Different Manners of Constructing in Different Contexts: Roebling's Niagara Bridge and Gerber's Cantilever Beam

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ABSTRACT: The comparison of both Roebling's as well as Gerber's construction techniques is supposed to shed light on the different work processes and communication structures of both engineers. Gerber was highly respected as the "Master of German Iron Bridge Construction". He was the founder of a method of working that was summed up by the term "Gustavsburg School." Its impact is still important today. Roebling, who was much more successful in economic terms, was at least as gifted an engineer as Gerber. He did not leave behind a certain school, but he was unique in a specific sense. This concerns his method of working as well as the structures he created. The selective comparison of both engineers' methods shows the different contexts in which both Roebling and Gerber worked.

JOHANN AUGUST ROEBLING (1806-1869)

The design of the Brooklyn Bridge is widely recognised as Roebling's most important achievement. He was trained in Germany. Coming from a family of tobacconists, Roebling completed the practically oriented School of Mathematics of Salomon Unger in Erfurt and subsequently attended the Academy of Architecture of Berlin, which had just been reformed by Eytelwein. For the 1820's, this was a very modern education in engineering.

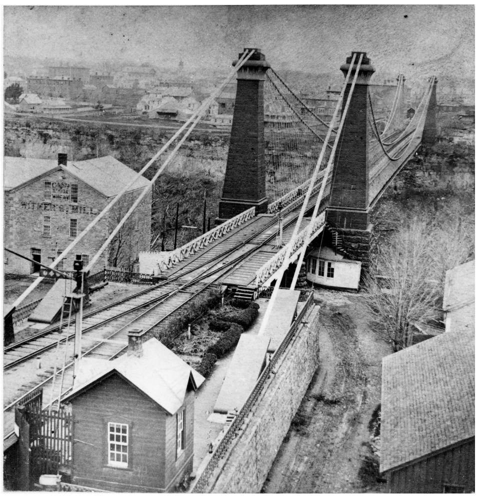
In the first years of his career, Roebling designed his first suspension bridges for the Prussian Department of Construction as well as for the businessman Harkort. However, these were never constructed.

After his emigration to the USA in 1831, Roebling was involved in the founding of a settlement. From 1836 on, he worked in canal construction and was soon involved in the planning of new railroads. Around 1840 he tried to copy and improve the wire rope, which had just been invented in Europe. After first successes in the wire rope business in connection with inclined plane cable cars that were used for canal boats, Roebling finally had the chance to construct a suspension bridge; in particular, a canal aqueduct in Pittsburgh. By the end of the 1840's, he had already built several aqueduct bridges suspended on iron cables, as well as a suspension bridge for road traffic. The Niagara Bridge, completed in 1855, had a span of 250 meters. With this structure, Roebling reached five times his initial spans, thus entering a completely new dimension in the construction of bridges: it was the world's first suspension bridge for railway traffic.

JOHANN GOTTFRIED HEINRICH GERBER (1832 – 1912)

From 1844, Heinrich Gerber attended the trade school in Hof, where his father was a drawing teacher. In 1847, he went to the Polytechnic School of Nürnberg, a school with a special emphasis on the metal trade. From its director, the physicist Georg Simon Ohm, Gerber received a distinction for his educational achievements. After completing two courses Gerber transferred to the Polytechnic School of Munich, becoming an assistant to one of its most famous teachers, Carl Max von Bauernfeind (1818-1894). Gerber helped him with his Album of Bridge Construction („Vorlegeblättern zur Brückenbaukunde"), which appeared in 1854.

In 1854 he started working for the Royal Bavarian Railroad Administration. According to the plans of Friedrich August von Pauli, Gerber and the mechanical engineer Ludwig Werder built the railway bridge in Großhesselohe in 1857.
In August 1859 he took over the supervision of the bridge construction facilities of the metal construction company Kramer and Klett. Its first large contract was the construction of the bridge across the Rhine River close to Mainz. The temporary institution became a permanent construction company for bridges. In the beginning of the 1880's however, large contracts significantly decreased; in 1885 Gerber retired from his business activities.
The most important student of Gerber, Anton Rieppel who had hitherto supervised the shop of Kramer and Klett then took over the company (Hilz 1992) and continued to lead it very successfully.
The most famous achievement of Heinrich Gerber is a beam with free movable supports „Balkenträger mit freiliegenden Stützpunkten", also called Gerber Beam or Cantilever Beam. It was patented in 1866.



Figures 1(left): Niagara Bridge after 1855; (Smithonian Institution Washington). Figure 2 (right): Gerber on the Bridge in Großhesselohe in 1909 more than fifty years after construction; (MAN Gerber 121. 7)

RAILWAY BRIDGES – A COMPARISON

Until about 1850 it was not yet clear, into which direction the construction of large railway bridges would go. In the USA, the many wooden Howe trusses with cast iron links and pre-tensioned posts were regarded as the most convenient form of construction. Bauernfeind even places them on the title page of his album of bridge construction. The wrought iron tubular bridges that had just been completed by Stephenson were sensational. They were still widely discussed, but for continental Europe and also for the USA, the material costs were simply too high. Just as initially Stephenson's Britannia Bridge, two bridges across the Rhine River in Cologne and across the Weichsel River near Dirschau were at first planned to be realised as suspension bridges. The latter were both planned or in the process of being constructed in 1851.
The idea of using a wrought iron tube truss or alternatively a wrought iron lattice truss as a superstructure makes more buttresses necessary, but on the other hand it enables whole trains including the locomotive to cross the bridge. One could see wrought iron lattice trusses as a kind of less expensive response to the successful advent of Stephenson's tubular bridge.
In the same year of 1851 Culman and others firmly believe, after having thoroughly analysed the American wood constructions, that the determination of the forces involved is possible for statically simpler systems with turnable joints. However, this also means that the possibilities of the construction are limited, as they have to be designed as statically determinate systems. Gerber followed these basic ideas, since he had gained knowledge about the problematic appearance of secondary tension, for instance, in 1854 when the upper chords of the Günzburg Bridge moved sideways (Schleicher 1932, p. 15 and Mehrtens 1908, p. 558). Roebling with his Niagara Suspension Bridge, on the other hand, favoured a highly statically indeterminate system and controlled the action of the forces by experiments on the construction site: the truss he used was not supposed to contribute to the main load capacity, but instead the work load was to be distributed among the largest number of hangers possible.

