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Strengthening historic pedestrian suspension bridges: Public safety goes first!?

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ABSTRACT: In the 1820's an impressive amount of early iron suspension bridges was constructed. Since all of the large span suspension bridges of that period of the European continent have disappeared, the smaller pedestrian ones gain interest. Only four iron suspension bridges built before 1825 remain on the continent (Vernosc-les Annonay, Bazel-Kruibeke, Saint Petersburg and Nuremberg). They are the last materialized witnesses of an experimental phase in iron suspension bridge engineering. Given their antiquity and the modern demands, those bridges must be renovated. Strengthening the bridge to comply the current safety standards is in direct contrast with the wish to preserve the historic fabric. It is within this complex problem that different renovation strategies for the early 19th century pedestrian bridges, ranging from replica to contemporary interference, are analyzed and discussed.

1 EARLY IRON SUSPENSION BRIDGES

In September 1823, after returning from a study trip to Great Britain, the Frenchmen C.L.M.H. Navier published his famous report '*Rapport à Monsieur Bequey et Mémoire sur les Ponts Suspendus'*. Navier outlined a historical overview on the construction of suspension bridges, starting with rope bridges in Peru, over realizations of M. Poyet, M. Belu, J. Finley, M. Telford, S. Brown, M. Stevenson, M. Brunel, concluding with the footbridges of M. Seguin in Annonay. Subsequently, he established some general theories on the calculation and the construction of suspension bridges.

Looking back at this impressive list of early iron suspension bridges, one has to conclude that most of the mentioned bridges are lost. Some of them failed soon after they were built, some were destroyed by wind or water, some were bombed, others were dismantled for safety reasons or replaced while upgrading them to new design standards. The only suspension bridges, listed by Navier, and still remaining, are the Union Bridge over the River Tweed (United Kingdom), built in 1820 by Samuel Brown, and the experimental bridge in Vernosc-les Annonay, over the river Cance (France), built in 1822 by Marc Seguin. Moreover, the Union Bridge is the oldest remaining vehicular iron suspension bridge open for traffic.

Although Navier included many suspension bridges in his Memoire, the list was not meant to be exhaustive. Most of the large span bridges were discussed, but the smaller pedestrian bridges were not included, apart from a few pedestrian bridges built in Scotland and France. Since the large span suspension bridges have disappeared, these smaller pedestrian bridges gain interest. In America, all the suspension bridges built before 1825 are lost. In Britain several early suspension bridges remain. They are well documented (Paxton 1999, Ruddock 2003). So this paper will focus on the less known bridges on the vast continent.

When focusing on the remaining experimental iron suspension bridges, built before 1824, on the vast continent, the following bridges can be listed:

– 1822, private bridge by Marc Seguin, Vernosc-les Annonay, France
– 1824, castle bridge by Jean-Baptiste Vifquain, Bazel-Kruibeke, Belgium
– 1824, Post office bridge by Wilhelm Von Traitteur, Saint Petersburg, Russia
– 1824, Kettensteg by Konrad Georg Küppler, Nuremberg, Germany

Remark: since information about small pedestrian and park bridges is rather scarce and the castle bridges are often inaccessible, it is likely that more bridges will be revealed in the near future.

These bridges are the only relic of this experimental phase in iron suspension bridge engineering and since their existence is a lucky coincidence rather than a well-considered policy of patrimony, we are curious to see if these relicts represent the rich history they stand for.

2 HISTORICAL CONTEXT

2.1 *Suspension bridges*

The beginning of the 19th century is a very fascinating time for engineering. Several iron builders and engineers experimented with different structures, among which suspension bridges. Various construction systems were in circulation originating from local habits. In America James Finley used chains to build up the main cables, in England they used flat rods or round bars. The Frenchman Claude Navier illustrated the systems in his widely spread Memoire. Due to the high material costs compared to labour costs in France and Suisse, wire cables were less expensive than chain cables. As a consequence, the Frenchmen Marc Seguin started building suspension bridges using wire cables. Other engineers as H. Dufour, J. Chaley and L. Vicat were inspired by the work of Seguin and Navier and adopted wire cables as well (Wagner 1989).

