Johann August Röbling (1806-1869): Early Projects in Context

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FIRST SUSPENSION BRIDGE DESIGNS

Johann August Röbling - one of the greatest engineers of the 19^{th} century - was born on the 12^{th} of July 1806 in the town of Mühlhausen, Germany. Roebling received his training at a time when engineering was being transformed into a scientific discipline. This transformation was not merely an application of mathematics and physics to technical problems, but rather a methodical development of the science - and art - of construction itself.

After his studies at Erfurt (1821-1823) and Berlin (1824-1825) where he learned Navier's theory of suspension bridge construction (Dietlein 1825), Röbling was set to work planning roads and bridges in the Prussian province of Westphalia (Kahlow 2003). Very soon he began to think about designing a suspension bridge as an exam project for his construction degree. Roebling wrote to his teacher, Dietlein, who had publicized Navier's work in Germany in 1825 and received the newest technical literature on the subject. During a trip along the Ruhr and Rhine rivers in January and February of 1828 he arrived at the town of Wetter. A business company led by Friedrich Harkort was at that time planning a new road from the Geite Bridge to the city of Witten. For this purpose a new 450 foot long bridge over the Ruhr was needed, situated near Harkort's mechanical factory at Wetter (GStA PK I. HA, Rep 93 B Nr. 3736) (Güntheroth, Kahlow 2005). From a letter to his son we know that Roebling was involved in this project. His son, Washington A. Roebling, travelled to Europe in the winter of 1867-1868 and sought out Harkort's factory. The elder Roebling writes: "I stopped 3 weeks at Wetter an der Ruhr … Mr. Campe was a young man of 18, who took me over the whole Establishment. I made a Survey on the Ruhr, for location of the Suspension Br. which I had to plan as a Thesis for my 2. Examen." (RPI Box 5 Folder 4). We have evidence of two further suspension bridge projects, neither of which was realised: one near Finnentrop over the Lenne river and one at Freienohl over the Ruhr. Both were planned in spring 1828, and are therefore connected to the trip made by Roebling from 1827-1828 (RUT Student Book #1a)

Documentary evidence of these projects varies greatly. Harkort's project is only referred to sketchily in the minutes of his business association. The Freienohl bridge, on the other hand, can be reconstrued, since we have extensive documentation (Grunsky 1998) (LAER, JAR, Entwurf) . It was planned to use an inclined hanger plane and a rigid roadway (**fig. 1**). The main cable was to be composed of either linked iron rods or sheafs of parallel wire (**fig. 2**).

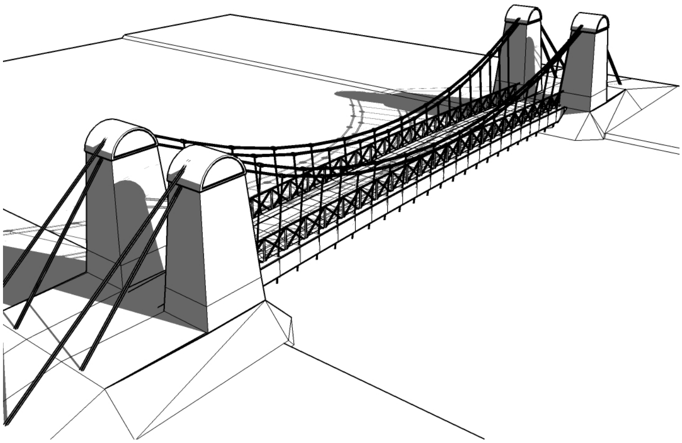

Figure 1. Freienohl suspension Bridge over the river Ruhr, as designed by Roebling in 1828. Computer animation by Dipl.-Ing. Göran Werner, FH Potsdam

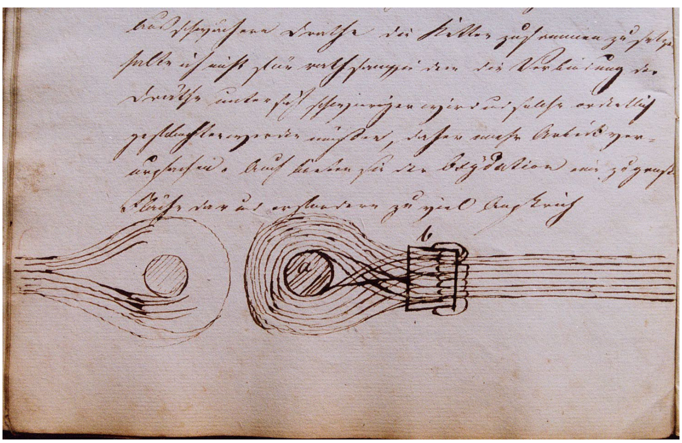

Figure 2. Proposed elements for the main cables of the Freienohl Bridge (LAER, JAR, Entwurf)

But a wrapped wire cable was not yet envisioned. Again, the bridge planned for Finnentrop is only evidenced by the expert opinion given by the governmental planning department. Roebling's design was submitted to the governmental office at Arnsberg on June 1st 1828 and it was then sent on to the Ministry for the Interior at Berlin on July 8th. The designs were then sent to the construction planning department (Oberbaudeputation), whose decision of August 28th was then relayed from the

Ministry to Arnsberg on September 9th. The letter of rejection includes words of praise and some indications as to the manner of construction employed: "The project for this suspension bridge must be rejected, because the chains and especially the rings that connect the chain elements, as well as the wire cables and the anchoring of the chains in the earth are surely too weak. As well, the non-perpendicular form of the suspenders, the manner in which the roadway is suspended on two independent chains, the iron saddles, the intention of using railings to assist in the suspension, the wooden blocks on the columns under the chains etc. do not have our full approval. Nevertheless, the industriousness with which the engineer Roebling has completed his suspension bridge project deserves our full recognition, and we wish to convey to him our encouragement." (MÜNSTER LWL C40 I A725). This communication had still not reached Roebling by November 26th, since he again wrote to the department at Arnsberg to ask about the progress of his project.

The fact that various elements of this construction, such as the "non-perpendicular form of the suspenders" and the "intention of using railings to assist in the suspension", were later characteristic of the great suspension bridges built by Roebling in America, was something that this critic – presumably Crelle – could not have anticipated.