ROEBLINGS NIAGARA BRIDGE 1852 TO 1855

The guiding principle of Roebling's design was to combine two superposed suspension bridges in one structure. Initially, these were constructed independently of one another, while both hung from two main cables each. The lower corridor, hanging from the lower pair of cables was for pedestrians and wagons. It was opened as early as June 1854. The upper suspension bridge was completed by January 1855, to carry railroad trains. On this level, there were two longitudinal strong beams that supported the railroad tracks.

On Feb. 14th, 1855 the upper and lower levels were connected by lattices. Additionally, stays were attached to the upper and lower deck. Thus the bridge was a structure hanging from four cables which was stiffened by a wooden lattice truss reinforced with diagonal iron tension rods.

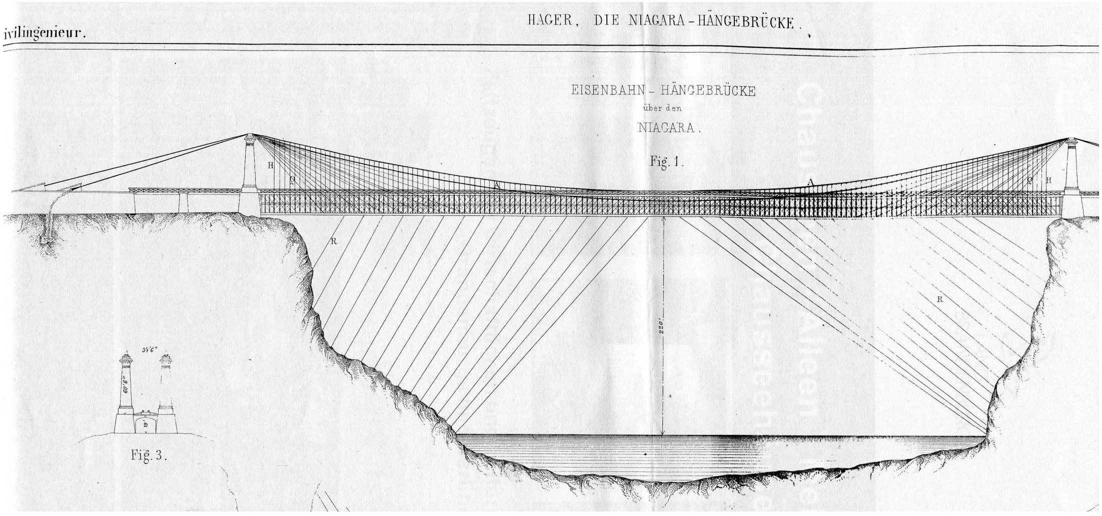


Figure 3: Roeblings Niagara Bridge; (Hager, *Civilingenieur N.F.* Vol. IV (1858) Taf. 4). In 1855 Roebling's Niagara Bridge report was published (Roebling 1855), and reedited with drawings a year later in London (Roebling 1856). The drawings of Hager (1858) however, are more reliable.

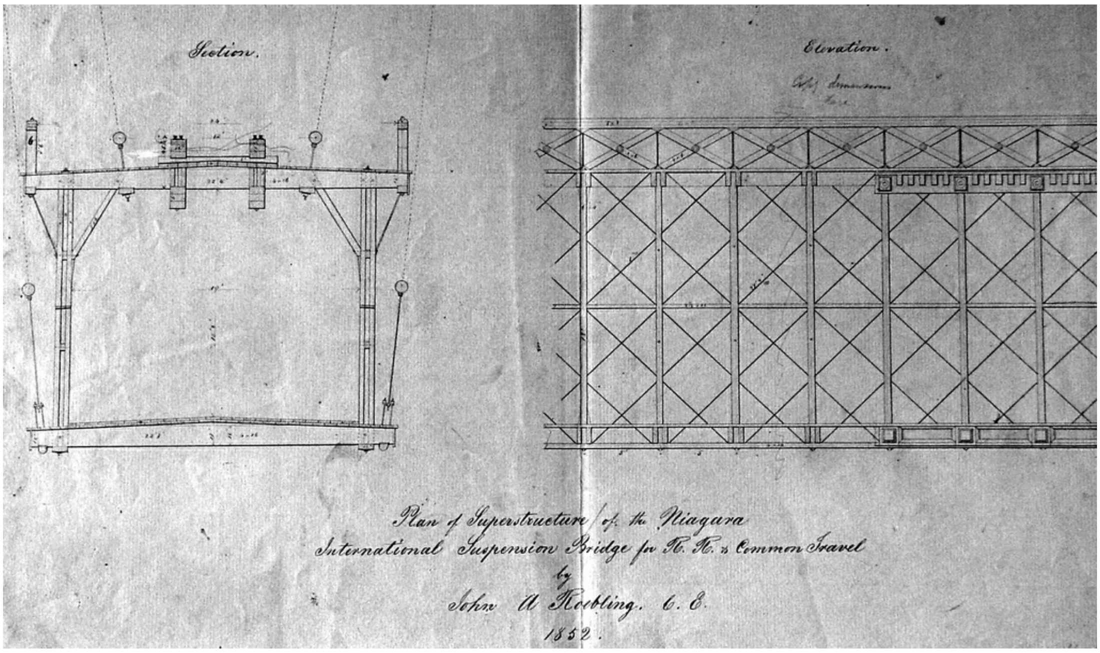


Figure 4: The most important elements of the lattice truss were tension rods spanning across an area of eight arrays of a length of five feet each. The influence of a potential concentrated force was thereby distributed along a length of 40 feet. Drawing by Roebling; (RPI Archives D4 F7)