2.2 *Engineering schools*

Great Britain and the United States took the lead in the industrialisation, instantly followed by France, some of the German States and Belgium. Although the larger modernisation of Russia will be realised only in the 20th century, one cannot underestimate the local development in the beginning of the 19th century of the Saint Petersburg's area. The relations of the tsar with France and the German state of Baden, where Von Traitteur had emigrated, have strongly contributed to this development.

From the industrialisation on the one hand and the democratisation on the other, a need for new types of constructions (bridges, water ways, infrastructure. . .) and new types of buildings (factories, schools, stations. . .) was formulated. Those types were dominated by functional and technical requirements, which the traditional architect not always mastered. The polytechnic schools had to train a new group - the civil engineers – to fulfil this task with a controlled rationality and a mature knowledge of the new materials and construction systems. The foundation in Paris of *L'Ecole Centrale des Travaux Publics* in 1794 (changed as *l'Ecole Polytechnique* in 1795) under auspices of the French Ministry of Defence, gave an adequate answer to the new construction requirements of the developing modern society. In imitation of the Parisian *Ecole Polytechnique*, similar schools were founded all over Europe. In 1806 in the German state of Baden, Johann Gottfried Tullas laid the base for a local school of engineering. The same was done by the Frenchmen Augustin de Bétancourt in Saint Petersburg (1809). This bilingual Russian/French polytechnic school embedded the French culture of engineering in Russia (Federov 2000). It was in that context that the young Von Traitteur travelled in 1814 with his German/French experiences, from Baden to Saint Petersburg to cooperate in an intense way with de Bétancourt. At the end of the same year, the Belgian Jean-Baptiste Vifquain obtained his engineering title at the French *Ecole Polytechnique*, in spite of his active participation in the military defence of Paris (de Bouw 2003).

2.3 *Architectural detailing*

Analysing their work reveals that Von Traitteur and Vifquain do not focus exclusively on the design of bridges and infrastructure, but at the same time on the design of buildings. Their oeuvre is certainly not without architectonic ambition. With the designs of an expedition building (1815–1818), the barracks at Pella (1819), the transformation of a military school (1820), the school of building conductors (1820–26) etc., it is clear that the work of Von Traitteur must be written in a context of architectural classicism and early historicism and eclecticism (Schoonjans 2007). In the same way, the work of Vifquain includes not only bridges and infrastructure, but also several buildings and urban plans as the Barricadesquare, the hospital of the city of Tienen and the extension of the castle at Bazel-Kruibeke where he also designed the iron suspension bridge in 1824. This broad practice of the engineer was not so exceptional at that time. The well-known J.J. Durand developed in 1805, with his *Précis des leçons d'Architecture données à L'école Polytechnique,* in Paris a method to enable the engineer to design an architecture that was usable in all contexts but still remained in contact with the idea of a building as cultural artefact (Szambien 1984). It was the choice of the engineer to address rational constructions or to aspire within his oeuvre an architectural commitment. This was certainly the case with Von Traitteur. His bridges were seldom considered as purely rational constructions but had to be appropriate in larger urban ensembles for developing the new cosmopolitan city. This is particularly visible in his design for the Panteleimon Bridge, the Egypt Bridge or the Lion Bridge over the Katharina canal. Von Traitteur himself refers in his publications to the importance of using the correct proportions and ornaments when sketching a bridge. The need to open a historical pallet and to consider forms of the past as a possibility to introduce elegance into objects of a pure utilitarian nature was present in the work of Von Traitteur. His bridges are a perfect match between the technical and stability requirements and the architectural demands within a typical 19th century embellishment of the city. But even the more straightforward Post Office Bridge or Vifquain's bridge at the castle at Wissekerke, contain a particular architectural detailing. The portals and railings have a refined ornamentation beyond pure technicality. Whereas the Post Office Bridge is formulated within a classicistic

ensemble, Vifquain (like at the Panteleimon bridge by Von Traitteur) uses a neo-Gothic language. This way, the design is clearly anchored in the culture of the simultaneously developed English landscape garden that the Viscount Vilain XIIII commissioned around his castle in Wissekerke. Such architectural ambition is not found to the same extent at the Kettensteg of Küppler or at the experimental bridge at Vernosc-les Annonay.

