The History of the Wire Rope's Invention

and the Decisive, but Unfortunately Transitory, Role of French Engineers

by Jean Marc Teissier and Don Sayenga

Part One: History Begins in France, with Suspension Bridges

Wire rope was invented to replace fiber rope, or chain, in many applications, including the construction of suspension bridges, and hoisting of heavy objects with machines. Fiber ropes were produced using natural fibers, mainly hemp and sisal. The use of fiber ropes dates from before the age of antiquity (3000 BC). The use of chains, which is much more recent, followed the progress of the iron/steel making techniques.

The first chain suspension bridges were built at the very beginning of the 19th century. They were designed and built by American engineers (James Finely) or English engineers (Thomas Telford). These first constructions were mainly based on empirical approaches.

Claude Navier was a "polytechnicien"* engineer, most known for his mathematical works, especially those applied to fluid mechanics (Navier-Stokes equations). He was also a civil engineer "des Ponts et Chaussées," and worked on the construction of the first Invalides Bridge in Paris.

This chain suspension bridge was intended to be an example of optimization, as opposed to the same type of bridges built in England and in the US. Claude Navier, an expert in mathematics, developed a global theory on the matter of suspension bridges. As a result of the accuracy of his theoretical approach, the safety factors were reduced. Unfortunately, there were not enough margins of error. In September 1826, when the bridge was fully erected, an underground water pipe on one bank broke, compromising the foundation of one of the piles. The bridge began to crack. It was dismantled even before its grand opening. The Alexandre III Bridge was later erected in the same place.

Claude Navier published in 1823 a book Rapport et Mémoire sur les ponts suspendus, which was re-published in 1830 with additional information related to the Invalides Bridge. This book has been used as a reference for the design of suspension bridges. Although it was written for chain suspension, the exposed theories were fully applicable for wire rope suspension bridges. In fact, today the equation for the equilibrium of weighing wire is still named the equation of catenary, or "équation de la chaînette" in French.

Parallel wire cable was invented at that time. The invention of parallel wire cable is usually credited to Marc Seguin, but the story is a bit more complicated.

Marc Seguin began working on the Tournon Bridge project in 1820. In 1822 he built a prototype over the Cance River. The construction of the Tournon Bridge was delayed because the project was changed from a pedestrian bridge to a bridge for vehicles, and because Seguin was busy with other projects.

Navier considered parallel wire cable to be a competitor of chain. But by 1824, the problems faced by Navier with the Invalides Bridge, had weakened his position. The Tournon Suspension Bridge opened to the public in August 22, 1825.

Independently of the Tournon Bridge, Swiss authorities were managing the project of the Saint Antoine Bridge in Geneva. Marc Seguin submitted a bid, but the contract was finally awarded to Guillaume Henri Dufour. The Saint Antoine Suspension Bridge opened to the public on August 1, 1823. Factually this is the first wire cable suspension bridge in history. Credit for the invention of parallel wire cable is usually given to Marc Seguin because, not only was his project ready before Dufour's project, but also

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Rope with parallel wires (Marc Seguin).

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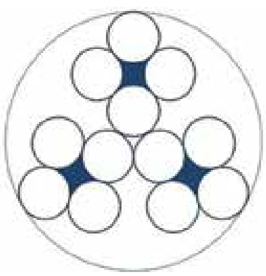

Multi strand rope (Julius Albert) – theoretical section (left), and replica by Roland Verreet (right).

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the Tournon Bridge was larger than the Saint Antoine Bridge.

Suspension bridges made with iron wires were very advantageous. They were hugely successful, and a very large number of such bridges were built up until 1850. These ropes were fulfilling the needs for suspension bridges.

HISTORY CONTINUES IN GERMANY AND THEN IN ENGLAND AROUND THE HOISTING SYSTEMS

The solution for hoisting systems was developed by Julius Albert who was a mine engineer at the Clausthal mine in Germany. This is the first multi-strand rope in history.

The wire rope is made with several strands. Each strand is made of several wires twisted according to a helix. Several strands are then twisted on the same way to form the wire rope

The Albert rope was made with 3 strands of 4 wires. The diameter of the rope was 18 mm and the diameter of the wires was 3.5 mm.