Roebling's surprising solution instantly became famous worldwide. In Europe, the tempting idea of constructing a suspension bridge for railroads had been discussed, but after the success of the first wrought iron tubular bridges and lattice girders this concept was abandoned (Klein 1860).

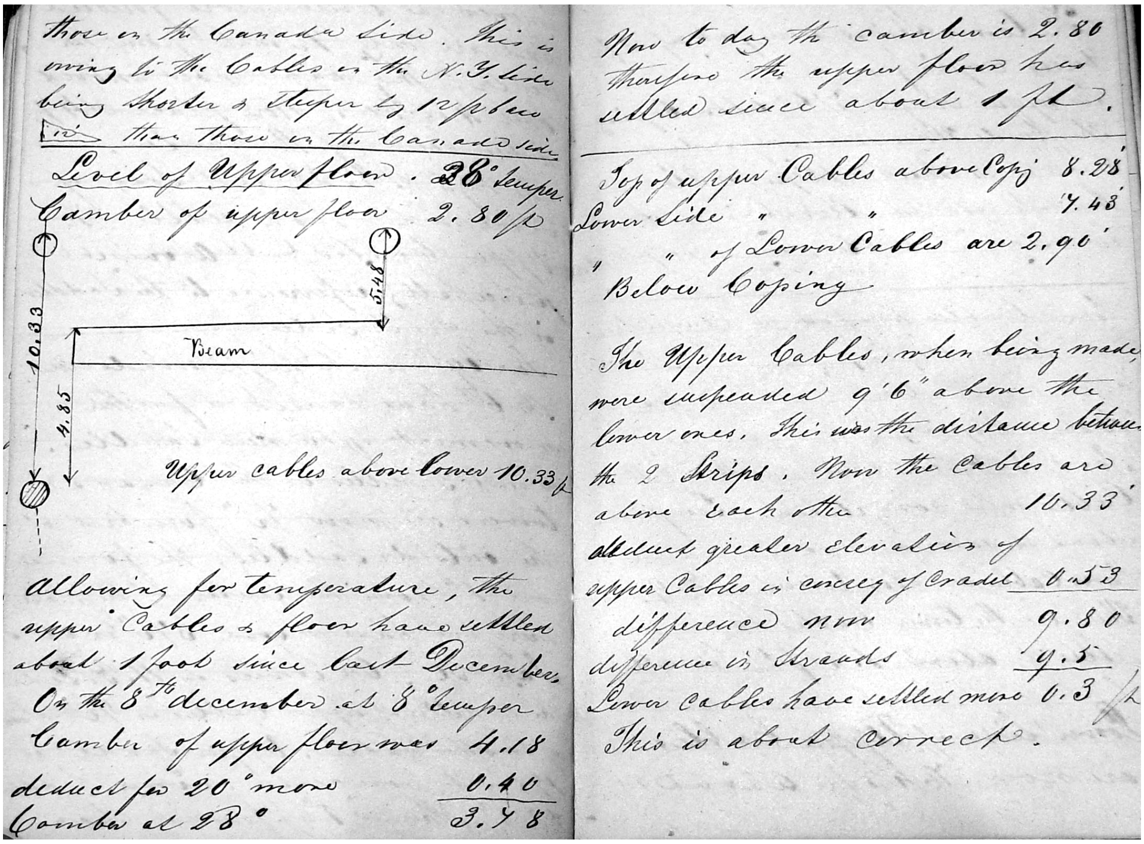
At the time, Roebling's design did not fit into the picture of an increasingly scientific debate that favoured the terms "trusswork" and "continuous beam". Even the mere question of which load capacity a trusswork of 250 meters should have in relation to the main cables was basically not to be solved analytically. Roebling's system was statically highly indeterminate.

In his „Final Report", first printed in 1855, Roebling explained his design and the load carrying effect of the bridge. However, he barely mentioned any facts about the construction process, measurements, and constructive details which were crucial to the interaction of the inclined stays, hangers and trusses.

One important detail should serve as an example for his approach: the connection of both the higher and lower passageways to one single truss. When looking at his notes, it becomes clear that this step had been very carefully planned.