PREPARATIONS FOR THE "BAUMEISTER" EXAMINATIONS

In the summer of 1828 Roebling ended his work as construction engineer in Westfalia and returned to Mühlhausen. Since his hopes to gain approval for his suspension bridge were not fulfilled, he turned his attention toward preparing for his Baumeister-examinations and assembled a large library of specialized literature. He carefully studied the latest suspension bridges, for example the bridge in Malapane, Silesia of 1825 and the Hammersmith bridge in England, as well as the collapsed Navier bridge in Paris. Roebling could actually visit only one suspension bridge in Germany. He travelled to Bamberg from May 17th to June 15th 1830 to examine the suspension bridge that had been built over the Regnitz and was officially opened for travel on December 31st 1829 (**fig. 3**).

He analysed its construction and costs, criticizing what he considered to be the faulty construction of the pylons because they did not permit the chains to have a balanced movement, but rather held them rigidly in place (JAR 1830a). After this trip, Roebling submitted his examination papers. However, he did not choose a suspension bridge, but rather a stone bridge with five arches over the Ruhr at the town of Wetter. His design is dated August 1830 (**fig. 4**).

Roebling's son speaks here of a submission for the Baumeister examinations (RUT, WAR 1907, p. 10). There is no proof that Roebling actually sat the exams (they usually lasted several days), and we have no evidence that he travelled to Berlin at that time. His emigration papers also do not identify him as "Baumeister" but merely as "Baukondukteur". One might speculate on the reasons for this. Presumably Roebling found the entire procedure in Berlin as too long-drawn out, and his preparations for emigrating to America were inordinately more important to him.

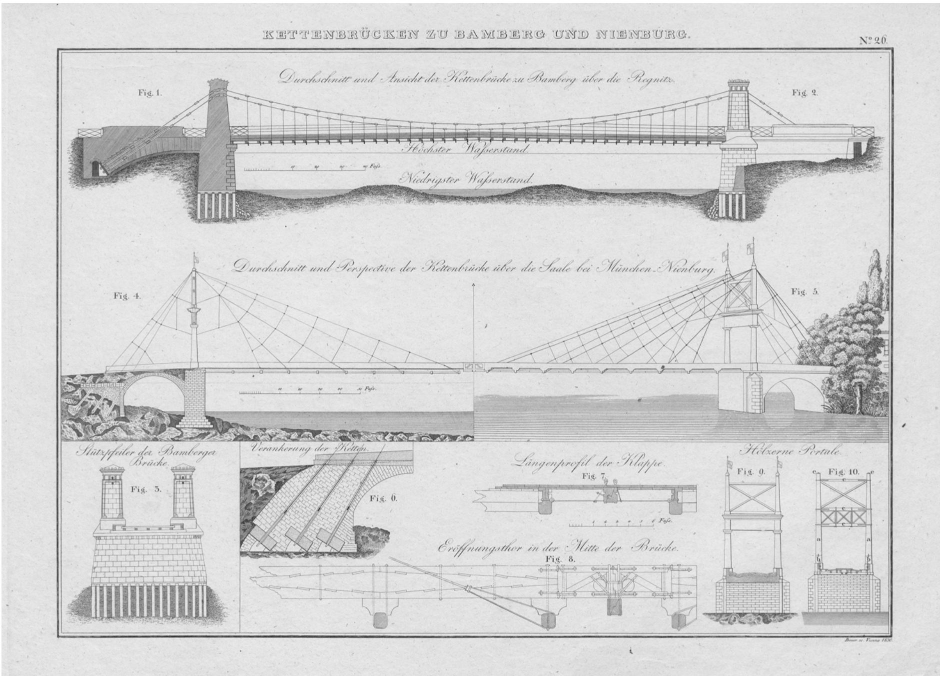

Figure 3. Bamberg Bridge (1829) and Nienburg Bridge (1825) (Gerstner 1831-1834, Tab. 26)

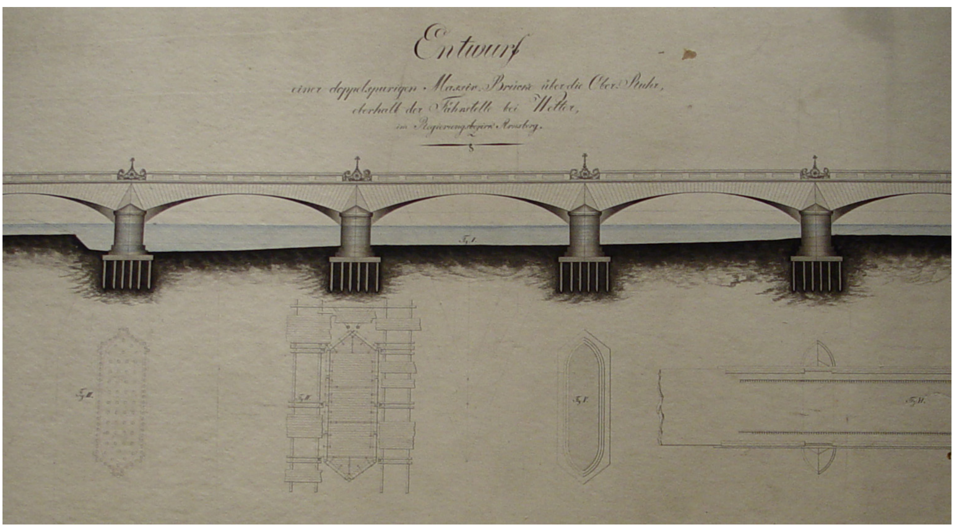

Figure 4. Roebling’s design of a massive stone arch bridge (1830) over the Ruhr in the town of Wetter. (RPI D5 F32, JAR, Miscellaneous)

EMIGRATION TO AMERICA

The July revolutions in Paris that ended the Restoration in France led to a period of repression and spying in Prussia, including Roebling's town of Mühlhausen. His decision to emigrate was largely influenced by an engineer in Mühlhausen named Johann Adolphus Etzler, who later unsuccessfully attempted to build technical utopias for the use of wind and water energy in the USA and Venezuela. Etzler, 15 years older than Roebling, had already lived in the USA and actively sought emigrants. Together they published an information pamphlet in the autumn of 1830 (JAR 1830b). By the spring of the next year, they had formed a society large enough to enable the first group to leave (JAR 1832). After some preliminary investigations, the group to which Roebling belonged settled on inexpensive land 25 miles north of Pittsburgh and established the colony named "Saxonburg".

