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Construction and Collapse of An Early Cable-Stayed Bridge with a Movable Span

by

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CONSTRUCTION AND COLLAPSE OF AN EARLY CABLE-STAYED BRIDGE WITH A MOVABLE SPAN

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INTRODUCTION

On September 6, 1825, a cable-stayed bridge with a double-leaf bascule at midspan was opened to traffic across the Saale River at Nienburg, Germany. The main span between towers was about 82 meters and the deck width 8 meters, double the span and 6 times as wide as the largest prior "pure" cable-stayed bridge. (Herein "pure" cable-stayed bridge denotes a cable-supported bridge with only diagonal stays; without catenary cables as in a suspension bridge.) The bridge was the first cable-stayed bridge with multiple forestays and backstays in a fan arrangement. It was not built as a curiosity, but to serve a definite need; to improve transportation within the Duchy of Anhalt-Cöthen and, indirectly, with the surrounding duchies. Three months after being opened to traffic it collapsed during a celebration honoring the Duke with the loss of 55 lives. The disaster has been cited as one of the reasons that few "pure" cable-stayed bridges were constructed until some 130 years later when cable-stayed bridges were built across the Rhine River to replace structures destroyed during World War II (Leonhardt 1970, Roik 1986). Thereafter, cable-stayed bridges became popular worldwide for intermediate spans. Another reason given for the hiatus in cable-stayed bridge construction was the supposed criticism of this type of bridge made by Navier in his famous report on suspension bridges (Navier 1823). However, the writer has not found any serious negative opinions about cable-stayed bridges by Navier to support that position. Navier did not essentially rule out cable-stayed bridges as some authors have suggested.

Despite the fact that the Nienburg Bridge was the largest cable-stayed bridge at the time and so many people died in the disaster, the collapse received little attention in the engineering literature. Drewry and Bender both wrote of cable-stayed bridge

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failures, but did not mention the Nienburg Bridge (Drewry 1832, Bender 1868). The only publication with graphic and technical descriptions of the structure and the collapse that the writer has found is that of Bandhauer (Bandhauer 1827).

Bandhauer was the highest ranking building official in the service of the Duke of Anhalt-Cöthen and the promoter, designer, and construction manager for the bridge. After the collapse he assembled drawings and calculations, correspondence, expert witness testimony, etc., and had the material printed at his expense. He wanted the collapse investigation records to be readily available in order to protect his professional reputation and his position with the Duke.

After a three year-long criminal investigation, Bandhauer was exonerated of all blame for the collapse. No single cause could be established for the failure. It was probably a combination of unsymmetric overloading, defective wrought iron joints, inadequate design factor of safety, and vibration of the bridge induced by exuberant youths. A description of events leading to the building of the bridge and its collapse has been presented elsewhere (Birnstiel 1996). The emphasis in what follows is on the design of the bridge superstructure, especially the movable span, and operation of the bascule leaves.

DESIGN OF NIENBURG BRIDGE

Fixed Superstructure

Bandhauer's report included plates showing overall views of the structure and details of member connections. Figures 1 through 4 herein are based on those plates and data in his text. Figure 1 is a half-elevation which shows that the bridge actually comprised two independent single-tower cable-stayed bridges with a double-leaf bascule at midspan that could be opened to permit passage of sailing ship masts. The opening created by lowering the leaves was 3.5 meters wide. Wrought iron stays radiated from cast iron saddles atop the timber towers to alternate floorbeams of the river span. The stays were not directly connected to the longitudinal girders (which Bandhauer called barriers). From the saddles, wrought iron backstays radiated diagonally downward through stone anchor blocks embedded in the bottoms of the anchorage wing walls.

