system of vectors.

At Follonica there was a royal plant for the manufactory of the iron (Magona): the minerals were excavated from Elba’s mines. Probably the iron used to build the bridge comes from this site.

The International Scene at the Beginning of the 19th Century in the Field of the Suspension Bridges

In England at the beginning of the 19th century great works are in progress: these activities will culminate with the building of the Menai Bridge of Thomas Telford (Telford T 1838), a bridge 1370 feet (417 meter) long. The main central span is 580 feet long (176 meters). Telford describes both the events that led the English Parliament to approve the construction of this extraordinary bridge, and the events during its erection, and its designs, bringing us drawings of great accuracy. It is useful to read the dissertation of the mathematician Davies Gilbert published in the Philosophical Transactions of The Royal Society of London (Gilbert 1826). Gilbert is evidently a member of the commissioners appointed by Parliament to improve the communication between England and Wales: he criticizes the geometry of the chains of the Menai Bridge as inconsistent “*with the due execution of a great national work”*. He also applies his researches and studies on catenaries to suspension bridges with “*the hope of doing something serviceable to the public, by expending in two tables the formulae from which my approximations were derived*”. The work of Gilbert shows as the mathematician has contributed to the engineering plans and designs of that time.

But more important is the theoretical contribution of Navier. He was sent to England by Monsieur de Becquey, official supervisor on the constructions of roads and bridges in France, in order to observe the innovative suspension bridges that England was building. Among these bridges, he observed the first step of the construction of the bridge of Telford on the Menay (Navier 1823).

The work of Navier is composed of a rapport to Monsieur de Becquey and a study on the theoretical aspects of the suspension bridges: the contribution of Navier is absolutely original.

In the first part Navier writes down a summary on the history of the suspension bridges, starting from the bridges in ropes of South America, of India and of China: he also points out the designs of M. Poyet on cable stayed bridges, that have not yet found any practical application. The first cable suspension bridge in iron, 21 meters long, was built in 1796 by James Finley on the Jacob Creek in the

United States. Other and more important suspension bridges were built in the following years; for example the bridge near Schuylkill, 92 meters long, the bridge at Comberland, 39 meters long, the bridge on the Potowmac and others. In England the first chain suspension bridge was proposed by Telford in 1814, on the Mersey; then many bridges for crosswalk were built on the Tweed, as explained by M. Stevenson. Then a wire one was constructed near Kings Meadow, still on the Tweed, 33.5 meters long in 1816, up to that built by Telford on the Menai, 1819-1826. Out of the report of Navier it is evident that at that time the building of suspension bridges was developing and spreading.

In the second part of his work, Navier asserts that the first problem taken into consideration by Bernoulli (but also by Leibniz and Huygens) is to determine the curve of equilibrium of a chain. He proves a more general case, when the chain is submitted to any system of vertical forces, not necessarily to a constant one. It is worth remembering briefly some hypothesis stated by Navier. He considers the case of a cable supported in A by two forces, a horizontal one **P** and a vertical one **Q**, and submitted to a system of vertical forces, function of the place and the stress T. A Cartesian orthogonal reference system x, y has its origin in A. So the equations of equilibrium of the cable are the following:

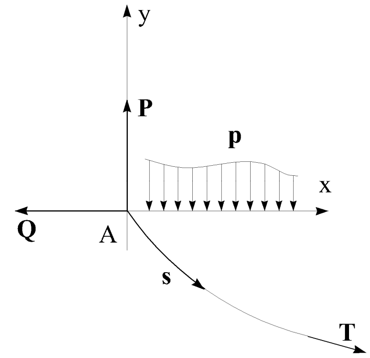

Figure 3: Navier's original figure

$$\boldsymbol{T}\frac{\mathrm{d}\boldsymbol{x}}{\mathrm{d}\boldsymbol{s}}=\boldsymbol{Q} \tag{1}$$

$$\boldsymbol{T}\frac{\mathrm{d}\boldsymbol{y}}{\mathrm{d}\boldsymbol{s}}=-\boldsymbol{P}+\int_{\mathrm{A}}^{\mathrm{s}}\boldsymbol{p}\,\mathrm{d}\boldsymbol{s} \tag{2}$$

Navier goes ahead dealing with the suspended bridges, hypothesizing that the forces **p** are equally distributed on the horizontal axis, ignoring the curvature of the arch and the weights of guys. By the way Eq. 2 yields:

$$\boldsymbol{T}\frac{\mathrm{d}\boldsymbol{y}}{\mathrm{d}\boldsymbol{s}}=-\boldsymbol{P}+\boldsymbol{p}\left(\boldsymbol{a}-\boldsymbol{x}\right) \tag{3}$$

and dividing both members of equations, he obtains:

$$\frac{\mathrm{d}\boldsymbol{y}}{\mathrm{d}\boldsymbol{x}}=\frac{-\boldsymbol{P}+\boldsymbol{p}\left(\boldsymbol{a}-\boldsymbol{x}\right)}{\boldsymbol{Q}}. \tag{4}$$

