Reconstruction of the oldest cable wire suspension bridge in Italy «Leopoldus II»

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Close to Florence, in Tuscany, a very old suspension bridge: «Leopoldus II» from the name of the Grand Duke; is probably the very first wire suspension bridge in Italy and one of the first in the world. In Italy earlier only some small pedestrian structures are historically recorded.

The first suspension bridges were designed in England and in France. As the Grand Duke of Tuscany Leopold II knew that, willing to be ahead with the progress, he sent Alessandro Manetti, his best engineer, in France. For this reason, the experiences about French suspension bridges were revealed through the Manetti’s direct knowledge, recorded in an ancient day diary (see references).

When Manetti was back he received the assignment to design a cable wire suspension bridge in Poggio a Caiano, (Province of Prato, nearby Florence) next to the Royal Palace, to provide a new way out for the Grand Duke to his lands, on the other side of the river Ombrone. The bridge, constructed in 1833, had three wire cables for each part and a wooden deck, and is remembered as a work of art, as results also from photographic documentation of years around 1935. Unfortunately the German Army destroyed it under the World War II while they were retiring.

Now it is possible to see on both sides of the river the monumental masonry piers. In lately years interest is growing for a restoration of the bridge. Different levels of renovation/restoration are presented in the paper:

1. conservative maintenance. This is possible where we still have the structure and higher loading condition is not required
2. reconstruction of some parts of the bridge with new materials

The paper starts with a documentation of the design of the old bridge based on historic documents, presents a verification with numeric models of the old structure and the new one, and at last proposes different design strategies for the reconstruction of the bridge.

INTRODUCTION

At the beginning of the 19th century, thanks to the progress and to the industrial revolution, steel started to be used in civil construction. The advantages of the steel, even from an aesthetic point of view can be seen in suspension bridges. In this kind of structures it is possible to obtain lightness and elegance that were before impossible. In fig. 1 it is possible to see the bridge, which was the first wire suspension bridge in Italy. The bridge represented the advanced technology, the will to introduce scientific innovations in the art of construction. The Grand
Duke Leopoldo II wanted the construction of the bridge in order to be not inferior to the other Sovereign in Europe. The «Leopoldo II» Bridge was constructed in 1833 and was used until the World War II. Now only the powerful masonry arcs remind us of his presence and, even though after the World War II they were forgotten, they now capture again our attention although of its small dimension. The bridge has always provoked great admiration and astonishment in the people who crossed it.

The paper presents the story of the bridge and of the people who wanted it. Through the knowledge derived by a deep research in historical archives, we tried to understand the reasons and the will that regarded it. The experience and the knowledge that were available at that time are analyzed.

A proposal of reconstruction is made paying attention to the philosophy that was in the previous construction.

**BEGINNING OF ENGINEERING SCIENCE**

At the beginning of 19th century there was not a definite typology of Engineer. Men who were both architect and engineer designed important constructions. Most of the time, the dimensions of the structural elements were determined by experience rather than by calculation. The industrial revolution had already started in England; technology was therefore growing up. From the point of view of bridge-construction history, many innovative techniques and materials were coming out. The new material, steel, gave the possibility to build structures that were impossible before, thanks to its tensile capabilities. The mentality of that age, orientated to the future, gave confidence to the new type of structures.

There were many problems for the designers of new typology of structures. Information could only travel through books and very often we could find architect-engineers travelling in Europe or outside it to find new answers. We have seen Navier, sent by Louis XVIII, in England to learn about new bridges that were built there. From Italy the Cavalier Luigi Giura was in the same lands where Navier had been before to design his suspension bridge on the Garigliano in the Reign on Naples. Ellet visited France in 1831 to see the new suspension bridges made with wire cables instead of iron eyebars chains, then he returned to America to realize the Wellinig Bridge, the so-called «Thousand-footer», for its dimension. During the same years we can also see Alessandro Manetti, who will design the suspension bridge in Poggio a Caiano, travelling around France under the order of the Grand Duke Leopoldo II. During his travel he took all the new technology used in that country not only for suspension bridges but also for other construction techniques. When he returned to Italy he presented a report of what he had seen to the Grand Duke Leopoldo II. Travelling was very uncommon during those years, people were not
used to do it, and important architect-engineers were doing something special for the developing of the engineering science.

The suspension bridge can be seen as a product of the industrial revolution. After the first pioneer realizations, this kind of structures had an incredible growth. The key of the success of this kind of bridges has to be found probably in its simplicity and the possibility to cover distances that were impossible to cover before that time. Before that time the structures were designed only using empiric proportions. With the coming of suspension bridges simple calculations started to be made, simple formulas based on the concept of catenary can be applied. Wind and second-order effects were not taken into account; hence the decks were generally without stiffness. Before the beginning of the 19th century, the art of construction was given only by means of experience. With suspension bridges mathematical modelling started to be scientifically applied to structures: engineering was being born.