It is not clear whether Von Traitteur was aware of the latest work of James Finley, Samuel Brown, Thomas Telford, Marc Seguin, etc. (Peters 1987). However, it is without fail that the newly developed printing techniques made it possible to produce rather cheap journals and model books with very high-quality illustrations. Within the network of firm contacts, these publications – and with them the knowledge and insights – were rapidly spread throughout the western world from Paris, over Brussels and Nuremberg to Saint Petersburg.

The period 1823–30 seems to be a pivoting moment where the innovative aspects of the iron suspension bridges were elaborated.

2.4 *Design issues*

The questions that intrigued the engineers at the time were aspects of the geometry, the calculation of the horizontal and static forces and the creation of a sufficiently rigid deck. In the United Kingdom, one developed chains and eye-bars. French and American engineers experimented with (stronger) wire cables. The analysed footbridges in this paper clearly show that the engineers Küppler, Vifquain and Von Traitteur were informed on the French systems by means of the Parisian *Ecole Polytechnique* as well as on the English insights. It was rather common in Belgium that engineers, like Vifquain, finalized their study with a fieldtrip to Great Britain.

The design and the production of these iron suspension bridges were however not generic. The outline was not only based on the more obvious aspects of the specific static and dynamic forces, but also on the specific condition of the local quality of iron and the possible dilation, the urban or rural setting of the bridge, etc. The realisation of bridges was considered by Von Traitteur and Seguin, even more than by Vifquain or Küppler, as a laboratory of modern engineering and for a modern society.

3 IRON WIRE SUSPENSION BRIDGE, M. SEGUIN, 1822

3.1 *Historical value*

After an experiment in 1821 Marc Seguin and his brothers built a small cable suspension bridge on private land to span the river Cance in Vernosc-les Annonay. The private bridge was only 0.5 m wide, spanning 18 m. The cable consisted of iron wires. In 1823–24 Seguin built a second experimental bridge over the Galloire in St. Vallier with a span of 30 m. To stiffen the bridge he designed the railing as a truss. This intuitive solution appears to be valid and must be preferred to the theoretical solution of Navier, who claimed that the weight of the deck had to be increased to stiffen the deck (Wagner 1989).

Figure 1. Iron wire suspension bridge built by Seguin in 1822 in Vernosc-les Annonay, France (Photo: P. Stott, 2003, Structurae).

Together with Marc Dufour and Marc-August Pictet, Marc Seguin used this experience to build the Saint-Antoine iron wire suspension bridge in Genève, with a span of two times 41 m. From then on, Seguin built suspension bridges at a great pace. The *Pont de Tournon* in 1825 (ruined by flood in 1857), The *Pont D'Andance* in 1827 (partially destroyed in 1944, rebuilt in 1946), *Passerelle d'Arcole* in Paris in 1828 (replaced in 1854), *Pont de Sablons* in 1828 (replaced in 1933), *Pont du Doux* (1828, ruined by flood in 1857), etc. By 1841 more than 75 suspension bridges were built by Seguin.

At the time Navier wrote his *Mémoire* no one could have predicted the innovative role Seguin would play in building wire suspension bridges. Nowadays, Seguin is considered as one of the few engineers who mastered the complete design and building process of suspension bridges.

3.2 *Future*

The bridge in Vernosc-les Annonay was listed as historical monument in 1981. Although this fact reflects that France is aware of the historical value of the bridge, the local authority, who owns the bridge, is not in a hurry to take action. Figures 1 and 2 reveal the neglect of the historical monument and raise the question if this structure can be renovated or if it has to be labeled as lost already.

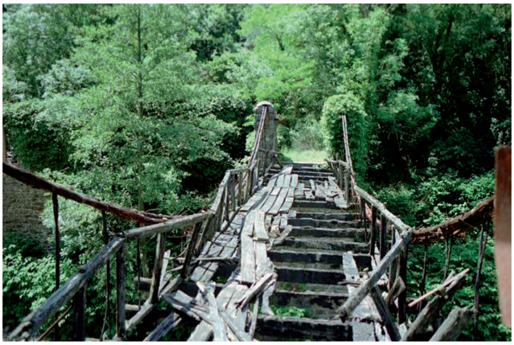

Figure 2. Detail of iron wire suspension bridge in ruin in Vernosc-les Annonay (Photo: P. Stott, 2003, Structurae).