This rope was installed July 23, 1834 in a shaft of 484 mm depth at the Caroline mine close to Clausthal.

The rope invented in Germany, at that time was produced manually. Later the technology for the production of ropes was developed in England. Andrew Smith and Robert S. Newall were the main contributors to these technological improvements, and they were at the origin of the invention of closing machines for the fabrication of ropes. They competed all the time, claiming credit for the inventions. In the 1840s Newall introduced an iron wire rope made of 6 strands with 19 wires wrapped around a textile core, which was fully produced on a closing machine.

John August Roebling

Photo courtesy of The Brooklyn Museum.

HISTORY IS ALSO BEING WRITTEN IN THE US

John August Roebling received his civil engineer diploma at Berlin University, where he learned about Navier's work, and the reports of Marc Seguin related to the Tournon Bridge. In 1831, he decided to move to the US to create a farmland community in the area of Pittsburgh, Pennsylvania, at a place that he named Saxonburg. Soon he had to take a position as civil engineer for the state of Pennsylvania because the income from the farm was not sufficient. He took part in the construction of canals and railways.

John August Roebling, who was obviously a better engineer than a farmer, was soon recognized for his skills and knowledge. He was asked to work on improving the hoisting system of the Allegheny Portage Railroad, which was then fitted with a hemp rope. First he tried to use the Seguin cable (made of parallel wires). This was unsuccessful because it had not been designed to be wound onto a drum.

He looked for another solution. So, in 1841 he developed a wire rope with 7 strands of 19 wires (6 strands twisted in a helix around a core which is a strand with the same construction as the external strands). It worked excellently. The architecture of this rope, which was at first manually produced in Saxonburg, is very similar to that of the Newall rope.

The wire rope was so successful that Roebling had to produce a closing machine (with a vertical main shaft, as opposed to Newall's, which had a horizontal shaft), and in 1849 he built a brand new factory in Trenton, New Jersey to produce wire ropes.

Starting in 1845, John August Roebling was also involved in civil engineering work. He began by renovating existing bridges, and in 1849 he built the aqueduct over the Delaware River in Pennsylvania, which was his first new work.

BACK TO FRANCE DURING THE GOLDEN AGE OF THE FRENCH ENGINEERS OF SUSPENSION BRIDGES

In France during that time, the construction of suspension bridges was hugely popular. A lot of companies began constructing them. The wire rope was fabricated on the ground close to the bridge. It was made of a bundle of parallel wires which were then enclosed by a system of ligature in order to keep a round section. When installed on the top of the piles, the cable took a parabolic shape. The wires were slid in between in order to adjust their length (wires located in the inner radius were too long and those located on the outer radius were too short), but these displacements were restrained by the ligature presented above. Ensuring a balanced distribution of the line pull in each wire was very difficult.

A large number of bridges were built. Unfortunately, the quality as well as the accuracy of the fabrication was not suitable for the challenges of such works, especially regarding the fabrication of the cables.

The administration of Ponts et

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This article was one of the last pieces of literature penned by Donald Sayenga before his passing in February 2019. When Don met somebody in France, passionate for the same subject, fruitful exchanges made possible the clarity on many points of the history of rope.

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Chaussées asked Louis Vicat to perform a survey of several of these suspension bridges. Louis Vicat, who was a "polytechnicien"* engineer like Navier and Dufour, had become famous in 1817 for the invention of artificial cement. He refused to patent this invention in order to ensure that it remained accessible to everyone. In 1830, he was the engineer in charge of the construction of the Argentat Suspension Bridge over the Dordogne River. Louis Vicat imagined a new technique for fabricating cable directly in its final position on the bridge. The wires were then laid in accordance with the final curvature of the cable, and thus naturally had the proper length. John August Roebling used and patented this technique for the construction of the suspension bridge over the Niagara River. This technique, called "spinning" is still used today.

Charles Ellet, Jr. is an American engineer who was very interested in suspension bridges. During a survey trip to France (1830 – 1831), he visited a lot of bridges and took courses at the "Ecole Nationale des Pnts et Chaussées – ENPC." Later he became the representative of the French school in the United States.

