The Development of Cable-Stayed Bridges since John Röbling

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Summary

John Roebling was one of the most visionary bridge engineers of the 19th Century. He started the fabrication of bridge cables and pioneered the design of suspension bridges for which he initiated the use of stay cables to stiffen them. After WW2 the use of stay cables was re-discovered and the new type of cable-stayed bridges became very successful. The developments Roebling started 150 years ago are still in progress today.

Keywords: Suspension bridges, stay cables, cable-stayed bridges, bridge construction, bridge ropes, deflections, aerodynamics, parallel wire cables, parallel strand cables, concentrated tendons

1. Introduction

Fig. 1 *Johann August Roebling*

Johann August Roebling, Fig.1, was born in 1806 in Mühlhausen, Thuringia, not far away from Weimar. After primary school he went to a college in Erfurt where he received an excellent mathematical education. At the same time he learned to draw, both important skills for his future work. In 1824 he attended the Academy of Civil Engineering in Berlin. In addition to his formal education he studied Navier´s book on suspension bridges. After initial work for the state on various civil projects in Germany he emigrated in 1831 to the U.S., together with a group of friends. For the next six years he worked as a farmer in the newly founded village of Saxonburg. After receiving U.S. citizenship in 1837 he changed his name to John A. Roebling and started again to work as an engineer, initially as a surveyor. In this connection he came in touch with the design of canals and bridges. He experienced that the hemp ropes used to tow boats on rails up and down a steep hill in the run of canals frequently broke and on occasion caused fatal accidents, [1],[2].

2. Bridge Ropes

In 1841 Roebling developed the little information he had from Germany on the production of wire ropes into practical use in the U.S. and applied for a patent on wrapped parallel wire cable. When applying it to the ship tow he realized that for this purpose spun coil ropes are required which can be pulled around wheels at both ends of the slipway. He, therefore, developed the type of open coil rope shown in Fig. 2, together with the required machinery. Both types of ropes are still being used and are further developed until today.

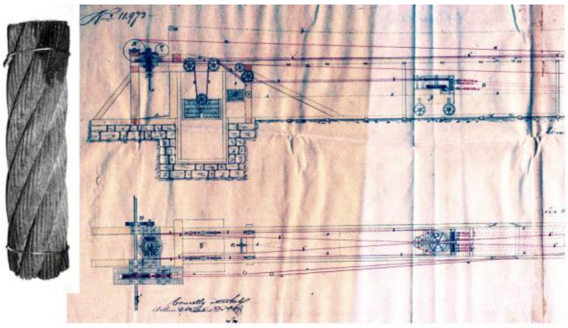


Fig.2 *Roebling´s Bridge Ropes*

Fig. 3 *Locked Coil Ropes*

Roebling´s coil ropes became the modern locked coil ropes of today with the corresponding modern machinery as shown in Fig. 3. They are used for hoisting machines as well as for bridges, especially in Germany.

While Roebling used spliced loops for the end anchorage of his cables, modern bridges require compact end anchorages. For the locked coil ropes anchor sleeves with hot metal fillings are used. The high temperature during casting causes a loss of fatigue strength of the individual wires and the complete rope. In addition, locked coil ropes tend to creep and have a lower stiffness than the individual wires. Due to these reasons Fritz Leonhardt initiated the development of parallel wire cables with HiAm (High Amplitude) anchorages, Fig. 4. The wires with a diameter of about 7 mm are clamped with steel balls inside the cone of the sleeves, and additionally anchored with button heads in an end bearing plate. Epoxy resin is used to keep the steel balls in place. These parallel wire cables have been used for stay cables since the 1960s all over the world.

For some bridges, e.g. Fig. 23, bundles of post-tensioning bars inside a thick steel pipe were used, the steel pipe carrying part of the fatigue loads in composite action with the bars and the cement grout. This did not prove successful.