CONNECTING BOTH FLOORS

For Roebling it was very important to determine up to which deflection of the main cables a permanent settlement occurred and starting from which point the cables were elastic. It was not before the cables started reacting reversibly, when both systems could be connected by a common truss. That was the point at which it was guaranteed that all four cables began carrying the same load.
To achieve this, Roebling decided to pre-stretch the upper cable pair by a heavy load.
On Dec. 12th and Dec. 25th, 1854 a total of 150 tons of stones were layered on the upper floor. In the beginning of January 1855 the displacement of the bearing seats was measured. On Jan. 20th, 1855 he wrote in his notebook:


those on the Canada Side. This is
owing to the Cables on the N.Y. Side
being shorter & steeper by 12 ft bec
than those on the Canada side
Level of Upper floor . 28° temper
Camber of upper floor 2.80 ft

allowing for temperature, the
upper Cables & floor have settled
about 1 foot since last December
On the 8th december at 8° temper
Camber of upper floor was 4.18
deduct for 20° more 0.40
Camber at 28° 3.78

Now to day the camber is 2.80
therefore the upper floor has
settled since about 1 ft.
Top of upper Cables above Coping 8.28
Lower Side " " 7.43
" of Lower Cables are 2.90
Below Coping
The Upper Cables, when being made
were suspended 9'6" above the
lower ones. This was the distance between
the 2 Strips. Now the Cables are
above each other 10.33
deduct greater elevation of
upper Cables in carriage of Cradel 0.53
difference now 9.80
difference in Strands 9.5
Lower Cables have settled more 0.3 ft
This is about correct.

Figure 5: Settling of lower cables; (RPI, Niagara Bridge Cables, Box 16 # 113);

Here, Roebling determined the deflection of the main cables by looking at the change of height of the upper deck, which is suspended from them. To obtain the amount of elastic deflection due to the additional weight, he had to deduct the difference in length of the length of the main cables due to the temperature difference between 28° and 8 ° Fahrenheit.
By measuring from the upper edge of the coping, he determined the position of the upper to the lower cable pair and found out the difference of the deflection. On the following pages he continued these comparisons and calculated that the settling of the lower cable was approximately 1,4 feet since construction began, so that he would not have to expect an overall settling of the cables of more than 1,5 feet.
Roebling carried out the adjustment and temporary connection of both levels on the 20th of January 1855. Roebling adjusted the length of the suspenders by using stirrups and connected the cross beams of the passage deck with the posts of the truss by means of wedges [cleets].
He calculated the weight of the upper floor at 524 tons. After removing the extra load of 160 tons of stones the upper floor weighed 364 tons. The lower floor weighed 272 tons; therefore, the upper pair of cables had to carry 90 tons more. Nonetheless, Roebling wanted to fixate the connecting truss structure in this state. As a reason for this, he wrote:

> … the upper cables will then be taxed with 90 tons more than the lower. But this will have the effect of an increased tension, and a lower position of the upper cables, which no doubt they would reach, if left alone another 2 or 3 months. The sett[l]ing of the Cables requires time. (RPI Box 16 #113, p 40)

According to his previous measurements, Roebling could assume that the upper cable pair would settle in the following weeks just so that finally, all cables would have the same tension.
On Feb. 14th, the wedges [cleets] were added and both floors together with the truss structure were then fixated to form one structure.

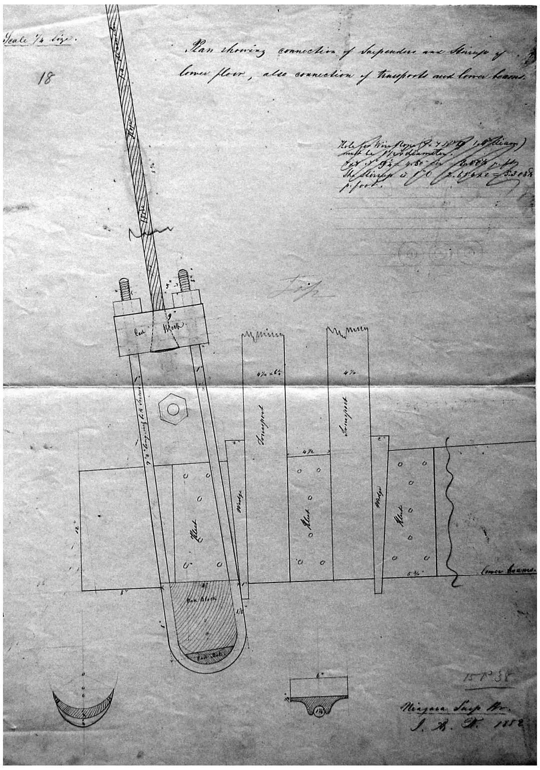


Figure 6: J. A. Roebling: Connection of suspenders, 10. Sep. 1852; (RPI, D4 F7)

THE EFFECTS OF THE TRUSS

At the turn of the year 1853 to 1854, before starting to spin the cables, Roebling calculated the deflection of the upper level of a 30 ton locomotive in the middle of the bridge, "without reference to stiffness of floor", as he wrote. Roebling assumed that the structure itself weighed 800 tons and that there was a cable sag of 54 feet. Then he added 30 tons of weight. The comparison of both parallelograms of forces resulted in a deflection of approximately one foot. „Considering the stiffness of the structure & the action of the stays, this depression will be gradual and uniform and not exceed 6 inch " Roebling wrote (RPI Box 16 #113, p.20). The following drawing illustrates Roebling's considerations:

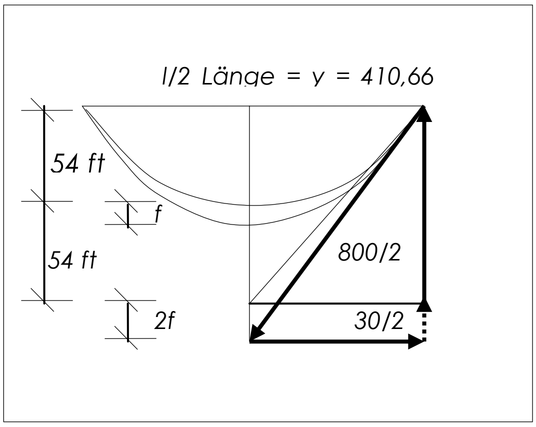


Figure 7: Roeblings approach; (Kahlow 2008)

After completing the bridge, Roebling could measure the real deflection. Roebling demonstrated the following example (Final Report 1855, p. 9): the effect of a local load of 47 tons in the middle of the bridge (a locomotive with a wagon), which, according to Roebling's calculation should lead to

$$f = \frac{59 \times 47}{2 \times 1000} \approx 1{,}386\ Feet \qquad (1)$$

assuming an average sag of the four cables of 59 feet and a weight of the bridge of 1000 tons. However, the measured deflection was only 0,45 feet. This demonstrates the distribution of load by the grid truss.