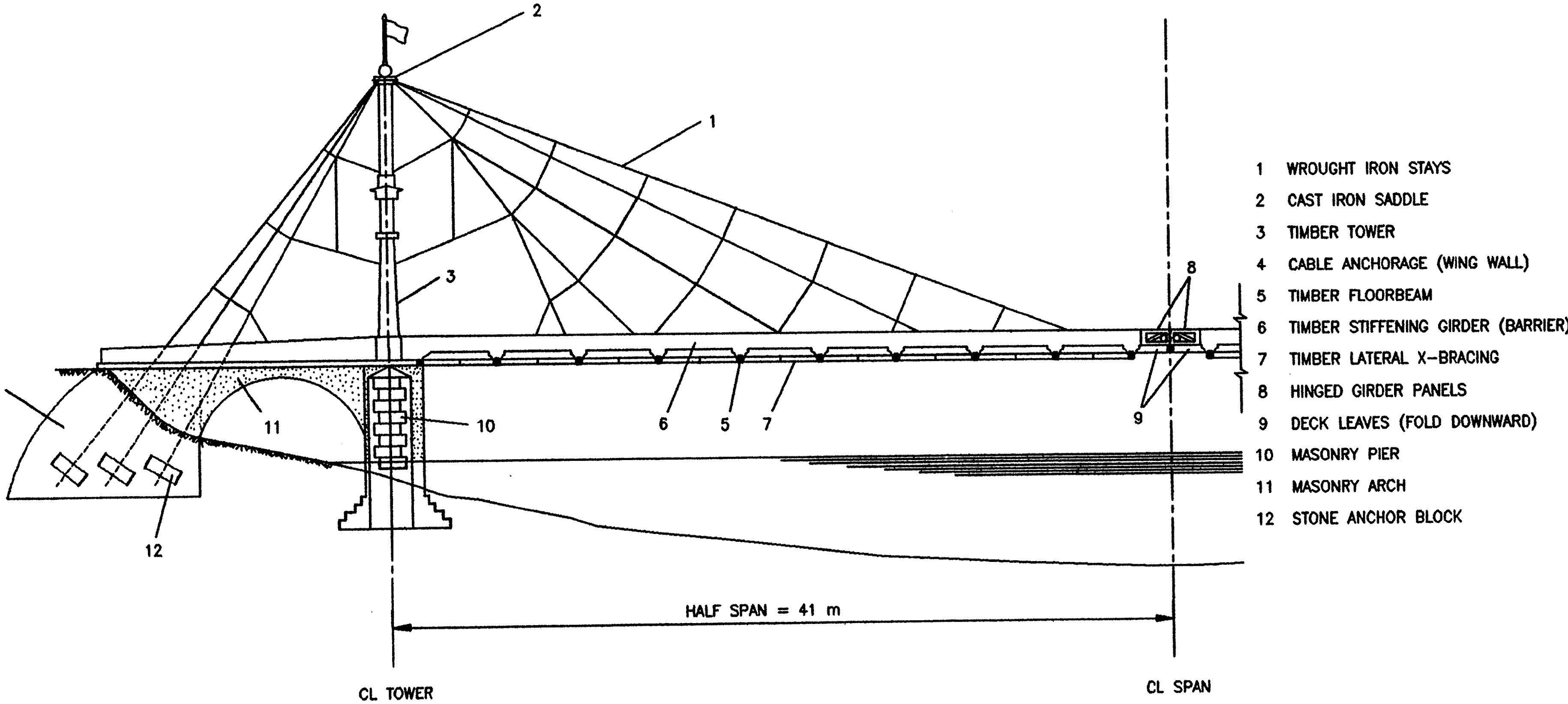


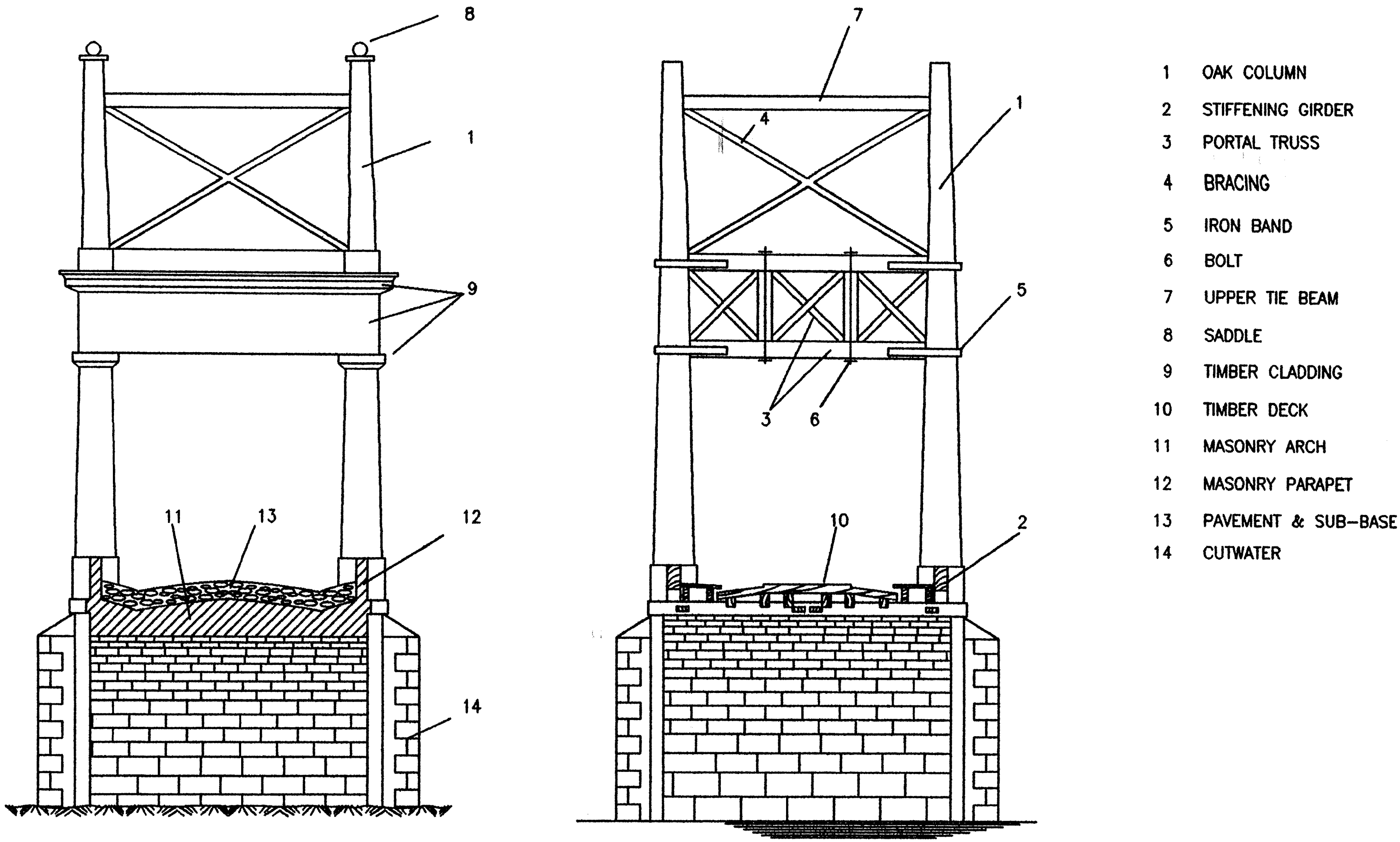
FIG. 1 - HALF ELEVATION OF NIENBURG BRIDGE

Each of the two towers comprised two oak columns spaced about 7.5 meters apart with timber truss portal bracing between them in the space above the roadway. The towers were clad with wood decoration detailed so as to resemble stone, a reflection of Bandhauer's neo-classic architectural preference. Figure 2 shows the design for a tower, bare and clad.