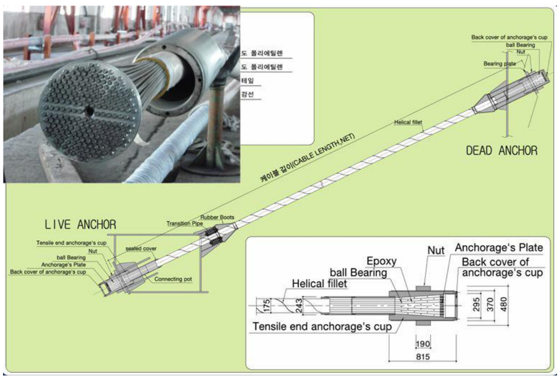


Fig.4 *Parallel Wire Cables with HiAm Anchorage*

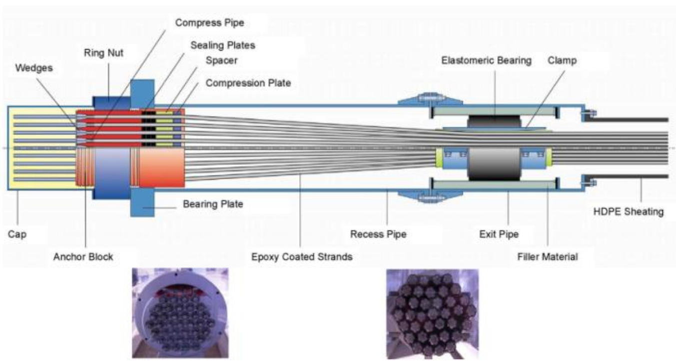
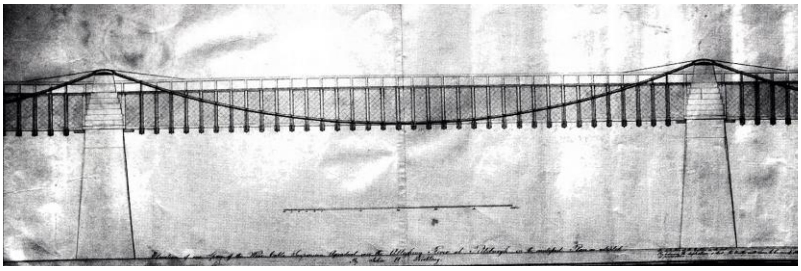


Fig.5 *Parallel Strand Cables with Wedge Anchorage*

If steel wires are drawn to even thinner diameters in the range of 5 mm their strength increases further. They are combined to seven wire strands up to 15 mm diameter and combined to parallel strand cables. They are usually anchored with steel wedges, Fig. 5. Initially these wedges caused an important loss of fatigue strength of the strands. Later improved shaping of their steel teeth reduced this disadvantage considerably.

While in Asia parallel wire cables fabricated e.g. in Japan and China, are in widespread use, the rest of the world today uses parallel strand cables. In Germany locked coil ropes are still used, but recently parallel strand cables have been introduced to the cable-stayed bridges across the Strelasund Bridge and the Rhine River at Wesel.

3. Canal Bridges



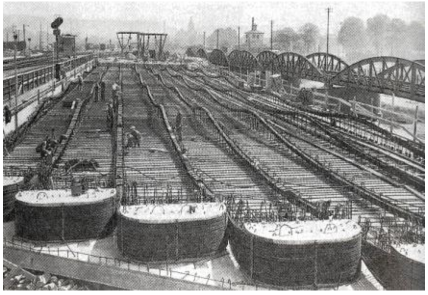


Fig.6 *Allegheny River Aquaeduct, Pittsburgh* Fig.7 *Concentrated Draped Tendons*

In 1844 Roebling was the successful bidder for the Pennsylvania Canal Bridge across the Allegheny River near Pittsburgh, Fig. 6. Roebling designed a seven span suspension bridge supported by parallel wire main cables with a diameter of 175 mm. With hindsight one can compare his canal bridge design with the concentrated post-tensioning tendons which Fritz Leonhardt introduced to prestressed concrete bridges in the early 1950s, Fig.7, [3]. Roebling´s basic idea became economically feasible nearly 100 years after his system of a true suspension bridge with heavy abutments for anchoring the tensile forces was replaced by a system which can be compared to a self anchored suspension bridges in which the tendons are anchored against the concrete beam itself and thus produce the desired compression force in the concrete, in addition to deviation forces, [1].

4. Suspension Bridges

Roebling had never given up his early intentions to design suspension bridges. After his canal bridges his first road bridge was built across the Monongahela River in 1845, a multi-span suspension bridge on existing foundations.

His breakthrough came with the Niagara Falls Bridge in 1851, Fig. 8. The main problem for this long-span railway bridge was the required stiffness of the bridge girder for the high railway loads. Roebling achieved the required stiffness in two ways: On one hand he used a stiff, about 6 m high timber truss for the beam and, in addition, he used stay cables. In this way the Niagara Falls Bridge with a record span of 251,5 m became usable for railroads. Until then the span record for railway bridges was held by the Britannia Bridge in Wales with a main span of 140 m.