It is interesting to remember the list of the subsequent chapters, in order to show the news of his ideas, also comparing them with those of contemporaries: "*The equilibrium of the supports on which the chains lay*", "*Stayed bridges*", "*How to fix the chains to the ground*", "*How to determine the thickness of the chains and their elongation*", "*About the effect of the temperature variation on the*

chains", "*About the vertical oscillations of the suspension bridges, supposing that the chains are flexible and cannot be extended*", "*About the longitudinal oscillation of the chains*", "*About the action of the wind*", "*About the equilibrium of the suspension bridges, with relation to the weights of the chains and the suspension guy ropes*"

In the course of this chapter he found by Eq. 4 the famous equation:

$$\frac{\mathrm{d}^2\boldsymbol{y}}{\mathrm{d}\boldsymbol{x}^2} = -\frac{\boldsymbol{p}}{\boldsymbol{Q}} \tag{5}$$

It has been shown (Cecchi A 2010) that Charles Hutton previously demonstrated Eq. 5 by means of an inverse procedure.

The Survey of the Bridge

On 10/02/2010 we went to Villa Borghese at Quinto and surveyed the bridge. The survey has been executed topographically by means of a Leica TCRP1205 total station, with a 2 millimetres + 2 parts per million accuracy in laser reflectorless electronic distance measurement and with a 5" accuracy in angular measurement. The points of the four cables holding the floor and the points of the guys of anchorage to the bridge and to the ground have been surveyed.

With a Nikon D300 reflex digital camera several photo shoots have been acquired: the pictures have been calibrated and the results are shown in Fig. 4.

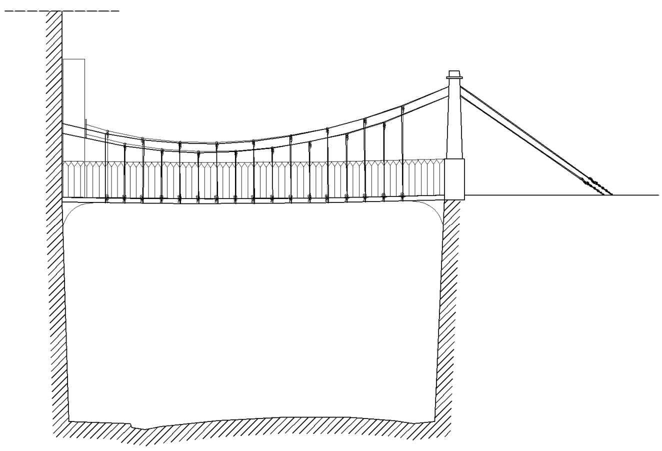

Figure 4: Surveyed longitudinal section of the suspension bridge

The bridge, 9.24 meters long and 2.86 meters wide, is composed of an horizontal floor held by four wire iron cables (diameter at about 0.02 meters), two for each side of the bridge, supporting 17 cast iron beams by means of vertical cable guys. As all wires have to hold the same tension, at the beginning of the technology the wires had been grouped and lined (Fig. 8).

You can note an asymmetry in the longitudinal disposition of the bridge. On the garden side two vertical piers, one for each side of the bridge, hold the four cables: they are equilibrated by the anchorages in the basis ground. As you can notice in Carcopino's design plan of Fig. 2, the masonry of Villa Borghese facing the interior of the building is not aligned with the vertical planes of the bridge, but it describes two horizontal arches: so it is not clear how Carcopino has anchored the cables of the bridge inside the building and it is surprising the apparent lack of cracks in masonry.

Fig. 5 shows the plan of the bridge: every cable guy of the bridge holds a rectangular beam, evidently a cast iron one, of section at about 0.07x0.03 square meters and length 2.86 meters.

The stiffening of the floor is granted by 9 longitudinal bars of section at about 0.03x0.02 square meters, spaced out by 8 rods of diameter at about 0.02 meters. The floor is leaned on the longitudinal

bars and rods exposed before and it is made of a thin plates of thickness at about 0.002 meters and of width at about 0.15 meters (Fig. 5).