The suspended structure comprised timber floorbeams that supported longitudinal timber stringers on which the roadway and sidewalk decking rested, stiffening girders, and lateral bracing. The lateral bracing extended from the bascule leaf to the masonry abutment. It comprised two parallel lines of horizontal timber x-bracing located at midheight of the floorbeams. The lateral bracing served two functions; as wind bracing and to equilibrate the horizontal components of the cable forestay tensions. Figure 3 is a cross section through the suspended span. It shows a 2.35-meter wide carriageway for wagons flanked on each side by a walkway for the draught animal tenders and a sidewalk. The sidewalk was elevated so as to form an open curb through which rain and roadway debris could drop into the stream below. The overall width of the deck was 7.6 meters.

Figure 4 shows longitudinal cross sections through the deck at midspan. The upper cross section is cut a short distance inward of the face of the stiffening girder. The deep, continuous, stiffening girder was assembled from narrower and shorter timbers scarfed together, with keys serving to transmit horizontal shear. Vertical through-bolts clamped the pieces together.

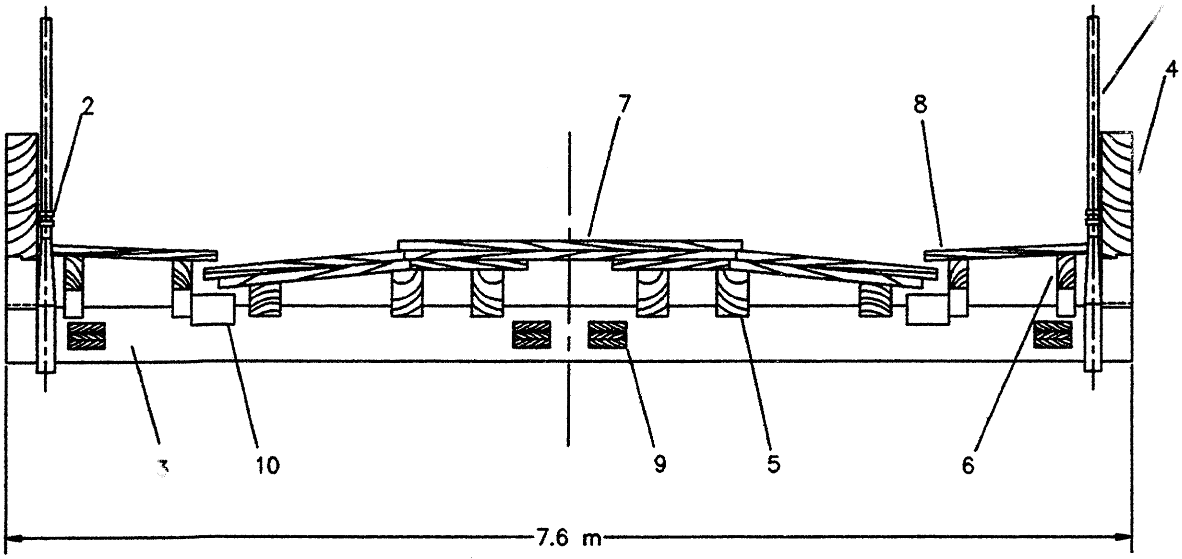
As mentioned previously the forestays were not connected directly to the stiffening girders. Instead the lower ends of the stays were made with loops which were wrapped around the timber floorbeams. The floorbeams were connected to the girder at each end by a bolt passing vertically through the floorbeam, a timber bolster, and the stiffening girder. This connection was not a suitable connection for transferring the horizontal component of the stay force to the stiffening girder. However, the writer believes that Bandhauer did not intend that the horizontal component of stay tension be transmitted to the girder. He probably wanted the horizontal components to be transmitted by the underfloor lateral bracing to the abutment. We may consider that force path to be poor design today, but it is consistent with his detail between the stiffening girder and the tower column, and the fact that the backstays were anchored into the abutment, not the stiffening girder.