Figure 3. Iron chain suspension castle bridge built by J.B. Vifquain in 1824, Bazel-Kruibeke, Belgium (2003).

4 IRON CHAIN SUSPENSION BRIDGE, J.B. VIFQUAIN, 1824

4.1 *Historical value*

In 1824 viscount Philippe Vilain XIIII commissioned to alter the castle Wissekerke at Bazel-Kruibeke, to turn the park into an English garden and to build a private bridge over the pond. The viscount approached the Brussels engineer J.-B. Vifquain, who realized important architectural projects and was involved in the design of the canals Pommereuil-Antoing and Charleroi-Brussels (de Bouw & Wouters 2005). As Vifquain spent numerous time analyzing the work of English engineers it is not surprising that the bridge is detailed according to the British examples.

He detailed the wrought iron cable as pinned eye-rods (Fig 4). The main cable spans from column to column (distance 23 m) and consists of 23 chain links. The tension force in the main cable is guided down trough compression forces in the cast iron columns and

Figure 4. Detail of the chains, hangers and railing. Iron suspension bridge Bazel-Kruibeke (2006).

tension forces in the ties that go over in the abutments. The sag of the cable is low: 1 over 19. The wooden deck is 2 m wide.

The eye-rods and the hangers are connected via bolts. Although the wrought iron eye-rods (14×31 mm), the ties (15×36 mm) and the hangers (13×13 mm) can take up considerable forces, it are the bolted connections that limit the permissible live load to only 0.1 kN/m^2.

To stiffen the suspension bridge and reduce the movements while crossing it, engineer J.-B. Vifquain detailed the railing in a stabilizing way, forming stiff diagonals. This solution is not only very efficient from a structural way of view, moreover it leads to a very light and elegant bridge of extreme beauty. (Fig. 4)

4.2 *Alterations*

During the years, the wooden bridge deck and the connection between the bridge deck and the wrought iron hanger have been adapted. New U-shaped steel beams were connected to the hangers to carry the wooden bridge deck. All other elements (cable, railing, hangers and columns) are still original.

The bridge was listed as a monument in 1981. From 1998 onwards the viscount sold parts of his property to the local authority and private investors. The local council of Bazel-Kruibeke bought the park surrounding the castle and opened it for public. Shortly after, in 1990, the bridge was closed because of its bad condition and unsatisfactory load-bearing capacity.

4.3 *Future*

In 2007 the mayor asked to strengthen the bridge such that it could serve as a public bridge. The imposed live loads on public bridges are 50 times higher than the actual capacity of the former private castle bridge.

Strengthening the suspension bridge would harm the monument in an irreversible way. As replacing original material by stronger alternatives was not an option for the council of Monuments and Sites two proposals were presented: keeping the bridge as an historic 'object', not making it accessible for people, or building a present-day bridge within the existing one. The latter solution will be implemented: the inauthentic deck will be replaced by a shallow box girder that lies within the height of the deck. This girder provides the required bearing capacity for the deck and is connected at its sides by a sliding connection with the historic suspension structure that will be restored. An additional handrail is designed to meet the stability and safety requirements. The handrail structure is fixed on the box girder and consists of a steel frame filled with a fine stainless steel net. Its vertical members follow the rhythm of the vertical hangers of the initial bridge.

Looking at the final solution in terms of setting priorities, one can say that safety went first. It was the challenge of the designing team to balance minimal visual impact with total preservation of the historic parts. Furthermore, it's remarkable that 'keeping original material' was set a higher priority than 'the view/visual impact of the intervention'.