Roebling agreed with the teaching at ENPC, which was based on Navier's theories, with one exception: the stiffness of the deck. He thought that the deck should be stiff, especially for large spans.

The accident which occurred on the Broughton Chain Suspension Bridge should have taken that more into consideration. A military company of 60 men found the vibration generated by their walk was pleasant and then tried to amplify it, which finally led to the collapse of the bridge. This occurred following the dramatic accident of the Tacoma Bridge in 1940, where this vibratory phenomenon should have been seriously considered.

On the other hand, the technique for anchoring the cable was not debated. All the experts agreed that embedding the cable's anchoring room with lime was a good option. The anchor was not inspectable, but there was (theoretically) no risk of corrosion. John August Roebling agreed.

At that time, Joseph Chaley was one of several French engineers involved in the construction of suspension bridges. In 1834, he built the Fribourg Bridge in Switzerland which, thanks to its large span of 273m, retained the world record until 1849, when Charles Ellet, Jr. built the Wheeling Bridge. In 1838 he built the Basse-Chaine Bridge in Angers.

THE BASSE-CHAINE ACCIDENT, WHEN HISTORY GETS FROZEN IN FRANCE

April 16, 1850, the 11th regiment of light infantry was crossing the Basse-Chaine Bridge. The weather conditions were dramatically bad (rain and strong winds). The bridge was oscillating under the wind action, and the men had to move laterally from right to left to keep their equilibrium. These motions finally amplified the swinging of the bridge. When the head of the 3rd battalion reached the other bank, i.e. almost all the column was on the deck, one of the cable's anchors broke. All the soldiers were thrown in the river. This accident caused more than 200 deaths.

The risks associated to the vibration of suspension bridges had been known since the Broughton accident (1831). After that, the British army ordered that troops should "break step" when crossing a bridge. The conclusions of the expert findings were undisputable. The anchors of a suspension cable broke because they were weakened by corrosion, despite the lime which was supposed to protect them from humidity inside their confinement structure.

It wasn't a fabrication mistake, nor was it a non conformity to applicable standards. This accident highlighted a failure in the compulsory regulation's requirements. All the bridges so far built were potentially dangerous.

A detailed inspection of all the French bridges was implemented. A lot of them were removed, mainly because of these inspections. This is why, for example, there are no longer any suspension bridges in Paris, where at least three were built, the Arcole Bridge (1828), the Bercy Bridge (1832) and the Louis Philippe Bridge (1833). Not a single suspension bridge built in France before 1879 remains.

MEANWHILE, HISTORY WAS STILL BEING WRITTEN IN THE UNITED STATES

John August Roebling and Charles Ellet, Jr. were the two main actors in the field of suspension bridges. Ellet, based on what he had learned in France, was proposing light structures. On the contrary, Roebling, who was convinced that stiffness was a major issue, was proposing stronger and heavier structures, which were more expensive.

Thus, in 1849 the contract for the construction of the Wheeling Bridge was awarded to Charles Ellet, Jr. With a span of 308 m, this bridge became the largest suspension bridge in the world.