COMPUTER SIMULATION

Roebling's method when connecting both floors was to obtain an even distribution of load on all four cables by adjusting the length of the suspenders. It was difficult to simulate such a procedure with the used "Dlubal R-Stab" program, since the geometry of the bar structure is altered when assembled under load.
Therefore, for both floors, two beams of identical stiffness were substituted for the two decks and the grid truss; this system was analysed in a reduced two-dimensional case. With this method, the effect of the inclined stay cables could clearly be demonstrated. By doing so, Roebling's adjustment of the structure through the "screwing" of stirrups in order to evenly distribute load could be simulated.

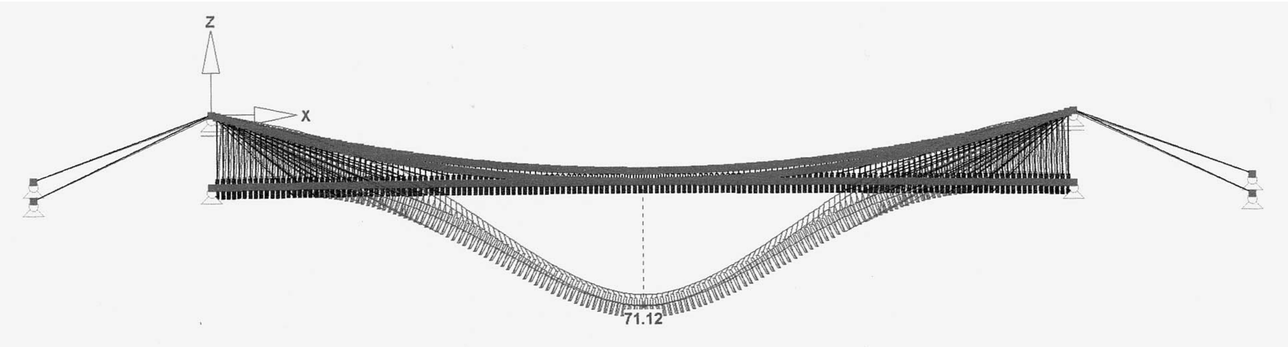


Figure 8: Computer simulation results for 47 t concentrated traffic load (Kahlow 2008)

For the mentioned case of a concentrated 47-ton weight in the middle of the bridge, Roebling calculated the deflection of 1.386 feet or 422mm (without the effect of the truss) and measured 0,45 feet or 137 mm (with the effect of the truss). The two-dimensional computer simulation results in a maximum sinking in of 71mm (with the above effect). However, the simulation does not consider the softness at the wood connection or other details of the connecting structure, due to a lack of information. The stiffening effect of the cables is clearly visible.

THE APPROACH OF HEINRICH GERBER - THE PAULI BEAM IN GROSSHESSELOHE

Starting in 1854 Gerber led the construction of the Großhesselohe Bridge. In the summer of 1855 he modified the design of the iron superstructure. The wagon and metal construction company Kramer-Klett was commissioned to carry out the contract. They had already built Bavaria's first iron bridge, the Günz Bridge, in 1853 (Mehrtens 1908, p. 558). The company had just recently started turning to the iron construction business in 1852, constructing the Schrannen Hall and the Glas Palast (1854) in Munich. Ludwig Werder, the technical director of the company, developed a machine for testing the strength of iron in 1852. It was one of the most powerful machines in Europe at this time and was largely responsible for Kramer-Klett's success in metal construction.
From the 5th to the 25th of January 1857 Gerber worked with Ludwig Werder and von Pauli daily, to coordinate the final design of the bridge. Gerber suggested a box-like structure of the pressure chord in order to achieve more stiffness. The assumptions for the calculation of the connecting struts of the bearing planes were set after lengthy debates. As early as this, Gerber introduced the principle of generally assuming the worst position of load, which he calculated by an iteration method. Since some construction elements such as the diagonal bars were pre-stretched at 1140 kg/cm^2 with Ludwig Werder's strength testing machine of 1852, material defects could practically be ruled out. In addition, Werder's machine enabled a mounting of the diagonal bars with a pre-stretched tension of 330 kg/cm^2. Slack diagonals would have had the disadvantage of greatly being deformed under compression (Schleicher 1932, pp. 8- 9). With this method, the stiffness of the girder was significantly increased. At the same time, secondary effects were avoided. These were mainly caused by the inflection of the upper chords.
Werder led the construction of the superstructure, for which Gerber had designed the centring, with the participation of Heinrich Gerber during the summer half-year of 1857. In September and October 1857 the load bearing capacity was thoroughly tested (MAN Gerber Lebenslauf, p.3).
In an 1859 advertising brochure of the Klett Company, Gerber summarised the experiences of bridge construction. Among other things, probably for the first time ever, the pamphlet undertook the attempt to mathematically calculate the lateral stiffness of pressure chords. The brochure of 1859 already included basic principles concerning the strength of joints with rivets and conical bolts, which had been experimentally ascertained. For example, experiments with riveted connections over a period of several years yielded exact results as to the relationship of shear and bearing stress, as well as to the permissible stress. The validity of $\tau_{zul.} = 0{,}8 * \sigma_{zul.}$ comes from these experiments.
The results were assimilated in 1922 by the regulations of the German Reich State Railway, the "Reichsbahn". Just as these, many other results of Gerber became part of the onset of the industry's engineering standards (Schleicher, 1932, pp.12-15).