CROSS SECTION THROUGH FLANKING ARCH

CROSS SECTION THROUGH SUSPENDED DECK

FIG. 2 - TOWER OF NIENBURG BRIDGE



1	WROUGHT IRON STAY	6	SIDEWALK STRINGER
2	LOCKING SLEEVE	7	ROADWAY DECK
3	TIMBER FLOORBEAM	8	SIDEWALK DECK
4	TIMBER STIFFENING GIRDER	9	LATERAL CROSS-BRACING
5	ROADWAY STRINGER	10	DEBRIS SHIELD

FIG. 3 - CROSS SECTION THRU SUSPENDED DECK

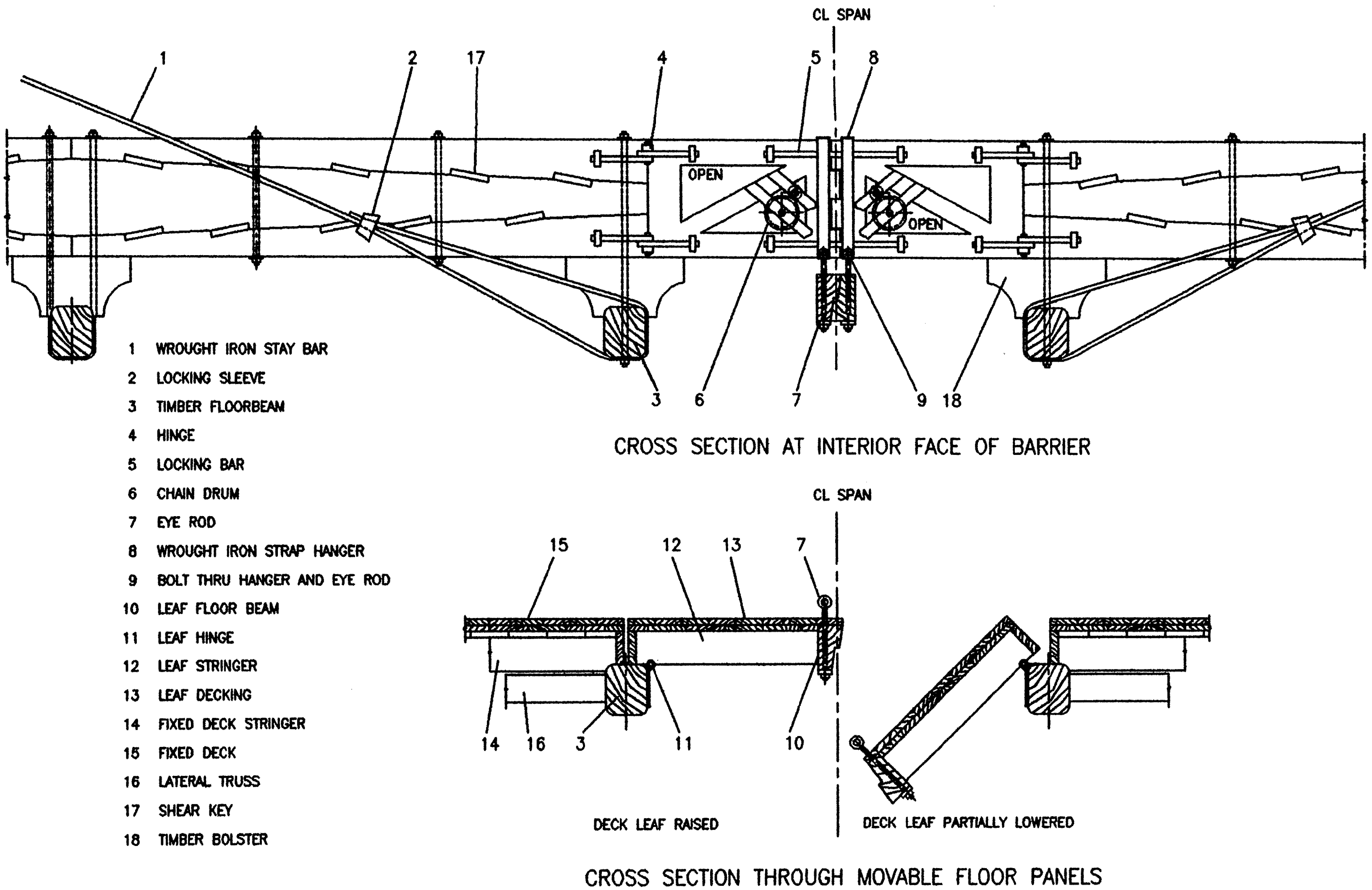


FIG. 4 - LONGITUDINAL SECTIONS THROUGH DECK

Intermediate floorbeams, those to which stays were not connected, were hung from the stiffening girder by wrought iron U-bolt hangers. The vertical reactions of the intermediate floorbeams were transmitted by the stiffening girder in bending to the floorbeams that were supported by diagonal stays.

Movable Span

At the time of the construction of this bridge, Nienburg was an inland port where agricultural products and minerals extracted from the earth were shipped to North Sea ports for transhipment to England and manufactured goods were imported from England. Because of the shallow gradient of the Saale and Elbe Rivers this could be accomplished by vessels that could maneuver upstream and downstream under sail. Except in calms or contrary winds, it was not necessary to haul the boats upstream by manpower. Bandhauer had to provide a means for passing sailing vessels headed upstream beyond Nienburg in order to gain acceptance for his bridge by the navigational interests. It is extremely unlikely that the Duke would have given permission to replace the ferry service by a fixed bridge that impeded navigation of sailing vessels. Raising the profile of the bridge above that shown in Figure 1 would have been expensive because of the topography and would have detracted from the economics of the bridge due to the need for more draught animals to pull the wagons upwards on the bridge approaches.

Figure 4 also shows the movable portion of the bridge at midspan. In the upper cross section the two gate leaves which formed the movable portion of the barrier are shown in the closed position. Each gate was connected to a barrier by hinges (#4), analogous to a garden gate, and held in the closed position by locking bars (#5). The joint between the two gate leaves was notched so that vertical shear could be transmitted across the midspan joint. At the other end of each gate leaf (the hinged end) there was a similar notched detail whose purpose was to transmit vertical shear between the gate and the barrier when the gate leaf was closed.