A few years later, in 1854, the deck of this bridge suffered huge damages dur-

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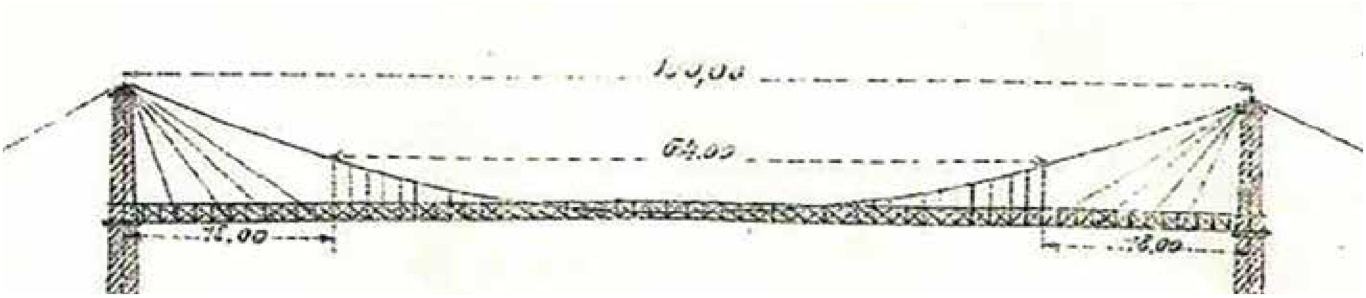
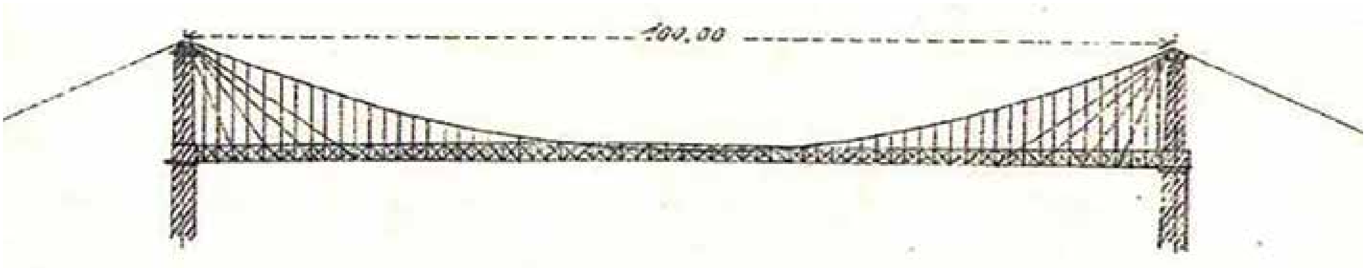


American suspension system. (Arnodin's interview by the commission)



French suspension system. (Arnodin's interview by the commission)

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ing a windstorm. A new, much stiffer, deck was installed. And later, Roebling added guy ropes among the suspenders.

This event gave credibility to the Roebling theory regarding the stiffness of the deck.

These two men were competing for the construction of the railway suspension bridge over the Niagara River. The contract for the temporary bridge was awarded to Ellet. But when Ellet and his client had a financial disagreement, John August Roebling was awarded the project. This bridge, with a span of 244 m, was inaugurated in 1854, and the first train, weighting 200 T, crossed the bridge on March 18, 1855. Roebling did everything possible to increase the stiffness of the bridge. It had a double deck – trains ran on the upper part, and pedestrians and horse carriages crossed on the lower part. Thus, the dimensions and the geometry gave a significant stiffness to the deck, although it was initially made of wood. The suspenders joining the suspension ropes and the deck were inclined, and additional under floor stays were also installed.

To fabricate the suspension ropes, Roebling used and patented the process imagined by Louis Vicat in 1831. In the report to the owner of the bridges, which was published in 1855, Roebling indicated that the accident of the Wheeling Bridge was the most critical that had ever occurred on a suspension bridge. This proves that at that time Roebling was not aware of the Basse-Chaine Bridge accident, and that he was not informed of what was happening in France. So it's highly probable that he didn't copy Vicat, but that he had the same idea about "spinning" wire cable.

The anchoring rooms of the suspension ropes were not inspectable, and were embedded with lime (exactly identical to those of the Basse-Chaine Bridge). John August Roebling was convinced that this was the proper solution. He applied for a patent in 1846. During his life he opposed any inspections. Roebling died in 1869 during the construction of the Brooklyn Bridge in New York, which would be completed by his son Washington. The son didn't agree with his father on that matter, and so he agreed that an inspection should be carried out. A summary report of this inspection was published in 1881 by the engineer L. L. Buck, who was in charge of that inspection. Buck clearly stated that the anchoring system was facing the same problems as those of the Basse-Chaine Bridge. Renovation was performed in 1887.

What might the destiny of suspension bridges have been, if the bridge over the Niagara River had collapsed in the same manner as the Basse-Chaine Bridge?

John August Roebling faced a bigger competition in the field of hoisting ropes. The English techniques had been introduced in California by Andrew Smith. His son, under the name A. S. Hallidie, created a factory in California in 1857, where he produced ropes for the gold mines and then for the cable cars. A. S. Hallidie is famous mainly for his role in the development of the cable cars in San Francisco (1872).