The Allegheny River Bridge in Pittsburgh, Fig. 8, was completed in 1860for which Roebling used again the principle of combining suspension cables with stay cables. It was considered the most beautiful suspension bridge of its time.

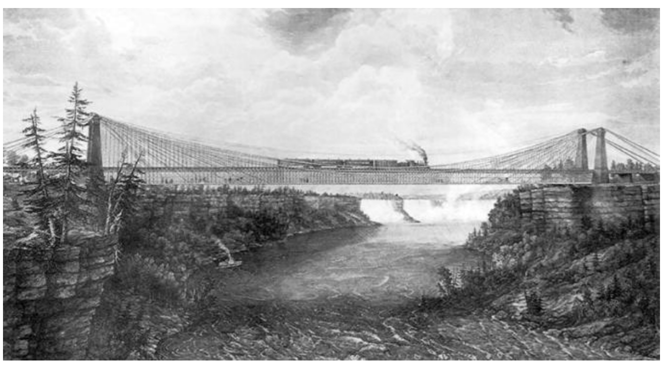


Fig.8 *Niagara Bridge* Fig.9 *Allegheny River Bridge, USA*

Fig.10 *Cincinnati Bridge, USA*

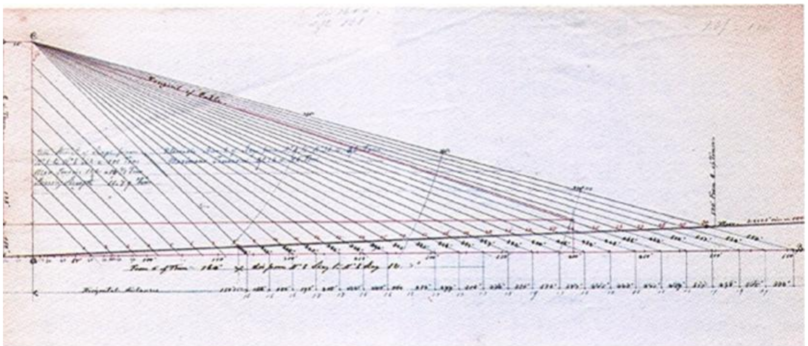


Fig.11 *Preliminary Design, Brooklyn Bridge, USA*

The Cincinnati Bridge with a record span of 322 m took unusually long for completion, Fig. 10. Roebling´s design was accepted in 1859 but progress was interrupted by the American Civil War between 1861 and 1865. The bridge was eventually opened in 1867.

The crowning achievement of John Roebling´s work as bridge designer was the Brooklyn Bridge in New York with a new record span of 486 m. He started designing the Brooklyn Bridge in 1865. Fig. 11 shows one of his preliminary drawings for the stay cables. Roebling tried to distribute the permanent loads evenly between the suspension cables and the stay cables.

Fig.12 *Brooklyn Bridge, USA*

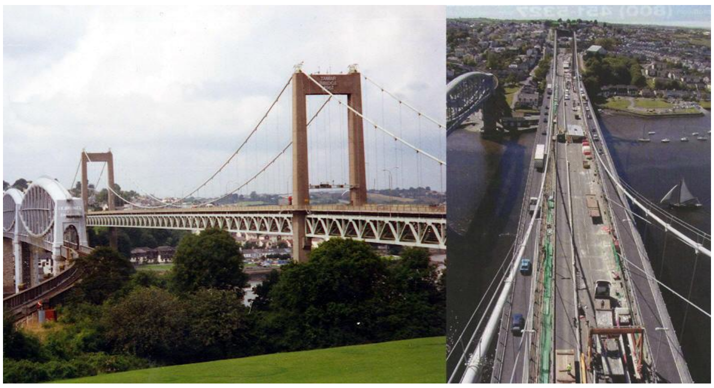


Fig.13 *Tamar Bridge, England*

John Roebling had completed the design and work on the foundations had started when he died from a accident on site. The construction of the bridge was completed by his son Washington Roebling. When he suffered from a caisson accident his remarkable wife, Emily Warren Roebling, run the site on his behalf and completed the bridge successfully, Fig. 12, [4].

Stay cables are still used today to strengthen suspension bridges. The Tamar Bridge, Fig. 13, was widened by two outer lanes. For supporting the additional loads stay cables were installed.