THE GUSTAVSBURG BRIDGE CONSTRUCTION COMPANY

As Kramer-Klett accepted the contract for the construction of the Mainz Rhine Bridge in 1860, there was the need for setting up a manufacturing facility at the bridge construction site. As early as February 1860, Werder and Gerber agreed to set up the necessary facilities in direct proximity to the site. In April 1860 Gerber planned the buildings of the shops and their equipment. They were set up in Gustavsburg (close to Mainz) in the following seven months. Not only was the method of working in the company well organised, but also backed by a series of scientific experiments, which were developed on the basis of technical mechanics. Kramer-Klett as the principal shareholder decisively encouraged this science-oriented process:

> The Bridge Building Company Klett & Comp. gradually became important, in particular since its owner, Baron von Cramer-Klett, clung, as much as possible, to a scientifically founded set up and to a solid realisation of the iron structure as a starting point. (Gerber p. 4)

The experience of scientific experiments that was available at Kramer-Klett clearly influenced the work of the company. In particular, the knowledge about the permissible stress of structural elements leads to a calculation of the influence of impact. Their systematisation, for example for the determination of the permissible stress considering the impact effect of a concentrated traffic load, was the basis of new solutions in construction (Schleicher 1932, p. 17).

Gerber had the problem of staying in contact with the manufacturing facility in Gustavsburg close to Mainz and the various construction sites. Gerber's frequent change of residence underlines this: in 1858, he moved to Nürnberg, the headquarters of the company Kramer-Klett, in 1860 to Gustavsburg, in 1863 to Nürnberg again, in 1868 to Mainz and in 1871 to Munich.

The resulting communication problems due to the remoteness of Gustavsburg were considerable, but Gerber solved these by a well organised control of the work process. The facilities as well as the single construction sites had to hand in daily reports. Technical drawings, materials, construction elements, production processes and allocation were systematised and standardised. From 1857 on, he indiscriminately used the meter as a unit of measurement to the point of rather cancelling an order of beams from a rolling mill than converting the values to the more common foot and inch units of measurement. For the standardisation of profiles, which was about to come, this was a very important step. Gerber spent several hours daily reading and answering the company's internal mail. He insisted on an exact documentation all the way to the point of the laborious copying and administration of the files, which cost Gerber much effort. However, it made it possible for other people to be involved as well. Through his elaborate system of communication, Gerber multiplied the abilities of the participating individuals.

THE GERBER-CANTILEVER

The main idea of the Gerber cantilever, that is of adding a middle piece between two cantilever arms to bridge the gap, is, at least in its basic form, very old. Examples of wooden cantilever bridges can already be found in the middle ages. The introduction of links, too, is not Gerber's personal achievement.

At the time the Menai Bridge was built, for example, an experimental model of a continuous beam over three pillars was produced. Under a uniformly distributed load it formed a flexible line, which in a particular distance of the middle pillar had its turning point. The model was cut at these points and equipped with links. This new cantilever beam showed no change of the deformation line. Before Gerber, other engineers introduced cantilevers, too. For example W.H. Barlow in 1859 or August Ritter, inspired by Köpcke, treated cantilevers at the Polytechnic Institute of Hannover as early as 1861, but he fixed the beams to the pillars. In 1862 Mohr warned of a sinking in of pillars in connection with continuous beams (Mehrtens 1908, pp. 571-576).

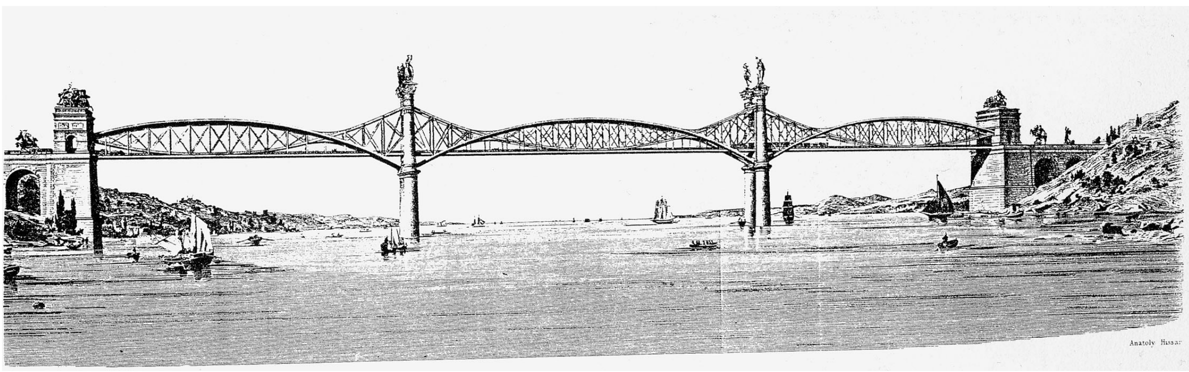


Figure 9: Ruppert's Project of the Bosporus-Bridge and Figure (Ruppert 1867)

A.J. Sedley handed in patents in England in 1861 and 1864 for the cantilever, which was back-anchored in the ground (Beyer 1908 p.116). The clear concept, that the hinges could be set at any point of the bridge and that the fixation of the cantilevers had to be realised in a more distant anchor point is Gerber's contribution. He was the first one to address this in his 1866 patent and he also constructed structures accordingly (Schleicher 1932 pp. 27-29).