Roebling wrote detailed letters describing the conditions they faced. An important addition to the colony came with the next group in the summer of 1832, the mechanic Ferdinand Bähr. He asked for permission to build a communal house for the first years, where new colonists could live and eat together, using a common workshop. "Those who will be employed in the workshop are Mr. Aug. Roebling as draftsman, Bähr as head of the workshop, our good man Boettger as finisher and two good journeymen. I will supply all of the carpentry equipment for cabinet-making, locksmithing, wood turning, polishing and the rest. We will all work for the betterment of life for everyone, whilst the others work in the fields and provide for our physical needs." (RUT B1 F17 letter Bähr 1832). It would take several years until the situation would progress to the stage where Roebling could once again devote himself exclusively to technical work.

SURVEYING WORK

Canals were an essential transportation system in the early industrialisation period in the USA and Europe. The completion of the Erie Canal in 1825 led to a second competitive project, the Pennsylvania Canal. The entire 400 mile stretch between Philadelphia to Pittsburgh was connected by means of canals and railway lines. The major part of the work was performed between 1826 and 1830, although the challenging 36-mile section over the Allegheny Mountains was only completed with an inclined railroad system in 1833. By this means the Ohio River provided a first stable link to the West (Lewie 2001, pp.11-34). Roebling himself had settled in Pittsburgh, in the expectation that the industrial development in that region would soon begun, which indeed was starting to take place.

However, the initial settlement period proved more difficult than expected. Most of the Saxonburgers attempted to work in their professions and found business contacts in nearby Pittsburgh. But at first survival was only possible by means of agriculture.

A German friend from his student days at the Unger Institute in Erfurt provided Roebling the contact and he began working on the Sandy and Beaver Canals in the beginning of August 1836 (RUT B3 F29, letter Thierry 1836). In this year he married Johanna Herting, the daughter of a German tailor. His first son, born on May 26th 1837, was the above-mentioned Washington August. He was named after an engineering colleague with whom he did surveying work (RUT WAR 1907, p.59) As the name of his son shows, Roebling was committed to working in an English-speaking milieu, something that clearly distinguished him from most other Saxonburgers. He attained citizenship on September 30th 1837 and from this point on anglicized his name to John Augustus Roebling.

In 1837 Roebling experienced significant changes in his life. His brother Carl died from a stroke in the summer while mowing and Roebling also lost his job on account of the economic down-swing that was just then beginning. He soon found work again thanks to his expertise in the field of water construction, gained during his studies at the Berlin Construction School, where this subject was given a great deal of attention after Eytelwein's school reform. He wrote to Edward H. Gill, the chief engineer of the Sandy and Beaver Canal project, suggesting ways to improve shipping conditions by means of dams and water retention. He was given the opportunity to work on a feeder canal for the Pennsylvania Canal. By the end of the decade he was acknowledged as a specialist on hydraulic works.

Roebling's texts and notebooks with improved surveying instructions and new calculated set of figures are still extant, the oldest of which dates to 1837. This contains a collection of ideas and designs for locomotives, steam engines and even a steam-powered motorcycle (**fig.5**).

The volume also includes the rough draft of a letter to Gill in which Roebling recommends a table of figures for surveying and calculating, which he had worked out to facilitate the calculations for laying of rail beds and rail line curvature. The other early volume with the title "Tables of Excavation" is the realization of this idea. It is a handwritten table for canal and rail construction and includes very fine sketches. Alongside such subjects as surveying methods and details of rail roadway it also includes two detailed drawings of wooden lattice bridges that were built in Harrisburg in Town's construction style (**fig. 6**)

The notebooks were continued into the period from 1839 to 1841, when Roebling worked as the chief assistant of the engineer Charles Schlatter on the planning and construction of the new railroad line from Harrisburg to Pittsburgh. Roebling made several surveying trips to find the best route. Much of the terrain was still virgin territory and he gathered information on its geology and geography. He originally decided on a more southerly route, but various businessmen influenced the final decision for a northerly path. At the same time, Roebling gained recognition for his work. (RUT WAR 1907, p.55). Roebling's studies at the Berlin academy 1824/25 had provided him with training in wooden bridge construction as well as hydraulic engineering. The study plan at the school included famous wooden bridges like the Limmat bridge at Wettingen or the new arch bridge systems developed by Wiebeking and others. Roebling included drawings of these bridges in his student note book while attending Dietlein's lectures on bridge building (**fig. 7**)

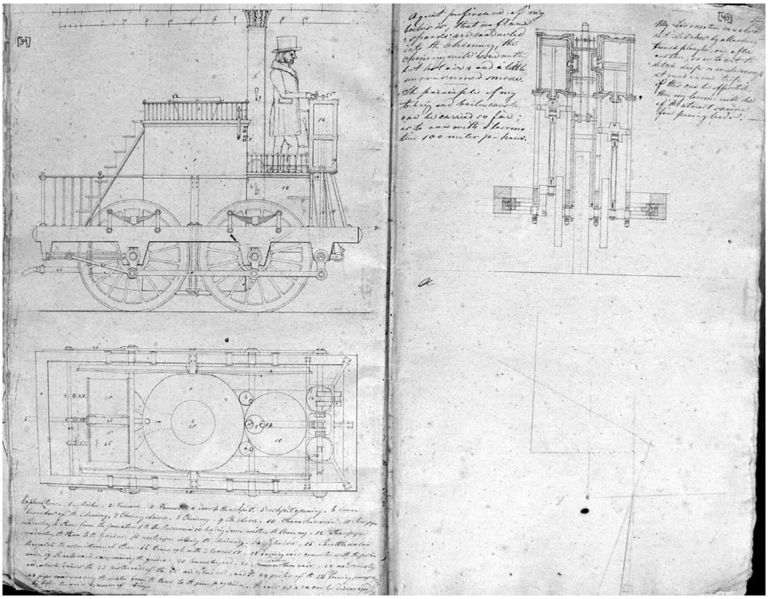

Figure 5. Drawings of a locomotive and motorcycle made by Roebling in 1837 (RUT B5 F44 "Copy Book")

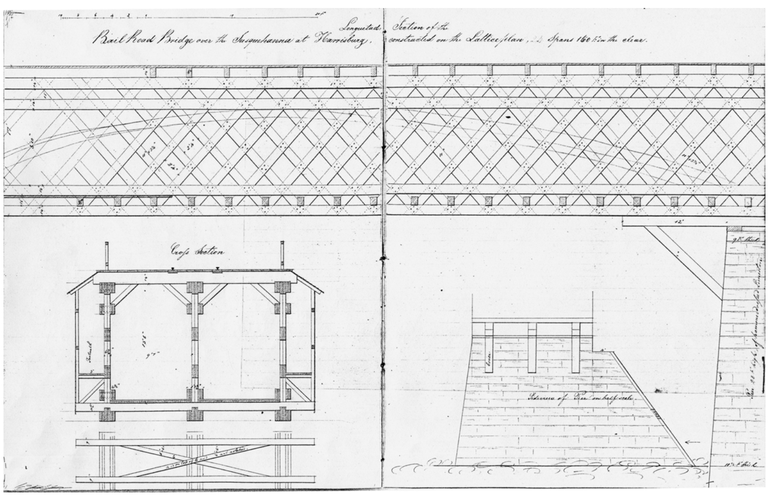

Figure 6. Longitudinal Section of the Railroad Bridges over the Susquehanna at Harrisburg produced by Roebling in 1840 (RPI B17a #148 Tables of Excavation).