HISTORY RESTARTS IN FRANCE, WITH FERDINAND ARNODIN

It was not until 1870 that France again authorized the construction of suspension bridges. Ferdinand Arnodin, whose father had worked for Marc Seguin, was very aware of Seguin's cable and of the Seguin suspension bridges. He did the inspection and the maintenance of these bridges.

Ferdinand Arnodin created his own company for the construction of suspension bridges in 1872. He became in fact the unofficial successor of Marc Seguin when he died in 1875.

In 1870, the French administration of Ponts et Chaussées mandated that engineer Emile Malézieux make a survey trip to the United States. In 1873 Emile Malézieux published a report entitled, Travaux Publics des Etats-Unis d'Amérique en 1870. A section of this report is dedicated to suspension bridges and particularly to the railway bridge over the Niagara River, which was built by John August Roebling in 1855. The bridge is described with a lot of details. This report was the basis, the founding reference, of the French engineers, starting with Ferdinand Arnodin. It was used to establish the new French school.

The bridge configuration with suspenders and inclined guy ropes connecting the deck to the head of the piles is identified as John August Roebling's suspension system. This is the "American" suspension system.

Engineer Jollois, who designed the Saint Ilpize Bridge, imagined a suspension system with a "French" stiffening beam. This is in fact the American system, but without the addition of inclined guy ropes and suspenders.

The engineer Maurice Levy developed in-depth calculations for that

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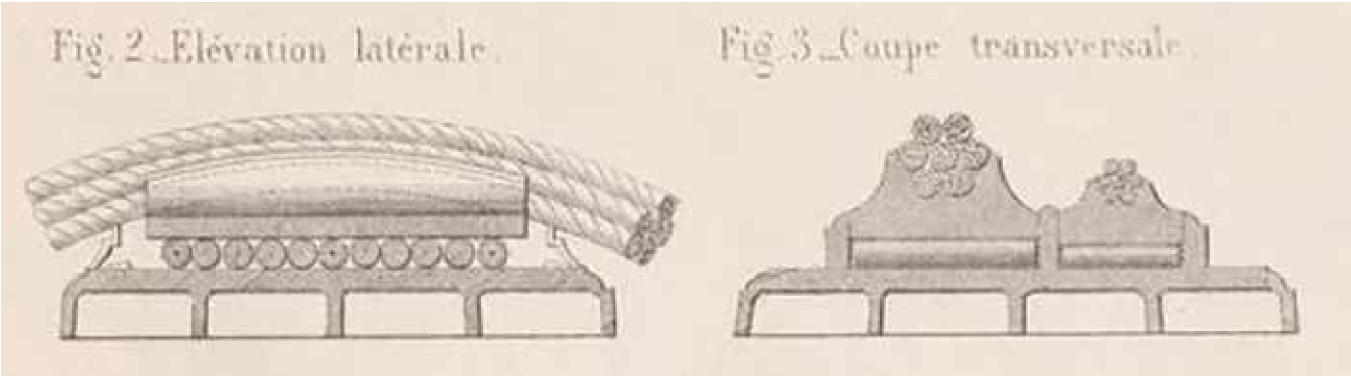

Two of Maurice Levy's in-depth calculations for the Saint Ilpize Bridge system.

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bridge system. (See Fig. 2 and 3 above)

For the suspension ropes, engineer Jollois followed the specifics of the Malézieux report. This report indicates that these ropes were made of multi-strand ropes. This is a mistake. Roebling used his multi-strand ropes only for the suspenders and the inclined ropes.

The suspension cables used by Roebling were like Seguin's, and were produced "in place" with a method identical to that described by Louis Vicat in 1831. So, engineer Jollois selected multi-strand ropes for the whole suspension system.

Ferdinand Arnodin's company had been in charge of the construction of the Saint Ilpize Bridge, as well as the construction of all the other suspension bridges which were erected at that time, including Chilhac and Lamothe, and also the renovation of the Tonnay-Charente Bridge. The Saint Ilpize Bridge, which was the first French suspension bridge after the "Basse-Chain" period, was completed in 1879.