In Europe there was a great diffusion of modern suspension bridges, which was partially due to Claude Navier; after his journey around England he wrote a manual about this kind of structures for the «Ecole Nationale Des Ponts Et Chaussées» of Paris. He revealed some formulas to calculate a bridge without stiffening deck. Considering for the cable a shape of parabola he has found the today well-known formula

\[ H = \left( w \frac{I}{8} f \right) \]

From which we can calculate the horizontal component \( H \) of the tension in the cable. For the meaning of the other elements \( I \) is the main span, \( w \) the weight for unit length and \( f \) the sag. The theory of catenary was already solved by Bernoulli in 1691, and the formulas of the parabolic cable were found out by Nicolas Fuss in 1794. Navier extended these theories to include the effect of variable loads. He has studied the variation of tension in the cable loaded with a concentrated force \( P \) on the midspan, founding

\[ h = 3 \cdot \frac{P}{f} \cdot \frac{f}{16} \]

and the maximum deflection

\[ v = \frac{P}{f} \cdot \frac{f}{2} \cdot \frac{w}{l} \]

Both formulas can be found using the hypothesis of having an inextensible cable. The greatest problem of a structure designed in this way is the lacking of global rigidity. Some designers tried to increase the rigidity of the cable to control the deflection of the deck. In some other solutions the cables were substituted with rigid frames.

Through the analysis of his formula, Navier suggested to have a ratio between sag and span of \( 1/12 \) and not more. A bigger sag increases the maximum deflection of the bridge. The formula also suggests that another way to limit these phenomena is to increase the self-weight of the bridge; this was a surprising result for that time. Just looking to early structures and their behavior was possible to understand the help of a stiffened deck. Even if not fully understood often was used a stiffening truss. In America Finley, who was the first to have done a patent for suspension bridges, suggests in his patent to build this kind of structures with a stiffening truss. His suggestions were received by the European engineers. On the contrary, Ellet suggested to build bridges with a completely unstiffened truss because this is the «simplest form» we can use, and to have stiffened deck bringing an «artificial rigidity».
Big attention was used on the realization of cables; the most common wire used in Europe, was generally the number 18 with a diameter of around 3 mm. The wire was made by the use of the Draw Plate, a plate made with progressively smaller holes with hot cast iron pulled through the plate. The mechanic characteristic of the material was controlled by traction tests and the resulting thin iron wires had a good resistance even if the material was not very homogeneous. The most common problem was the loss of resistance caused from folded wires.

Various systems were used to connect wires together to form the cable and to connect the cable to the anchorages. One system used to connect the suspenders with the main cables was the use of saddles, trying to keep the curvature of the cable as wide as possible.

One of the most interesting aspects of the construction was the disposition of the cables. It was not uncommon to have each one disposed with different sag and in the meantime inclined in respect to the vertical plane. The reasons of this disposition can be found in the search of a better rigidity of the structure and, not less important, a better view of the structure. See all cables disposed in different levels and inclined gave a nice sensation to the one who was entering.

People at the beginning of 19th century were not completely ready to see such light structures, and various systems were used to try to give the impression of a bigger stability. Potent masonry arc where built on the entrance of the bridges. On the Menai Bridge, in England, impressive arched piers support the two lateral sides.

But the beginning was not impervious to errors; the early structures collapsed few months after the construction, because of the wind or just few people jumping over the bridge: enough to cause the collapse. In a period of big innovation a collapse is a deterrent to the diffusion of the technique, but also an incentive to perfection. The most bigger problem encountered at the beginning was the oscillation of the structure and various way to limit this phenomena were tried. We have seen cables placed under the deck, stiffening parapets or just the use of supplementary stays. In 1830 Capitan Samuel Brown built a railway bridge over the river Tess, but after the construction the train caused big oscillations on the structure, Robert Stephenson wrote «Wave before the engine [. . .], just like a carpet». No mathematic modelling existed at that time to explain vibration of the suspension bridges. Thus, only in the second half of 20th century we were able to partially explain the motions of those structures.

A treatise on static was born only in 1859 with the Rankine theory where the cables were considered inextensible. This was because of the simplified mathematic involved with this assumption. But it was only in 1888 that Melan laid the formulation of deflection theory. The theory, called also the perfect theory, take into account the change in shape of the cable under live load. The longest suspension bridges in the world were built according to this theory; it was only with the advent of computer that changes were made in the design process, most of them calculated without the use of computer, even though the iteration included are time consuming.

At the beginning of the 19th century the voices about the new structure were starting to travel around. All the Sovereigns in Europe wanted to be updated about the new technologic progress. There was a widespread trust on new technologies.