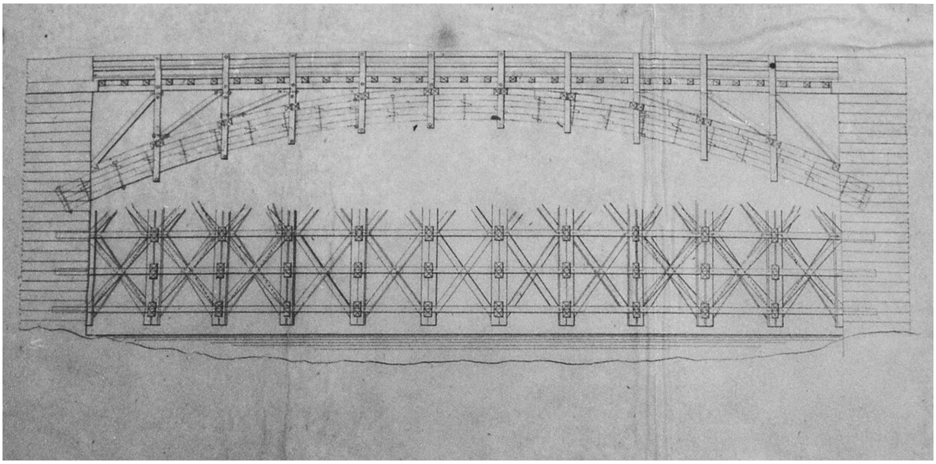

Figure 7. Wooden arch bridge drawn by Röbling in 1825. Prof. Dietlein used this type of construction as an example in his lessons. A similar bridge was built near Halle over the river Saale (RUT Bound, JAR Stud. Noteb. #1).

In Rabe's lectures on construction theory the subject of connections in wooden constructions was given a prominent role (RPI B17a #147 Stud. Noteb.). Indeed, if one wishes to understand Roebling's later work on suspension bridges, it is important to take into consideration his earlier background in the field of wooden construction. This was a Prussian specialty. Since there were no large supplies of stone in Prussian lands for use in bridges, there was a tendency toward "cheaper constructions" made of wood or toward using stone columns with a wooden superstructure to complete the extensive road construction plans of the 1820's.

Innovations that improved the possibilities of wooden construction in the 1830's and 1840's were the introduction of iron node castings and wrought iron threaded rods. The idea of pre-stressing wooden trusses was patented by Long in 1830 and 1839. The principle was to drive wedges into the material, thus pre-stressing the verticals or the diagonals of a truss. In 1840 Howe got his patent for pre-stressing the truss work by replacing the wooden posts with wrought iron rods. So in the years around 1840 the idea of stiffening wooden construction in this way was applied to railway bridges more often.

It is interesting to note how Roebling added European construction techniques in this context. He had already been familiar with the idea of precompressing the diagonals of a truss by replacing the posts with wrought iron rods; he had learnt this from Berg's book (Berg 1824), who discussed the deck stiffening truss used in Seguin's suspension bridges broadly.

After a nine-year interruption, Roebling returned to the concept of suspension bridges in a notebook begun in 1840. Here he abruptly changes subject on pages 33-63, adding sketches of bridge constructions. First there is a column of a suspension bridge with a roller bearing, then a drawing of a Laves-Beam, followed by third drawing of a lens-shaped arch supported by wire cables. (**fig. 8**)

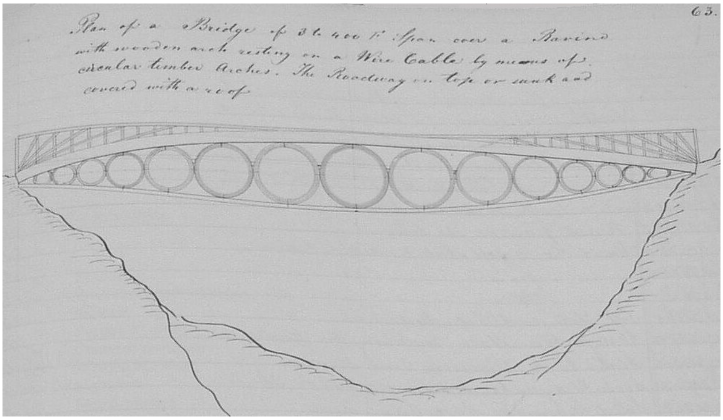

Figure 8. Inspired by a Laves – beam, Röbling drew a "Plan of a Bridge of 3 to 400 ft span with wooden arch resting on a wire cables" (1840) (RUT Bound, JAR Eng #1 "Railroad Surveys" pp. 33-63)

SUSPENSION BRIDGES

In 1839 the matter of suspension bridges became an issue in the USA. The occasion was the proposal to erect a wire cable bridge to replace Louis Wernwag's famous "Colossus-Bridge" over the Schuylkill River, which had burnt down. The proposal came from a young American engineer, Charles Ellet (1810-1862), who had studied for two years at the famous Ecole des ponts et chausées in Paris (Sayenga 2001, p.16), (Ellet 1839).