The use of multi-strand ropes as suspension ropes was not successful. Ferdinand Arnodin was very aware of the problems related to Seguin's ropes. He was now discovering the disadvantages of the multi-strand ropes, which had not been designed for such an application. This is when he invented his rope with alternate directions of lay, which in fact is a combination of the two other ropes.

As a result of a request by Ferdinand Arnodin, a special commission was established August 27, 1885 with the mission of studying questions in relation to the suspension bridges, and more specifically the evolution and improvements of the modern suspension bridges, compared to those built before 1850.

At that time Ferdinand Arnodin, who was the expert in the construction of suspension bridges, was either the originator, or the first to implement these evolutions: the principle of removability, the rope with alternate directions of lay, the French stiffening beam, and the the articulated railing.

The commission based its works, on the one hand on the feedback data from site works which were mainly documented by the reports published in the Annales des Ponts et Chaussées, and on the other hand on an important work of calculations performed by Maurice Lévy. It was published in 1886 in a book entitled Mémoire sur le calcul des ponts suspendus rigide, or Report on the calculation of stiff suspension bridges.

The conclusions of this commission were published in July 1889. The principle of removability as well as the rope with alternate directions of lay were unanimously approved. Some limits were established regarding the use of stiffening guy ropes (French suspension system), and the articulated railing was unanimously rejected.

Like other great men, including John August Roebling, Ferdinand Arnodin rejected any reconsideration. So, he continued using guy ropes that were too inclined and using his articulated railing.

A few years later Ferdinand Arnodin crossed paths with Alberto de Palacio. In 1893 these two men built the very first transporter bridge in Bilbao. For the transporter bridges Ferdinand Arnodin used the techniques of the suspension bridges.

From March 1898 to July 1900, Ferdinand Arnodin built the Martrou Transporter Bridge, using the same design as for those of Bizerte/Brest and Rouen, i.e. a deck with his articulated railing, and with guy ropes too inclined. He also used his rope with the alternate directions of lay. By contrast, for the Newport Transporter Bridge (1906), the deck was not fitted with articulated railing, but rather had a geometry which provides a huge stiffness. Also, the inclination of the guy ropes was in accordance with the conclusions of the special commission which was published in 1889. This bridge is still in operation with its original deck, whereas the decks of the transporter bridge of Martrou and Rouen had to be replaced because they quickly showed signs of weakness.

For the Newport Transporter Bridge, Ferdinand Arnodin was assisted by Georges Camille Imbault, an "Art et Métier" engineer who had started his career in 1895 at Arnodin's company. In 1901, Georges Camille Imbault resigned from his position, and moved to England to work as well as improve his English. He also worked abroad for English companies, contructing bridges such as the Harbour Bridge in Sidney.

Ferdinand Arnodin and Georges Camille Imbault always had a good relationship. It was the absolute opposite with Gaston Leinekugel Le Cocq, the son in law of the Ferdinand Arnodin. We must keep in mind that Georges Camille Imbault decided to resign and to leave France just after Gaston Leinekugel Le Cocq married Aline, the daughter of Ferdinand Arnodin. Probably Imbault's interest in moving abroad had less to do with learning English and more to do with hiding a deceitful love affair.

Although he was not living in France, Georges Camille Imbault had been the brain of Basile Baudin since the creation of the Basile Baudin company (1919). When Ferdinand Arnodin died (1925), Baudin and Imbault decided to capture the position of the Arnodin's company, which was still the premier company in the field of suspension bridges. They produced a new closing machine for the fabrication of rope with alternate directions of lay. In 1932, when Basile Baudin suffered a stroke, Georges Camille Imbault went back to France and became the director of the Basile Baudin company. The Basile Baudin company (Georges Camille Imbault) and the Ferdinand Arnodin company (Gaston Leinekugel Le Cocq) entered into a vicious war, until one of the two companies collapsed, to the detriment of the memory of Ferdinand Arnodin. WRN

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Part 2: The Legacy of Ferdinand Arnodin: His Rope, His Closing Machine