**History of «Leopoldus II»**

In 1831, Leopoldo II di Lorena not wanting to be inferior to the other sovereigns in Europe, sent his best man in France to study what they were doing there. Alessandro Manetti after his journey exposed what he had seen there and the decision of the construction of
the first wire suspension bridge in Italy came out. On autumn 1833 the bridge «Leopoldus II» designed by Manetti was built up. Manetti writes: «I made them built a suspension bridge with hamps of iron wire on the Ombrone in the park of Poggio a Cajano [. . . ], it was the first bridge of that kind that we made, suitable for the step of the coaches, and those which it was destined belonged to the Monarchs and the Court». The magnificent opera were used by the Lorena to move from their lands to the Villa del Poggio, the house they used to live. On the other side of the river there was the park of Pavoniere, the English garden with canals and ludic places where the Sovereigns used to bring their guests and come back from the suspension bridge to show what they where able to do.

Basic simple rules have been applied to the construction of the bridge: the masonry foundation of the anchorages of the wires must be connected to the foundation of the piers, the wires must be far from each other in order not to be differently influenced by the temperature and carry equally the weight of the bridge, and the piers that sustain the cables should be connected by arcs not only for a matter of solidity but to give the impression of power («Hanno la figura di una potenza»).

Many years after the construction of the bridge, Alessandro Manetti, in his memories published posthumous, said that a bridge like that shouldn’t have been built because of the small span. Suspension bridges have to be built with bigger span to exalt the power of these structures. The «Leopoldus II» seems to be too much powerful for the kind of structure it is.

The wires where made at Follonica were there was the royal industry of cast iron. About 50 thin wires of a metal in between steel and cast iron formed the cables. In total 12 cables sustained the bridge, 6
cables for each part, inclined respect to the vertical plane to give transversal stiffness to the structure.

The wires of about 3 mm of diameter are placed one by one over the bridge to form the cable. Each wire was pretensioned to eliminate defect and to test its tensile strength. Every 30 cm of the cable were rolled up a thin wire under hot temperature.

A long search in the national archives was carried out to find information about the bridge. On the National Archive of Florence some documents where found with some indication about the renovations made to the bridge during the first years. The truss was made by oak, a wooden structure like this requires to be kept during years. Some voices about renovations of the truss or the parapet have been found in the books of the economic entrance of the royal land. After 1841 the bookkeeping book is clearer and it is possible to infer a big renovation every 10 years. The treatment of the cables is interesting: they were very often painted, about every two years, with a mixture made of oil and vegetable substances. This special treatment was to prevent the cables to be attacked by the water or other atmospheric agents. Sometimes the cables were painted in white. Very often the stone pavement lying just before the entrance was renewed. The wooden truss is a more flexible material than the stone of the pavement; vehicles while entering the bridge made a slow opera of erosion.

On the 11th September 1849, 25 lire are paid for a stuck of steel that have been stolen. This can make us reflect about the value of the steel at that time. The metal was precious and suspension bridges were often controlled 24 hour to 24 hour. The Leopoldo II Bridge was inside the land of the Grand Duke and 5 guardians controlled the whole territory.

The greatest part of material used for renovations is generally wood. The principal wooden beams are made by oak, the beams were inserted inside the water of the river for 10 years to make the wood stiff and resistant to the atmospheric agents.

In 1859 many revolutionary events introduced changes to the power. The Grand Duke Leopoldo II was sent to exile and the Savoia took the power. During those years Florence was going to be the capital of Kingdom of Italy. The new King, Vittorio Emanuele II, soon started to live in Poggio a Caiano, whose lands were cured and preserved again.

All documents about the renovations made in those years were discovered in royal archives, some of them still hidden or not well know; many important papers were found in the Archive «Guardaroba di Palazzo Pitti». In the discovered papers it was possible to find detailed renovations of the bridge and the dimensions of the various elements of the structure. Through this analysis it is possible to propose a reconstruction able to respect the original proportion of the all elements. When the old structure is not anymore present, a valid reconstruction should always been supported by an historical analysis. Through the documents it is possible to know and to understand the proportions of the structures and the reasons behind them.

From the papers of the Savoia archive was also possible to see the beginning of bureaucracy of
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constructions. Generally a big renovation is made by the company who has won an auction made with a special game called of the «three cards». No one knows how that system worked, but we can see that during those years it was always the same company to win. The beginning of the work is stipulated by a «report of beginning» in the papers with the date of beginning and the description about the duration of the work. On the end is stipulated the «Report of finishing», which name is clear itself. Interesting is the «Act of submission», where the responsible of the work were taking the engagement of finishing the work in within the money of the estimate. We should say that the estimates generally were always much more than the money really needed at the end of the work, not properly the same of today!