Gerber himself says that Ruppert's design for a Bosporus Bridge of 1864 had inspired him to draft his cantilever bridge. Ruppert's construction was statically indeterminate and was supposed to take advantage of the framing effect of the fixation in the pillars. It was conceived as a continuous beam and followed the concept of Stephenson's Britannia Bridge. The applied line of the maximum bending moments was supposed to be determined by the iterative procedure of Schinz (Mehrtens 1908, p. 576).

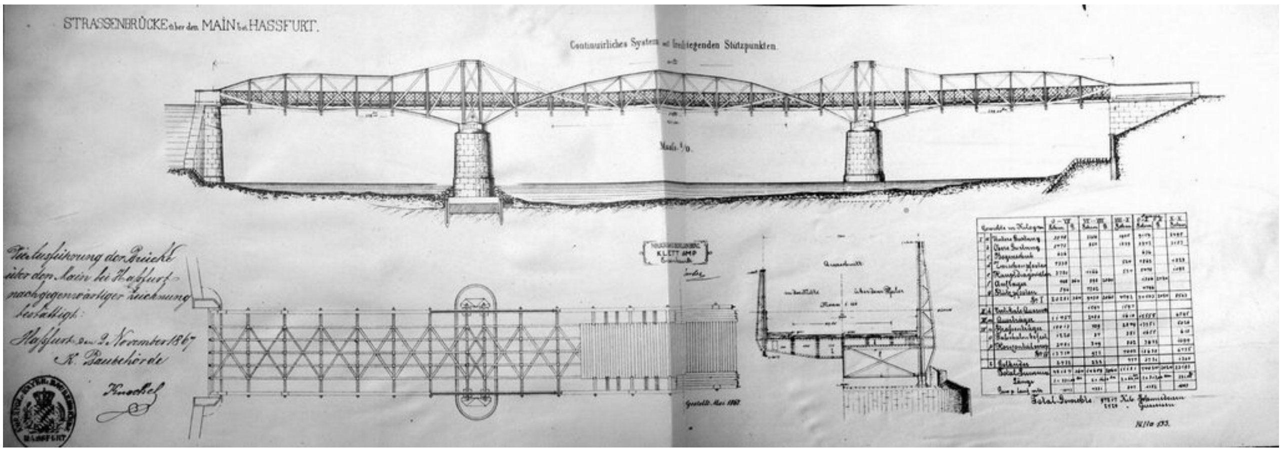


Figure 10: Haßfurth Bridge 1867, constructed according to Gerber's patent for cantilever-beams; (MAN 121.7)

Looking back at the later development of iron construction, the extreme attitude towards statically indeterminate constructions seems exaggerated. Due to inaccurate fabrication, the inflexibility of hinge connections which was commonly observed, or their gradual jamming often led to secondary stress in the structure. This secondary stress was barely less than for riveted structures. Therefore, the additional costs due to a more elaborate production were hardly justified. In addition, riveted structures are more stable in cases of extreme loads, a fact which gained increasing importance with raising traffic loads.

For Gerber as well as for other engineers, too, the preference of statically determinate constructions was based on the worry of uncontrollable secondary stress leading to a collapse of the structure. Gerber knew about early experiences with the deflection of chords of the first Pauli cantilever construction, the Günzburg Bridge. The constructive problem was often an insufficient consideration of the issue of buckling.

This means that the origins of Gerber's constructions in mechanical engineering together with his desire to have a clean and transparent construction in every detail represented a strong impetus in his approach.

GERBERS "HANDSCRIPT" OF 1885 TO 1911

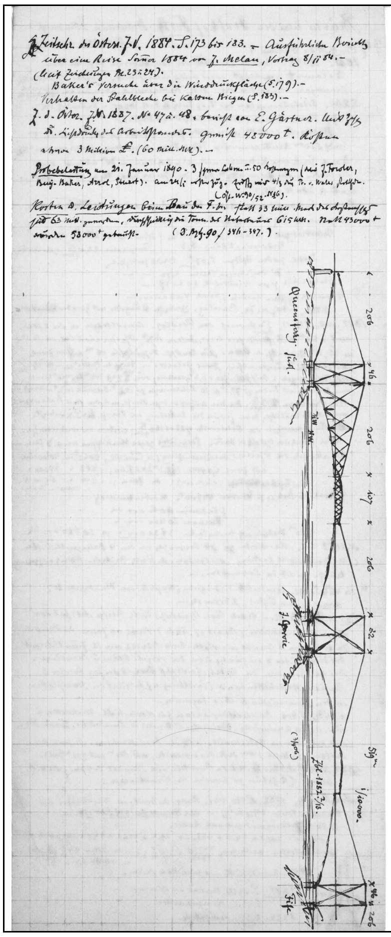
A few years ago, hitherto unknown notebooks and diaries of Gerber of the years 1850 and 1885 to 1911 were found. Among them is a "Handscript" which illustrates his systematic approach very well. All papers were recently made accessible and transferred to the MAN archives in Augsburg (Kurrer 2009, pp. 116-118).

After Gerber had retired from the leadership of the Gustavsburg Bridge Building Company, he began with a thorough evaluation of trade publications, starting a compendium of topics. For about 25 years annotated 41different topics concerning civil engineering: Gerber evaluated about 2200 articles of 25 German and English trade publications. Most of the short comments to each of these topics briefly describe the subject of the article or cite the title, name the author and point to the particular publication. In most cases, they do not contain more than one or two lines. However, Gerber attentively noted any debates that appeared between different experts. For a number of articles, Heinrich Gerber briefly summarised the content that was important for him.