5. Stiffness of Cable-Stayed vs. Suspension Bridges

In 1841 John Roebling published an article in the American Railroad-Journal, [5], in which he outlined the higher strength and elasticity of parallel wire cables against wrought iron chains in use until then. He also pointed out that the additional use of stay cables would stiffen the bridge girder considerably. The superior stiffness of cable-stayed bridges against suspension bridges is illustrated by a comparison of their deflections under life load, Fig. 14. Under uniform live load in the centre span a suspension bridge deflects 55 % more than a cable-stayed bridge. Under live load in only one half of the main span the deflection of a suspension bridge is about 200 % higher. The reason is that in this case the suspension bridge can deflect nearly without increase of main cable stresses whereas the direct load path of a cable-stayed bridge always creates additional stresses in the stay cables. Concentrated loads like a railroad locomotive create deformations up to five times higher. Regular suspension bridges are, therefore, unsuitable for railways. Cable-stayed bridges, however, can be used very well as demonstrated by the Zarate-Brazo Largo Bridges, Fig. 15.

In that publication Roebling further stated that gusty wind can easily put a suspension bridge into dangerous resonant oscillations which may destroy it as had been the case for the wheeling suspension bridge in 1854. For suppressing such dangerous oscillations he also proposed stay cables.

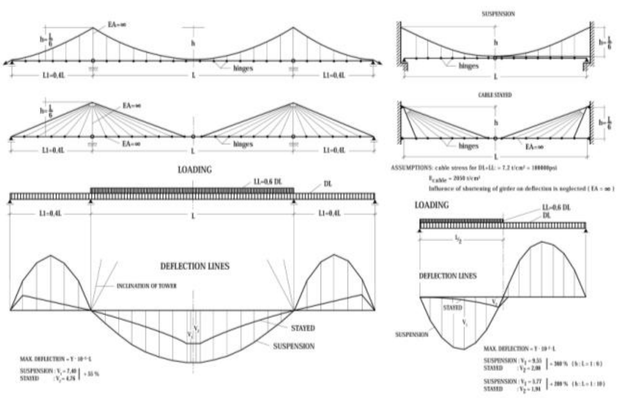


Fig.14 *Deflections*

Fig.15 *Zarate-Brazo Largo Bridges, Argentina*

Fig. 16 gives the critical wind speed for dangerous flutter oscillations of similar suspension and cable-stayed bridges. For a main span of 500 m this critical wind speed is about 100 km/h for a suspension bridge but 200 km/h for a cable-stayed bridge. The high wind resistance of cable-stayed bridges is demonstrated by the Helgeland Bridge, Fig. 17, which is located at a storm-prone region at the West coast of Norway near the Polar Circle.

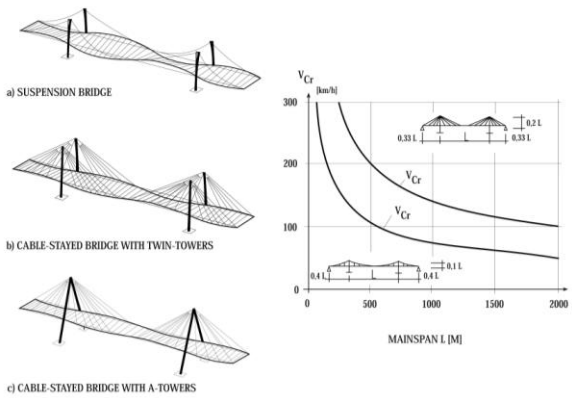


Fig.16 *Aerodynamics*

Fig.17 *Helgeland Bridge, Norway*

With a main span of 425 m its beam has a vertical slenderness of 1:355 and a horizontal slenderness of 1:36. The bridge appears thus rather sensitive against wind oscillations but even during construction of the bridge, when it is especially vulnerable, wind speeds up to 200 km/h occurred but the bridge oscillated only within the pre-calculated limits. Such aerodynamic stability is only possible for a cable-stayed bridge.