Roebling felt himself challenged. Up till now he had not been able to apply his German expertise and experience. But at once he saw the opportunity to prove himself in his field of proficiency. He wrote two letters to Ellet on January 28th (RUT, Bound, Transcr. Books #1) and February 24th 1840 offering his engineering services. He added the sketch of a construction proposal for a movable cable bearing using a pier saddle with series of small, cast iron cylinders that he had submitted to the Prussian construction office "about nine years ago". A colleague of his, so writes Roebling with assurance, had built a bridge with a 250 foot span (he is referring to the Bamberg Bridge) which had suffered tears because of the immovability of the main cables on the pylons. His own roller bearing would prevent this phenomenon (JAR 1840, letter to Ellet). With this formulation Roebling managed to avoid mentioning the fact that he had not yet actually built a suspension bridge. The drawing sent to Ellet is similar to the one in his earlier notebook, showing a wire cable on top (**fig. 9**)

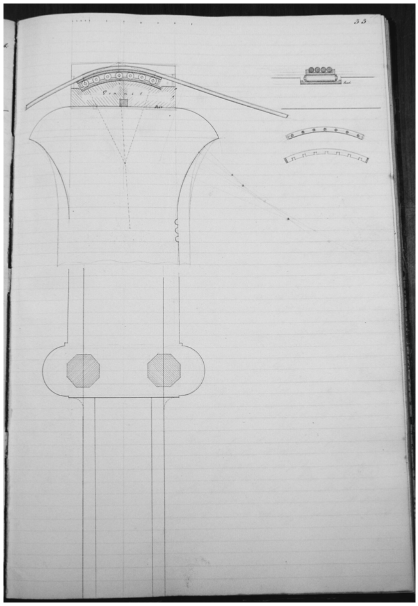

Figure 9. Construction proposal for a movable cable bearing. Roebling sent a similar drawing to Charles Ellet jr. on the 24th February 1840. Roebling wrote Ellet that he “submitted this construction to the Prussian Engineer Department about 9 years ago”. However, this is probably the first sketch of the drawing, 1840 (RUT Bound JAR Eng #1”Railroad Surveys”, p. 33).

Roebling wrote an article for the *American Railroad Journal* in the spring of 1841, in which he divulges his ideas on wire rope and wire cable bridges. He emphasizes that wire cables have a greater stability and flexibility than wrought iron chains. He also refers to the dynamic problems faced by suspension bridges. He notes that when winds of alternating intensity cause a bridge to move in resonating waves, “the effect that will then be produced cannot fail to be deconstructive”(JAR 1841, p.194). Wire cable has the advantage over wrought iron chains and rods because their flexibility reduces the danger of oscillation. At the very least the suspenders should be made of wire (JAR 1841, p.165) and “should always be suspended in inclined, or rather curved inclined planes…this cannot be done with chains. Herein consists one of the main superiorities of cables over chains” (JAR 1841, pp. 194, 195). This “give at once the floor a greater horizontal stability, especially at the middle of the bridge, where it is most needed” (JAR 1841, p. 195). If they are placed perpendicularly, they would get unequal load during oscillation.

And in order to compensate for horizontal forces, the main cables should be supported by towers instead of unconnected columns (JAR 1841, p. 195). The main cables should be composed primarily of two compact cables. This has greater stability than many thin cables during sheer winds. And finally, the weight of the cables themselves should enter into the calculation of the rigidity of the complete construction.

This early article of 1841 gives the impression of anticipating the later construction of his famous Niagara Bridges in the years 1854-1855. The major concern is the subject of wrapping wire cables, by means of which the wire cable is given a rod-like rigidity.

WIRE CABLE MANUFACTURE IN SAXONBURG

In 1841 Roebling almost succeeded in being the first person to construct a wire cable bridge in America, but Ellet was awarded the job in Philadelphia (Sayenga 2001, p. 25). As it turned out, the two men did not become colleagues, but rather bitter rivals. Still, the disappointment of Roebling's hopes was perhaps a great fortune. He now turned his complete attention to the manufacture of wire cables, which would prove to be of decisive assistance when he came to constructing suspension bridges. He was building on the experiences with iron wires in Westfalia 13 years previous. Back in 1828 he had already been thinking about using bundles of wire rope instead of iron rods as main chains (LAER, JAR "Entwurf"). In March of 1841 Roebling submitted a patent for a parallel wire cable that was wrapped with annealed wire thus forming a "round rope" (RUT Bound, Transcr. Books, letter to the commissioner of patents, March 27, 1841). The advantage of this design was the equal tension of all the wires. The "wrapping" patent was targeted toward suspension bridge construction, but Roebling also saw how it could be used to replace the hemp ropes being used on the "Portage Railroads", where ships were towed through the Allegheny's.

After finishing his survey work for the railway from Harrisburg to Pittsburgh in 1841, Roebling turned his attention to the production of wire rope. He gained the permission of the proprietor of a small subsidiary inclined plane in Johnstown to replace a hemp rope with a wire rope what was in fact a wire cable. The experiment failed: his wrapped parallel cable broke immediately.

Roebling had to take another approach. Instead of the parallel wires, bound together by wrapping, that were appropriate for suspension bridges, he needed to use twisted wire rope (RUT, WAR 1907, p. 81) that was fit for running and could be wound up on drums (JAR 1843 p. 321). Roebling made a second attempt to produce wire rope in 1842, similar to that used by Bergrat Albert in 1834 for hauling ore from the Harz Mountain mines. But Roebling did not know the production process and had to make numerous experiments.

The competence of his Saxonburg colleagues was of great help for this self-made production. Numerous highly-skilled craftsmen had settled in the colony during the 1830's. Especially Roebling's friend, Ferdinand Bähr, who ran a small wool factory in Saxonburg, played a key role in the development of the appropriate cable technology. (RUT, WAR 1907, p. 60-63). He ordered various kinds of wires from the wire makers Robert Townsend and Samuel Wickerham in Pittsburgh and experimented with them (Sayenga 2001, pp. 20-27). The first wires were not made with a rope machine, but rather by hand on the 500 yard long meadow behind Roebling's farm in Saxonburg. "The strand top was carried on a cross bar by two strong man who walked along, regulating their speed and the lay of the wire in the strand entirely by their eye. At the end of the meadow was a simple twisting machine, spurwheel, pinion and crank by which two men turned the twist into the strand." (RUT, WAR 1907, p. 82) A cable of 1 000 foot length could be produced by 20 persons working for one to two days. Before twisting the strands the wires were rubbed in linseed oil. The individual wires were joined along the length of the cable by splicing, causing for knots at certain points, which in turn led to problems with twisting the strands. Numerous experiments were made by the mechanics and metal workers and they developed special machines for the production. One great difficulty was moving the finished drums of cables. They were usually transported the 10 miles to Freeport by horse-drawn vehicles, where they were then loaded onto canal boats and sent east.

When these cables were set to use on the Portage Railroads, the entire equipment needed to be replaced. New cable drums were constructed, and the drive mechanism had to be changed. These alterations were also constructed by Roebling. But by the middle of the 1840's, Roebling had succeeded in turning his invention into a practical success in ship transport along the Delaware and Hudson. He then returned to the matter of suspension bridges.