By the way the bridge Leopoldus II was renovated very often. The Villa of Poggio a Caiano and all the lands annexed remained property of the Grand Duke until 1919. After that time the property was donated to the State and this was the beginning of the end. Just after 2 years in 1921, the secular unity of the lands was broken and part of the territory, included the suspension bridge, was donated to the National Veterans Organization. After some years of bad administration big part of property was sold. When the damage was done there were some attempts to save the bridge by the State Superintendents but nothing went out. It seems that a renovation of the bridge was done in 1938, but information are scarce and contradictory. Some witnesses from the old people of the area around said that the bridge was in bad condition before the War. The World War II finished the job: during the retire of Germans, in September 1944, the bridge was mined at anchorages and fell down into the water.

Time goes by and the last decades are enough to let the structure be forgotten. No trace is there anymore of the cables and the truss. Only the monumental masonry portals are there to remind us of the existence of the bridge.

RECONSTRUCTION

Reconstruction, more than a renovation, puts forward a number of questions to be solved. Does the structure have to be rebuilt exactly the same way as it was? Or is it only the philosophy that was behind the structure that has to be maintained? Very often the loads for which the structures were designed were generally much lighter than the ones that the bridges have to carry today, and even the hydraulic imposition can be different. These conditions obligate to change the stiffness of the original structure. Changing the original structure can be made maintaining the philosophy of it. Using different materials can be one solution. Thanks to modern technology, resistance of modern outfit can be much higher than the one used for the original structures.

A courageous way of thinking can be the separation of tasks. It is possible to create a main structure with modern and technologic materials and to maintain secondary elements as they were before.

For the Leopoldo II Bridge evaluations are made with collected data to find the loads that the structure were used to carry. It is seen that an exact
reconstruction of the structure as it was before it is impossible. The loads that the bridge should carry today are much higher than the ones used for the earlier construction, even if a pedestrian solution is chosen. As well the rigidity of the structure must be higher in the new construction; this serves in order to reduce the maximum deflection of the bridge. One valid solution can be to change the material of the parapet, originally made in wood, with steel. A steel parapet can have the function of a frame truss with high stiffness. The use of high technologic strength steel can renovate even the cable system.

The analysis of the structure is made, before implementing the Steinman formulas in a spreadsheet, and then comparing the results with data carried out by a finite element program.

The original parapet was made by oak; in the project of reconstruction it is rebuilt with rectangular hollow sections with exactly the same dimensions of the original one. The exact dimensions were founded in historical papers: during renovations of the bridge where presented a detailed report of the work with the dimensions of the renovated elements. The wanted rigidity of the parapet is given by modification of the wall thickness. On the table 1 it is represented a comparison between data of the old structure and the project of reconstruction. Due to the lack in bending stiffness of the original bridge the maximum deflection was really high. It is possible to reduce this deflection increasing the parapet rigidity. The self-weight of the original structure is much higher respect to the new one because of the greater number of cables, a bigger wooden truss and the presence of a wooden sidewalk.

The biggest problem encountered was because of the river. The actual position of the bridge does not allow a reconstruction: recurrent overflows of water could invest the wooden deck of the structure. To by pass the problem the masonry piers are taken apart and the foundation is risen to a security level. Than the piers are mount in the same position as they was before.

The cable force on the foundation is separate from the old base. A new footing is made behind the structure capable to absorb alone the cable load. The old foundation will carry only the weight of the bridge and the risen part of the foundation.

| Table 1. Bridge Properties, the * values are guessed thanks to historic documents and to other data taken from similar structures of the same age |
|----------------------------------|-----------------|-----------------|
| Main span length [m] | 34.89 | 34.89 |
| Sag [m] | 2.90 | 2.90 |
| Sag-to-span ratio | 1/12 | 1/12 |
| Cable area [m²] | 0.01326 | 0.02851 |
| Cable modulus Ec [N/m²] | 1.62985E + 11 | 1.2962E + 11* |
| Truss modulus Et [N/m²] | 2.10000E + 11 | 1.0000E+10 |
| Moment of Inertia [m²] | 0.00680096 | 0.00024*
| Dead load [KN/m] | 11.26 | 21.86 |
| Live load [KN/m] | 18.92 | 11.28* |
| Dead load tension H [KN] | 591.019 | 1147.40 |
| Max increase in cable tension due to live load h [KN] | 1604.49 | 1934.22 |
| Max bending moment [KN - m] | 494.46 | 10.89 |
| Deflection v [m] | 0.034 | 0.1536 |
CONCLUSIONS

Several difficulties were encountered during the reconstruction project. Keeping always in mind the history of the bridge, the original design’s decisions and the philosophy that were around the structure it is always possible to find a right solution. A solution that will respect the original structure, and in the meantime can be modern and highly technological, can always be found.

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