5 IRON CHAIN SUSPENSION BRIDGE, W. VON TRAITTEUR, 1824

5.1 *Historical value*

Colonel Wilhelm Von Traitteur, working for the engineer corps in Saint Petersburg, was charged in 1823 with the construction of a traffic (Panteleimon Bridge) and a pedestrian bridge (Post Office Bridge) over the Mojka. He convinced the duke Alexander of Würtemberg that a suspension bridge was the best typology to meet the need by pointing to the *Report and Mémoire* of Navier. But before using the theory and best practices that were listed by Navier, Von Traitteur asked to start a research program to determine the strength of the iron produced in Russia and to investigate how the mechanical properties of iron changed when the temperature dropped.

In 1824 the research project was completed and the foundation was laid for the use of Russian iron in engineering constructions. Subsequently, the structural elements of the suspension bridge could be dimensioned and the production of the construction elements started. After proof testing the chains and the assembled cable on a – for this purpose designed – apparatus, the structural elements of the Post Office Bridge were assembled on site.

Each of the two main cables was built up by two chain cables, which consisted of nineteen identical

Figure 5. Iron chain suspension bridge built by W. Von Traitteur in 1824, Saint Petersburg, Russia (Photo: O. Blinkova, 2007).

Figure 6. Iron chain suspension bridge Saint Petersburg (Photo: O. Blinkova, 2007).

1.75 m long bars with a diameter of 35 mm. (Fig. 5) On every side of the bridge, 18 hangers, with a diameter of 16 mm, are attached to the cable, in a similar way as Samuel Brown did for his Union Bridge in 1820. Because of the limited space available on the footpath, Von Traitteur came up with a compact solution: he added a quarter of a circle to the column to lead the tension forces vertically into the foundations. In August 1824, the bridge was opened for the public.

The Post Office Bridge was the first iron suspension bridge of Russia. Other suspension bridges would follow at a great pace. The Panteleimon suspension bridge, which is known for his architectural refinement and detailing, was opened that same year. In 1826, the Egypt Bridge over the Fontanka was opened for public, as well as two pedestrian bridges over the canal Katharina: the Lion Bridge and the Bank Bridge.

The striking characteristics of the bridge designs of Wilhelm von Traitteur are the integration of the bridge as an architectural object in the city landscape, the transfer of the tension forces in the main cable to the abutments, and the possibilities he creates to adjust the geometry of the bridge by detailing the connection cable-tie and tie-deck.

5.2 *Alterations*

Almost immediately after the opening of the bridge additional actions were undertaken to stiffen the deck and to avoid the swinging movements. Wooden beams were placed diagonally in the deck in order to increase the rigidity.

At the same time the top of the cast iron columns started to lean towards the canal. Wilhelm Von Traitteur was optimistic and said the phenomenon would stabilize. To demonstrate the strength, he stated that he already observed an assembled crowd of about 600 to 700 people on the bridge. The weight of such a crowd (almost 6 persons/m^2!) leads to a live load of 4 kN/m^2. This number contrasts sharply with the load-bearing capacity Von Traitteur communicates to C.F.v. Wiebeking, who was working on the publication '*Mémoire sur les ponts suspendus en chaines de fer*' published in 1832:

Technical data of the Post Office Bridge:

- self- weight 0.7 kN/m^2
- live load 1.5 kN/m^2
- total load 2.2 kN/m^2

In 1905, after the collapse of the Egyptian iron suspension bridge, which was built in 1826, the confidence in the historic iron suspension bridges was lost. The Panteleimon Bridge was, under public protest, dismantled for reasons of security. The smaller pedestrian Post Office Bridge was strutted.

In 1935, the Post Office Bridge, as well as the Lion Bridge were recognized as historical relics by the city of Saint Petersburg. This action could however not safeguard the structure.

There were plans to restore the bridge to its original state while upgrading the load-bearing capacity to the current standards. Wrought iron was replaced by high tensile steel (limit of stretching strain 1200 N/mm^2). During the successive interventions in 1956 and 1981–83, the cast iron columns, the wrought iron chains, ties and deck elements were replaced by steel specimen. The used renovation strategy was to upgrade the structure to the actual safety standards and maintain the appearance of the bridge by replacing the applied materials by stronger materials. Although this was common practice in the 1980's, nowadays this strategy is merely applied for renovations instead of restorations.