AQUEDUCTS

Roebling's opportunity to apply his parallel wire cable to suspension bridge construction came in 1844, when an aqueduct of the Pennsylvania Canal was severely damaged by ice in the winter and needed to be removed. Roebling's proposal to use a trough-like structure not employing stone supports, but rather wire cables won the competition against 43 competitors. He had offered the most economical bid. His design consisted of seven spans, each of them 48.77 meters wide. The support cables were to be of 17 ½ cm. diameter with 1 900 wires of charcoal iron. The total volume of water in the half-filled troughs was around 2 000 tonnes (Heinzerling 1870, pp.179-180), (**fig. 10**).

With this canal construction, Roebling was able to offer a practical demonstration of the functionality of his wrapped parallel cables. This method would prove to be the leading principle of cable manufacture for large American bridges until the 20th century, as distinct from European procedures. Roebling's first bridge construction contained yet another innovation: anchoring the cables with cemented anchor-chains. Whereas Ellet's bridge in Philadelphia placed his wire cables at ground level, which led to irregular tension in the wires when they were attached to the pylons, the wires in the cables manufactured by the aerial spinning process were only acted on by the force of their own weight, which was the same for all of the wires.

A decisive factor for Roebling's suspension bridge was once again the experience gained by the Saxonburg workers in working on wire cables since 1841. The bridge construction, which was in part completed during wintry conditions, faced numerous difficulties and caused the death of seven workers. In fact, Washington A. Roebling regarded this aqueduct project to be a greater accomplishment than the later, more famous Niagara bridge (RUT WAR 1907, p. 92). In the period up to 1850 four more cable aqueducts were built for the Delaware and Hudson Canal Company over the following rivers: the Redout (1850), the Neversink (1850), the Lackawaxen (1849) and the Delaware near Lackawaxen (1848). The latter bridge was later rebuilt as a roadway bridge and is still in use today (Vogel 1971)

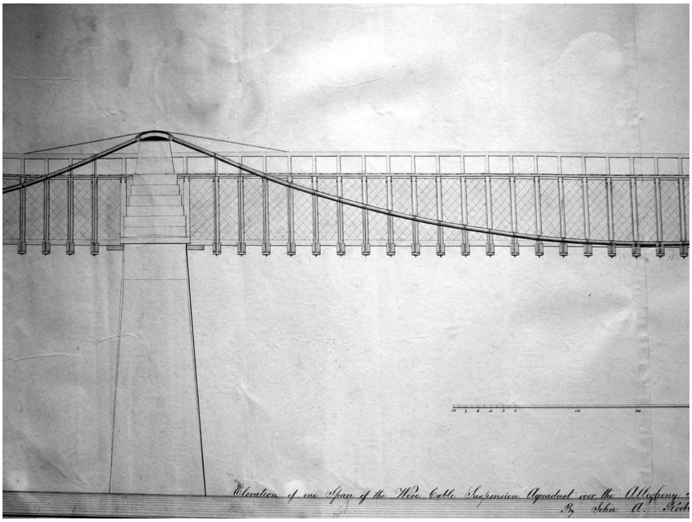

Figure 10. Allgheny River Aqueduct (Pittsburgh); Roebling's first suspension construction, 1845 (RPI D4, F1 Allgh. River).

ROAD AND RAILROAD BRIDGES

Roebling executed his first road bridge in Pittsburgh in the years 1845-1846 after the old city bridge over the Monongahela River was largely destroyed by fire. Using the seven pillars of the old bridge that were still standing and the two abutments a new wire cable bridge was built. Just as in the canal aqueduct, Roebling again used the technique of aerial spinning process and produced a cable of 11 centimetre diameter from a continuous wire that was pulled back and forth by a wheel. Just as in his canal aqueduct the suspenders at their lowest points were closer to one another than between the towers, which were inclined toward each other in order to attain the necessary rigidity. (**fig. 11**)

Roebling directed inclined cables from the same anchor points as used for the main cables to the roadway beams. In this way he applied the principle of an inclined stay bridge for the very first time, adding it to the suspension construction. In spite of numerous criticisms of inclined stay cable constructions, Roebling remained committed to this construction principle. Roebling applied this technique to his later constructions as well. His goal was to use inclined cables to make the carriageway as rigid as possible, so that without live load the structure would remain stable without the main cables. With his Niagara suspension bridge of 1855, half of the entire load was supported by inclined stay cables, the other half by the main cables (JAR 1855).

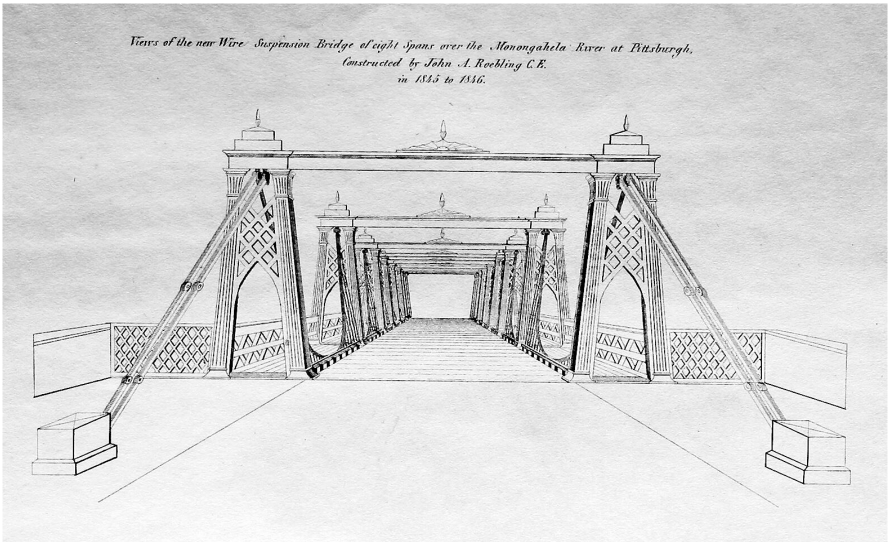

Figure 11. Monongahela Bridge in Pittsburgh built by Roebling in 1846 (RPI D4 F3 Monongahela Br.)

It is remarkable that Roebling began making specific plans for large bridge projects at a point in time when he was still largely occupied with the processes for manufacturing wire cable on the meadow ropeway behind his house in Saxonburg. Large-scale production of cable wire only began after he had moved to Trenton in 1849 (Zink 1992). Before that, beginning in 1846 he made concrete plans for a surprising number of large wide-spanned bridges, like those at Wheeling, Cincinnati and Niagara.