6. Re-Discovery of Cable-Stayed Bridges

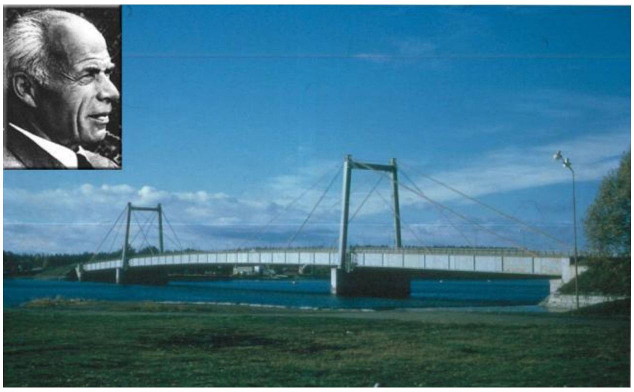


Fig.17 *Strömsund Bridge, Sweden*

Fig.18 *Düsseldorf Bridge Family*

The method of John Roebling to stiffen suspension bridges with stay cables was not continued for nearly 100 years. But when in 1938 Franz Dischinger, [6], tried to design a major suspension bridge across the Elbe River for railway loading, he again found that the deflections were too high and that stay cables at both sides of the main span would stiffen the bridge beam sufficiently. He published his investigations in 1949. Soon he and other engineers like Fritz Leonhardt realized that it would be even more effective to omit the suspension cables completely and to support the beam with stay cables only. Dischinger was then instrumental in designing the first modern cable-stayed bridge across the Strömsund in Sweden, opened in 1956, Fig. 17.

At about the same time Fritz Leonhardt, [6], designed the so-called "Bridge Family" in Düsseldorf across the Rhine River, Fig. 18. The three bridges vary in layout and tower arrangements, but have similar parallel so-called harp arrangement of the stay cables. The first one to be completed was the Theodor-Heuss-Bridge in the background in 1957.

Fig.19 *Knie Bridge, Düsseldorf*

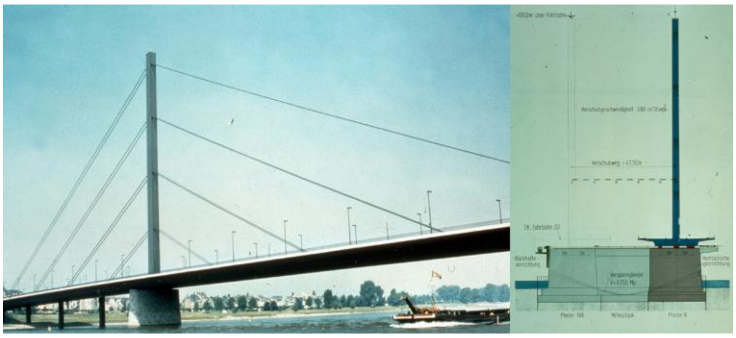


Fig.20 *Oberkassel Bridge, Düsseldorf*

The Knie Bridge, Fig. 19, has two independent tower legs without the usual cross beam due to aesthetic reasons. The c.o.g. of the tower coincides with the cable planes. The bridge was built by free-cantilevering without any auxiliary piers in the river. Those would have been very costly because they would have had to be protected against ship collision. This resulted in a record cantilever length of 329 m which was only surpassed in 1979.

The Oberkassel Bridge, Fig. 20, was the first cable-stayed bridge to be shifted transversely. The stay cables were used to concentrate all dead loads in the range of 10.000 tons onto the bearings underneath the tower. The transverse shifting took place on auxiliary bearings with Teflon pads sliding on polished steel.