In most cases, these short summaries are for the topics buckling, elasticity theory, testing methods, steel constructions and the production of steel structures. This category also contains sketches and short formulas. When looking at Gerber's private diary of the corresponding time periods, one finds a number of analogies. For example, after the collapse of the Swiss Birs Bridge on June 14th, 1891 Gerber spends weeks calculating the reasons for the collapse of the structure (Kahlow 2006, Gerber diary 1891).

The "Handscript" of Gerber can be seen as a chronological record of problems, debates and of processes of growing insight into steel construction. It clearly reflects the process and the development of the corresponding theories during that time period (1885 to 1911).

A page containing notes about reports on the Firth of Forth Bridge is illustrated as an example for the "Handscript". This bridge was built according to the Gerber cantilever at the end of the 19th century in Scotland.



Transcription:

Zeitschr. des Öster. I.V. 1884. S. 173 bis 183. – Ausführlicher Bericht über eine Reise Sommer 1884 von J. Melan, Vortrag 8/11 84 . –(mit Zeichnungen Bl. 23 u. 24.).
Baker`s Versuche über die Winddruckfläche (S. 179) . –
Verhalten der Stahlbleche bei kaltem Biegen (S. 183) . –
Z.d.Öster. I.V. 1887. N. 47 u. 48. bericht von E. Gärtner. Mit Z[ei]ch[nun[g].
ü. Luftdrücke, des Arbeitsstandes, Gewicht 48 000 t. Kosten
etwa 3 Millionen £ (60 Mill. Mk) . –
Probebelastung am 21. Januar 1890. 3 schwere Lokom u. 50 Kohlewagen (dabei J. Fowler,
Benj. Baker, Arrol, Stuart). am 24/1 erster Zug. Eröff[nun]g nur 4/3 der Pr. v. Wales […]
(Öst.W.90/52. Nr. 96)
Kosten u. Leistungen beim Bau der F.br. statt 33 Mill. Mk der Kstenaufst[ellun]g sind 63 Mill. geworden, durchschnittlich die Tonn[e] des Unterbaues 615 Mk. Statt 43 000 t wurden 58 000 t gekauft(D.Bztg. 90/341-347.)

Figure 11 (left) Gerber Handscript 1885-1911. Transkription p. 33-2; (Kahlow, A., 2006, Gerber Handscript 1885-1911)

SUMMARY

The construction of the Niagara Bridge shows that Roebling was not as much interested in acquiring scientific knowledge about bridge construction, but he rather wanted to prove the advantages and safety of his structure. It was virtually impossible for others to replicate his structures, since the art of connecting design and construction was closely linked to his person – the only exception was perhaps his son, who worked closely together with him (Roebling 2008). It was unrealistic to summarise this art in a set of rules, thereby rendering any form of reproduction impossible. This made his suspension bridges unique.
Roebling is attributed a certain ingenuity by D.B. Steinman and others in connection with the collapse of the Tacoma Narrows Suspension Bridge, since Roebling predicted the importance of the stiffness of the structure. Roebling's insights had been forgotten, as one can often read: Roebling had gathered these insights from experiences of the effects of tornadoes on bridges in the 1850's. It would surely be more adequate to say: Roebling's insights had no form that made it easy to pass this knowledge on to others.
In science but also in engineering the reproduction and stabilisation of knowledge in connection with its methods and procedures is crucial in order to pass it on. Whenever the reproduction of technical knowledge and the expertise of the realisation are bound to one single person, as was the case with Roebling, the "readability" is difficult for others due to a lack of knowledge transfer by the scientific community. In this case, sources of knowledge one can consult can only be, besides the person itself, the construction, descriptions, and personal notes. When knowledge can be reproduced in an expert community, it becomes explicit and obtains a scientific character.
At the same time, when Roebling with his wire rope company in Trenton was concerned about surviving the financial crisis, which began at the end of the 1850's in the USA, the young engineer Gerber grew into the field of experience of the Kramer-Klett Engineering Company. The company regularly obtained contracts of the Bavarian State. It is interesting to note which importance the scientific aspect now gained in Germany for the career of the engineers. An important indicator for this is the increase of Polytechnic Universities and the theoretical level of the trade publications, where debates of the time are reflected. Last but not least, this owes to the fact that a career in railway administration or in the Polytechnic Universities themselves was greatly dependant from the engineer's grade of scientific training, thereby fostering a development into this direction.
The density of technical communication was unequally higher for Gerber than it was for Roebling: In internal discussion groups, at first as a student in Munich, then with Pauli and Werder during the construction of the

Günzburg and Großhesselohe Bridge and later with Rieppel, Tetmajer and many others he intensely discussed issues and summarised his insights in company regulations as well as in technical publications. Gerber established a construction office and thanks to a good organisation of the technical documentation he could get all the participants to understand the background of the issues.

After retiring from the Gustavsburg Bridge Construction Company in 1885, Gerber stayed part of the scientific network, as his recently discovered diaries and his handscript show. His most important merit is the connection of material testing and the design of theoretical models with construction and standardisation in steel engineering (Klöppel 1960).

The discussion of the differences between Gerber's and Roebling's approach is not supposed to put the two into an antithetical opposition. Both, for example, share a similar basic understanding of the role of experiments. The portrayed difference in their approach lies, for the most part, in the preconditions under which their work of engineering took place. The interesting question of how to make the knowledge, which is objectified in the constructions readable, initiated a new perspective on technological knowledge under the aspect of the processes of their production and reproduction.

Historical research thereby serves the important objective of stating theories of lost knowledge, to reconstruct them and to guarantee an access to their heuristical function.

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