Interestingly, he also consistently maintained his construction principle for attaining stability by using rigid, wrapped main cables, inclined stays and wooden truss work. Although he must be then have known about the possibility of using wrought iron profiles, he stayed with wooden constructions in his basic plans up until his designs for the Brooklyn Bridge. In fact, the load capacity of wood in relation to its own mass is comparable to that of iron. The great disadvantage of his preferred method, namely the minimal rigidity of the connecting joints, was balanced out by internal pretensioning of the truss and external employment of stay cables. Today we are surprised at how often the need for "stiffening" the construction was addressed by Roebling, but that is because we are use to thinking in terms of "iron". This reinforcement would have been more easily attained by means of rolled wrought iron sections rather than by using wooden construction. But at that time there were no real, economically feasible alternatives. The issue of stiffening had of course been considered by Roebling in earlier suspension bridge design; for example, in Westfalia in 1828. However, when Roebling turned his attention to larger railway bridges like the Niagara bridge, the span had now increased to 250 meters, requiring a completely different view of bridge construction.

Roebling's concern for the problem of large spans shows itself in his design for the Wheeling bridge over the Ohio River, where he planned a central pier. Charles Ellet had made a bold proposal for one long 308 meter span, and he was awarded the job. The bridge was finished in 1849 and had a roadway width of only 5.2 meters. It was at that time the longest suspension bridge in the world and became famous in Europe. Carl Culmann published a travel report on "The construction of iron bridges in England and America" in the *Allgemeine Bauzeitung* in 1852, claiming that this was the only construction that had exceeded his expectations (Culmann 1852 p.208, Bl. 485). He expresses the opinion of many engineers of that day: the bridge at Wheeling was the epitome of the field of engineering. But - as well known - it failed in a storm on the 17th May 1854.

For his first design for the Niagara bridge in 1847 Roebling thought of using a wooden trough to increase stability, similar to those used on his aqueduct bridges (**fig.12**).

But gradually he went over to the idea of using a wooden truss frame of a narrow but high cross-section. And, aware of the susceptibility of the Wheeling bridge to wind load, he stiffed it with additional stay cables.

The disadvantage of pre-stressed wooden constructions like the Howe or Pratt truss is the contrast between the regular lateral stiffness of the wrought iron threaded rod and the shrinkage of the wooden braces or posts. Transport loads on railways gradually increased over the years and this phenomena led to frequent repairs being made to the support structure, and eventually led to the need to replace the truss of the Niagara Bridge in 1879.

The combination of wood and iron gradually lost its significance during the 1860's because of the introduction of new means of producing iron. In his last projects Roebling sought to apply these new possibilities. His project for the Mississippi combines arches and girders (**fig. 13**), a technique that he also recommended for bridging the English Channel (**fig. 14**)

The problem was that all-iron bridges were very stiff structures and often statically indeterminate. Additionally, with the secondary stress caused by the riveted connections, the structural analysis of the various forces became even more complicated. A second issue is that of the very great deflections of long-span bridges, especially suspension bridges, which led in 1880 to the introduction of the so-called second-order theory (Melan 1906, p. 39).

Roebling was unaware of this problems; it was the next generation of engineers who tried to apply advanced theory at the turn to the 20th century.

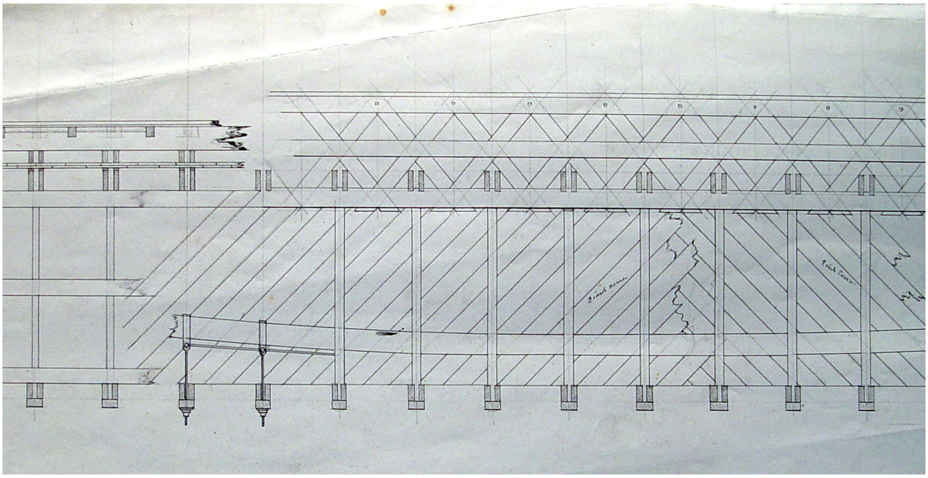

Figure 12. One of the first Roebling designs for the Niagara bridge (1847) (RPI D04 F05)

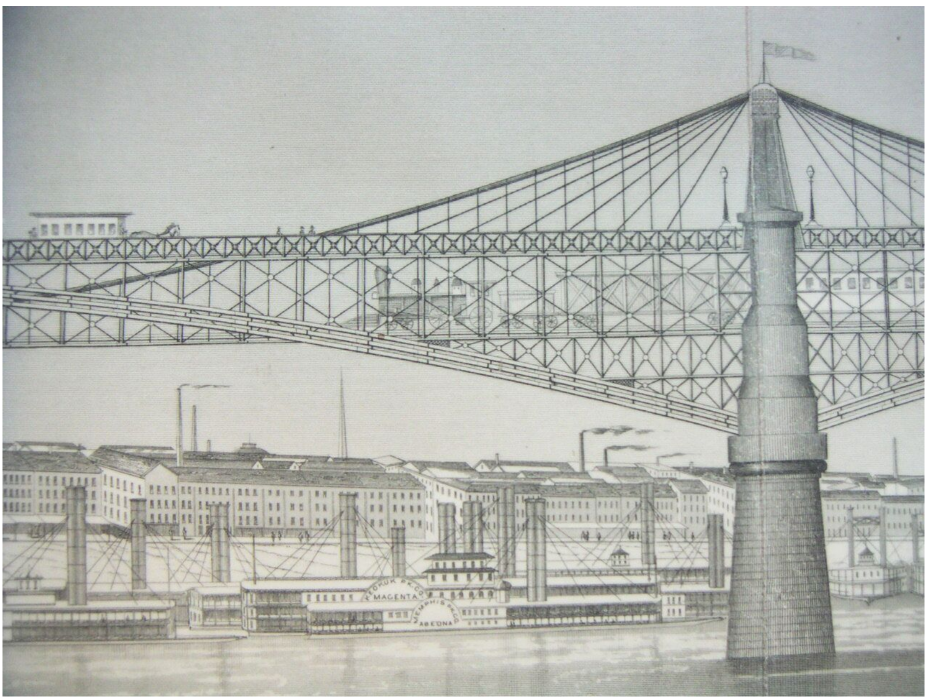

Figure 13. Detail of Roebling's proposal for a Bridge at St. Louis (JAR 1869)