The deck leaves are shown in the lower cross section of Figure 4. Each leaf was permitted to rotate about a horizontal axis by hinges fastened to the floorbeams. The leaves were not counterbalanced. At the tip of each leaf there was an edge beam, denoted "Leaf Floorbeam" in the figure. These two floorbeams were shaped so as to mate when the leaves were in the raised position. Vertical eyebolts (#7) were installed at each end of the floorbeam. When the leaf was raised to the fully-closed position, the eyes of the bolts (#7) lined up with holes near the bottom of the U-shaped hanger straps (#8) and bolts (#9) were passed through the matching holes. In this way the reactions of the leaf floorbeams were transferred to the tops of the trussed gates and the gates transferred the load to the ends of the stiffening girders. The bending moment at a hinged gate joint was resisted by the hinges (#4) and the shear reaction was through bearing of the gate on the bolster (#18).

A chain drum driven by a single-reduction gearset was located within the open trussed web of each gate. The chain hoist was used to raise and lower the roadway leaves. Each leaf weighed about 2 tonnes. The procedure for opening the bascule to enable passage of marine traffic was probably as follows:

1. Stop roadway traffic
2. Withdraw bolts (#9) passing through holes in straps (#8) and eyebolt (#7).
3. Lower right leaf by paying out chain from chain drum (#6).
4. Lower left leaf.
5. Withdraw locking bars (#5).
6. Swing gates inward (this required release of more chain) in order to clear passage for ship masts.

The procedure for closing the leaves to permit roadway traffic would have been essentially the same, except in reverse order. According to Bandhauer, the time required for an opening/closing cycle was 5 minutes, which included passage of the ship masts.

CONSTRUCTION AND TESTING OF NIENBURG BRIDGE

The first stone for the foundation was laid on March 24, 1824. The contract for the wrought iron stays was awarded to an ironworks in Blankenberg, a town in the Harz Mountains, on April 4 with the stipulation that half the stays were to be delivered in June and the remainder at the end of July. Meanwhile, work continued on the foundations and erection of falsework in the stream.