7. Further Developments

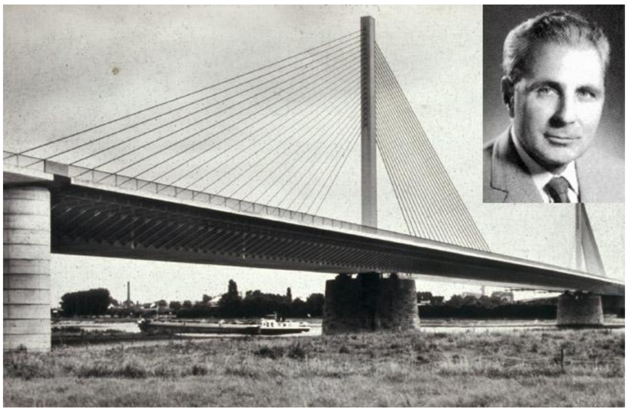


Fig.22 *Rhine River Bridge Bonn-Nord*

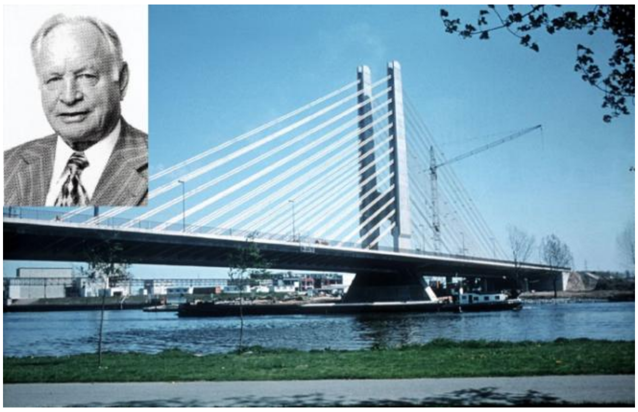


Fig.23 *2nd Main River Bridge at Hoechst*

The first cable-stayed bridges used few stays, each of which consisted of a bundle of locked coil ropes. This caused problems during free-cantilever construction due to the great distance between the stay cables and necessitated e.g. the use of auxiliary supports, Fig. 19. Furthermore, the corrosion protection inside the bundle of locked coil ropes was difficult. Helmut Homberg, [6], solved these problems by designing the Rhine River Bridge at Bonn-Nord with multiple stays at short distances, Fig. 22. Every stay consits of a single locked coil rope. In this way the erection was simplified and the corrosion problems were omitted.

The first major cable-stayed concrete bridge with multi stays and for railway loading was the 2nd Main River Bridge at Hoechst, designed by Ulrich Finsterwalder, [6], and Herbert Schambeck, [6], Fig. 23.

Fig.24 *Pasco-Kennewick Bridge, USA*

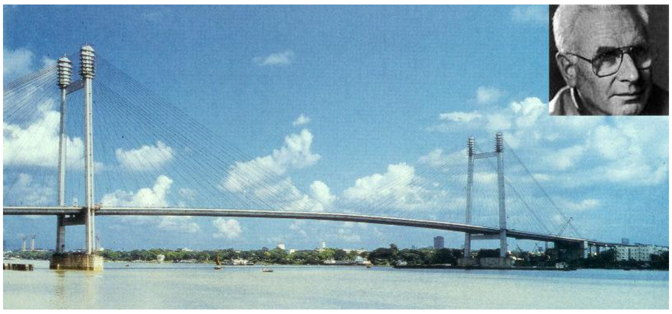


Fig.25 *Hoogly River Bridge, India*

The first cable-stayed segmental concrete bridge was designed during the mid 1970s by Fritz Leonhardt across the Columbia River near Pasco, Washington, USA, Fig. 24. For the first time match-cast segments with a length equal to the cable distance extending over the full width of the bridge with a weight of about 270 tons were used. They were lifted up from the river with hydraulic jacks and their epoxy glued joints were post-tensioned against the already installed beam.

The construction for the first major cable-stayed bridge with a composite girder and a record span of 457 m across the Hoogly River in Calcutta, Fig. 25, started in 1972 but was completed only in 1992. It used a concrete slab as roadway on top of a steel girder grid and was designed by Fritz Leonhardt and Jörg Schlaich, [6].

Fig.26 *Kurt-Schumacher-Bridge between Mannheim and Ludwigshafen*

Fig. 27 *Baytown Bridge, Texas, USA*

The first cable-stayed bridge to use a steel beam in the main span and a concrete beam as counter weight in the side span is the Kurt-Schumacher-Bridge across the Rhine River in Mannheim completed in 1972, Fig. 26. This design has been used later on for many major cable-stayed bridges for which piers were permitted in the side spans, e.g. the Normandie Bridge, France, the Tatara Bridge, Japan and the Stonecutters Bridge, Hong Kong.

The first cable-stayed bridge with a twin beam was built across the Houston Ship Channel, Texas, USA, Fig. 27. Six lanes with full shoulders required a very wide beam which was more economically suspended by four cable planes than by the usual two cable planes. The two unconnected beams were built in parallel by free-cantilevering in parallel. It was found that their independent oscillations dampen one another in case of the frequent hurricanes in the Houston area.

8. Conclusion

About 150 years ago John Roebling initiated important developments in the design of cable-stayed bridges which were neglected for nearly 100 years but today are still being further developed. These include wire ropes and cables and the use of stay cables. Although the calculation methods at Roebling´s time neither permitted the correct calculation of forces in the structure nor did they permit to calculate the aerodynamic stability, Roebling intuitively understood the inner workings of stay cables which can be proven analytically only today. His education in Germany and the possibilities in the United States permitted him to design outstanding structures like the Brooklyn Bridge still in use today. What he initiated for the design of cable-stayed bridges has meanwhile spread all over the world and cable-stayed bridges constitute the most important bridge system for major spans today.

9. References

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