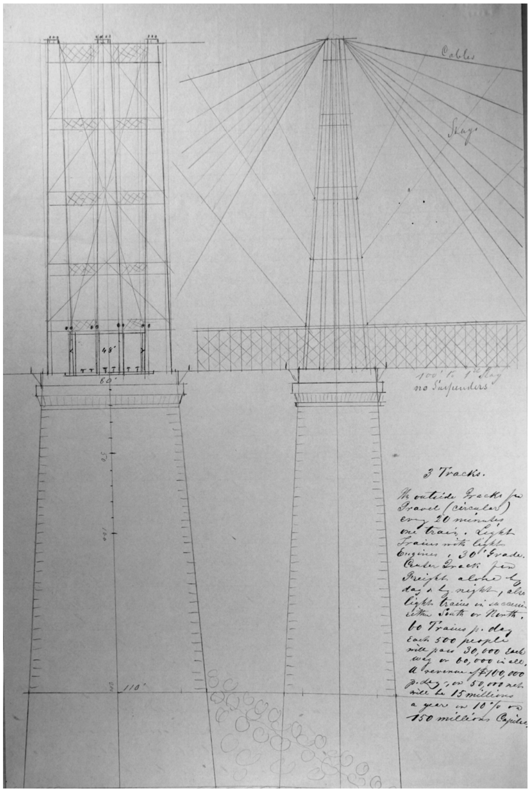

Figure 14. Detail of an all-iron bridge to span the English Channel. 1861 or 1868
(RUT B6 F15 Bridge across Eng. Ch.)

THEORY

It is worth considering the question as to how Roebling made such daring constructions as the Niagara and Cincinnati bridges. What methods did he use? What calculations did he make? Roebling was certainly not a theoretician, although he had no problems mastering the mathematics of his day. However, his training at the Berlin Bauakademie was limited to the application of Navier's suspension bridge theory, some Dietlein essays in statics and a good training in differential and integral analysis by Grüson (RUT Bound, Stud. Book # 4 "Höhere Analysis"). Only with the development of linear, elastic wrought iron did engineers have a material that was "amenable" to their calculations, and with its introduction progress was made in construction theory. But in praxis wood, stone and cast iron were essential materials for bridge building until 1850. Roebling was primarily a businessman and practical success was decisive for his constructions. If he had been a professor at a technical college, his ambition might well have driven him to spend more time working on mathematical analysis.

But Roebling calculated forces by a simply additive ordering of loads on hangers, stays and the truss-stiffened roadway. Adjusting the load capacity of the individual supporting elements was successfully achieved by modifying the tensions by means of clamp bolts and turnbuckles on the construction site. The difficulties caused by "modifying" the construction are described by Washington A. Roebling by reference to the example of the completion of the Cincinnati Bridge. In a tone of near desperation he tells how the balancing of forces in the stays and suspenders was only approximately attainable. (Gastright, F.J. 2000, p.7). Roebling calculated various load combinations only for single cases – a special theory using lines of influence had not been employed by him. Also the graphostatic methods that became common in the 1860's were only used sporadically by Roebling (**fig.15**).

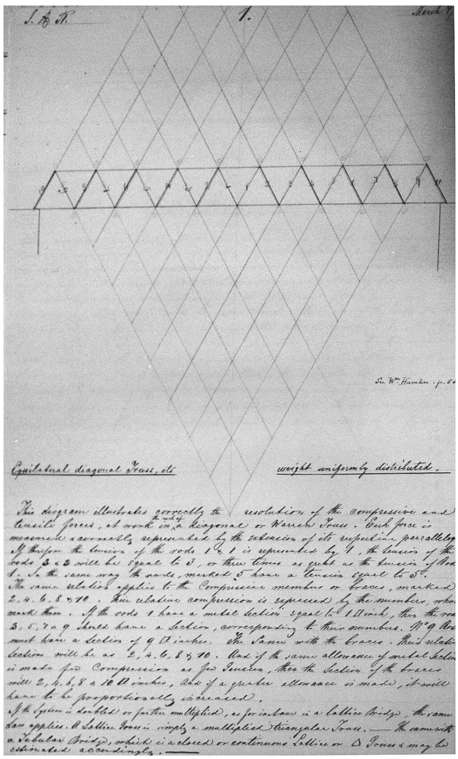

Figure 15. Graphostatic calculations made by Roebling in connection with his proposal for the Mississippi bridge at St. Louis (RPI D5 F20 JAR, St. Louis Bridge, Notes, Designs, Sketches (1868)

There is no evidence that he made any significant contribution to the theory of trusses such as that done by Whipple, Culmann, Gerber and others. Roebling's special talent lay in the precision of his thought, and his practical frame of mind. This is not only true in bridge building, but also in his numerous inventions in the field of wire cable production. Right up to his last design – that of the Brooklyn Bridge - Roebling's attention to detail is extraordinarily precise. He produced the majority of the sketch designs for the bridge himself and this was done with great accuracy. This imaginative approach and understanding of construction were the sources of his success. In this respect he resembles the builders of the Renaissance more than modern engineers.

That Roebling was capable of theoretical understanding is shown by his other activities in the field of natural sciences, where he produced large numbers of unpublished manuscripts. In the matter of discovering new materials there is an overlap between natural science and experimental investigation. His reflections on the structure of materials and the forces of attraction and repulsion led him to some remarkable insights and hypothetical speculations. The results of his experiments on iron also play a role in these ponderings. By 1840 Roebling was already aware of linear elastic limitation of iron (that this was equal to half its absolute strength). However, his explanation for this – a view based on a Hegelian world spirit flowing through the universe and affecting the material world – was not shared by many engineers and natural scientists, either then or now (RUT B4 F10-47 "Truth of Nature"). In this respect Roebling was a man of his age: an age in which the search for a holistic explanation of scientific phenomena was of general human interest and had not yet been separated from the practical striving to develop a modern technical civilisation.

ABBREVIATIONS

WAR Washington August Roebling
JAR Johann August Röbling or John Augustus Roebling

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