6 IRON CHAIN SUSPENSION BRIDGE, K. G. KUPPLER, 1824

6.1 *Historical value*

In 1824, the mechanic and later professor Konrad Georg Küppler, built an iron suspension bridge to span the river Pegnitz in Nuremberg, Germany. Küppler was also involved in the development of the first German railroad between Nuremberg and Fürth in 1835.

The iron bridge consists of two suspension bridges placed successively with a span of approximately 33 m and 34 m. The cable starts in an elevated abutment, runs trough three portals and disappears again in the abutment on the opposite bank.

The main cable consists of iron rods (30 mm diameter) ending in a T, connected to the next bar by means of two rings (Fig. 8). The hanger, also a bar (diameter 20 mm), passes trough the chain rings, and is fixed by using an iron plate. The other end of the hanger wraps around the timber beam that carries the bridge deck. Since no bolts are used in the chain connections, the demountable details of the bridge look like the blacksmith bridges that were built in Scotland from 1816 onwards. The iron railing works structurally independent from the suspension chain and reduces the bridge deck to 1.55 m.

Two cables run on each side of the deck. (Fig. 8) Since the 20 hangers are connected alternating to one of both cables, the curvature of the two cables staggers. (Petri & Kreutz 2004).

6.2 *Alterations*

The columns that supported the main cable were originally in oak. After the floods of 1909 the bridge was serviced. The oak columns were replaced by steel frame columns. The timber elements of the bridge deck were renewed, taking into account a live load of 2 kN/m^2.

Since the bridge was very lively, the connections had to be checked regularly. In 1927, the Nuremberg police prohibited people to make the bridge swing when crossing it.

In 1931, while discussing the upgrading of the bridge to a live load of 5 kN/m^2, the bridge was temporarily reinforced and stabilized. The detailing of the wooden bridge deck with extended timber cross beams, lends itself to be carried by a steel I-section.

The I-sections, on their turn are supported by wooden posts (Petri & Kreutz 2004).

6.3 *Future*

Thanks to the supporting structure, the bridge could be preserved up till now. Nevertheless, the cables and hangers are reduced to ornaments. The university of

Figure 7. Iron chain suspension bridge built by K.G. Kuppler in 1824, Nuremberg, Germany (Photo: N. Janberg, 2001, Structurae).

Figure 8. Detail of the iron chains. Suspension bridge Nuremberg (Photo: E. Bernstorff, Bridgemeister).

Nuremberg and the local heritage foundation exert pressure to restore the suspension structure.

7 CONCLUSIONS

From the early period of iron suspension bridges (up till 1824) there are still four bridges left on the vast continent. In spite of the rare character of these bridges they are treated with lack of respect. The wire suspension bridge in France is degenerating, the restoration of the iron chain bridge in Nuremberg is placed 'on hold'. However, the best way to ensure the long-term survival of historic buildings and structures is to guarantee their continuing usefulness. For early 19th century pedestrian bridges, this comes to defining a restoration strategy. Not only can we detect different problems in terms of stability because of the aging of the bridge, at the same time the bridge should be upgraded to the latest standards concerning comfort and safety. As a consequence, taking structural measures becomes a necessity. In architecture it is possible to adapt the building's structure in an invisible when the structure is hidden by cladding. However, in structural works like suspension bridges, this is far more difficult, since there is an interaction between the construction and the structural behaviour. Moreover, there is a direct visual impact, since the construction itself is the form. Do we want to keep this form and create a replica in steel, like in the bridge at Saint Petersburg,? In that case the argument in favour lies in the aim to retain the urban ensemble and its purely visual aspects. But then the discussion on the detailing and the imitation of that detailing starts. In the case of Bazel-Kruibeke, not the form, but the preservation of the historic artefact itself was put forward. An almost invisible present-day bridge is built within the existing one.

Between these extreme options (replica versus total conservation historic fabric) an interval of interesting conservation strategies is ready to be explored. These strategies can initiate a more explicit dialogue between the old bridge and a new solution. Arguments of stability, public safety, authenticity of the artefact, the bridge as a landmark, and other will guide the chosen strategy. It is the task of the design team to equilibrate strengthening versus conservation.

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