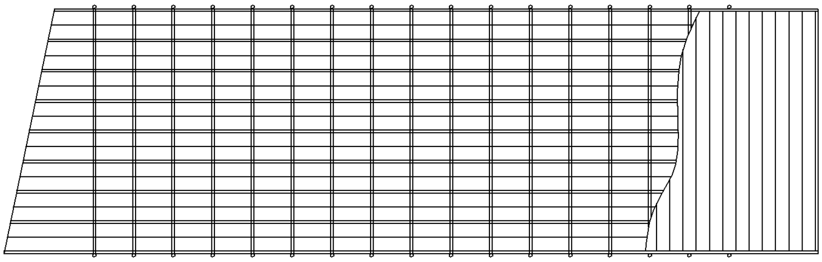

Figure 5: Surveyed plant of the bridge

Figure 6: Detail of the knot

It is evident that the plan of the bridge is trapezoidal: this fact is surely due to fitting the pre-existing road. The trapezoidal shape of the bridge imposes an imperfect symmetry between upstream and downstream cables, to which Carcopino put right by using 9 cast iron arches of different length in both terminal sections, mainly in that facing the building (Fig. 4 and Fig. 7).

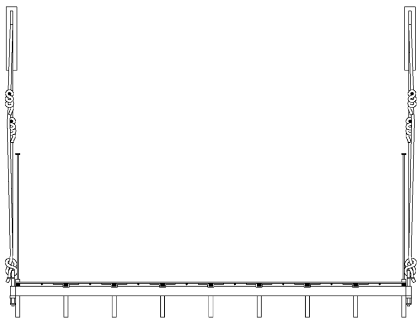

Figure 7: Surveyed cross section of the bridge

Figure 8: Wire iron cables

The cross section of the bridge in Fig. 7 shows that the vertical cable guys are linked to the cables by means of elegant knots and to the beams by eye-bolts (Fig. 6). As shown in Fig. 7, there is another reason of non perfect symmetry of the bridge: in fact while the guys linking the inferior cables are perfectly vertical to the floor, those linking the superior ones are slightly skewed, placed alternatively on the left and on the right side of the inferior cables.

Notice that, as all cable have to hold the same tension, at the beginning of the cable wire technology, the wires had been grouped and lined (Fig. 8).

The Funicular Polygon

We do not know if Carcopino knew Navier's memory: but surely the Florentine engineer Alessandro Manetti, as Navier in 1806, had been a student of the École nationale des ponts et chausses since 1809, and Navier could have influenced Manetti. It is sure that Carcopino designed his bridge between the 1825 and 1828: it is possible that he followed a funicular polygon, known since the 17th century (Varignon 1687). Manetti himself designed a suspension bridge few years later (Manetti 1885).

The funicular polygons can be computed in the following way: the bridge is subdivided into 4 series of equal loads, two for each side. So there are two funicular polygons for each side. The projecting lines of each funicular polygon are parallel to each cable polyline.

It is evident that the stresses of the projecting lines are unknown. In Fig. 4 the eastern superior and inferior cables are traced. In order to calculate the stresses in the projecting lines, the load hold by each guy has been computed and it has been estimated in at about 550 N: so the polygons of the forces are

traced and the poles P found (Fig. 8) and, for example, in each segment of the eastern inferior cable the stress varies at about around 7500 N.

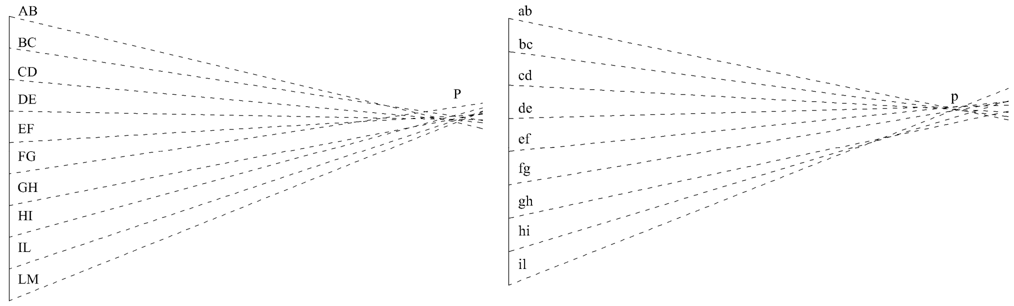

Figure 9: Eastern polygon of forces of the superior and inferior cables

The cables are designed for an allowable load in comparison with the kind of iron used by Carcopino. You can notice that the projecting lines of the funicular polygons meet in a short interval: this is due to imperfections and to small surveyed failures (at about 0.09 meters) of the bridge.

Conclusions

The suspension bridge designed by Carcopino, though a small span one, is an *unicum* in Italy and Europe in relation to heritage; its dating is certainly confirmed by documents. This bridge represented the beginning of a series of longer ones built in Tuscany: among these we remember the bridge Leopoldo II, built in 1833 on the river Ombrone at Poggio a Caiano by Alessandro Manetti and the two bridges San Leopoldo e San Francesco on the river Arno in Florence, built respectively in 1836 and 1837 by the French Society of Marc e Jules Seguin.

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