Apparently, the ironworks had difficulty in fabricating the stays as originally designed and the ironwork contract was amended with the delivery time extended to October 29, 1824. The initial shipment of bars was satisfactory, but the quality steadily deteriorated and it became necessary to proof-test each bar. Forty percent of the pieces failed the test. The failed pieces were sent to another ironworks for reworking. Besides the delays with the iron, there were other quality control problems and the workers erecting the timber suspended structure (built on the falsework) required much training. The type of construction was too advanced for the time and place. It became obvious that the bridge could not be completed before winter. Because the falsework could not remain in the river over the winter, on account of the spring freshets, the suspended deck timber was disassembled and the falsework removed. Construction resumed in the spring and was finished in August of 1825.

An official load test was made on the evening of August 22. In moonlight, officials verified that the bridge was free of the falsework and a wagon loaded with 5,154 kg of cut stone was hauled across the bridge by a 10-horse team. The total load was 10 tonnes on a loaded length of 26 meters. The officials again checked if the deck was free of the falsework and found this to be so. However, voices were raised questioning the validity of a load test made under conditions of poor illumination. Therefore, another load test was made on the afternoon of August 27, in view of many observers. A loaded wagon was pulled across the span three times, loaded with successively more stone. The last trip was made with a total load of 10.6 tonnes. No permanent change in the shape of the bridge was noticed and no unusual movements of the structure were reported during the test runs. Bandhauer was satisfied that the strength of the bridge was adequate and it was opened to traffic on September 6 with ceremony. It was used continuously without load restrictions until it collapsed on December 6, 1825.

COLLAPSE OF THE BRIDGE

The events leading to the collapse have been described elsewhere (Birnstiel 1996). Briefly, during the celebration honoring the Duke there were at least 309 persons on the span. Most of this crowd was concentrated on the southeast side of the span, between midspan and the south tower. As the band played a rousing tune, some youths attempted to excite the bridge in time to the beat of the music. The three most highly stressed backstays (at the southeast) parted, followed shortly by fracture of the southwest stays, Because the connection between the tower and the abutment could not resist bending, the tower rotated about its base and the left half (south half) of the bridge dropped into the river. The right half remained standing.

After the collapse the physical evidence at the site was secured. The backstay fractures were inspected by an expert from the Kingdom of Hanover. He found old defects covered by paint, fissures, porosity and an excess of slag modules in the wrought iron. The Duke also engaged two other experts to review Bandhauer's design. They reported to a legal commission appointed by the Duke. The testimony of witnesses and experts was eventually sent to the Faculty of Law at the University of Göttingen for their findings. In May, 1829, Bandhauer was absolved of blame for the collapse.

SUMMARY AND CONCLUSIONS

In the years 1824-25 a notable cable-stayed bridge was constructed across the Saale River at Nienburg, Germany. It was the first cable-stayed bridge with a fan-type arrangement of multiple fore-and backstays. It had the longest span and widest deck of any pure cable-stayed bridge at the time and the unusual feature of a double-leaf bascule at midspan. Unfortunately, it was also notable for its short life of three months when it collapsed under a crowd of celebrants with the loss of 55 lives.

The movable span comprised two deck leaves that were not counterbalanced. Each leaf could be lowered and raised to permit the passage of marine traffic by means of chain hoists mounted within the movable parts of the stiffening girders. It was reported that the opening/closing time was five minutes.

The presence of the movable span did not directly contribute to the collapse. The bridge actually comprised two independent, single-tower, unsymmetric cable-stayed bridges with a double-leaf bascule between them. Only the southern bridge was loaded at collapse. The other bridge remained standing.

For contemporary bridge designers the lessons to be learned from the disaster are:

- Avoid designing projects that cannot be adequately funded.
- Avoid designing systems that are beyond the local state-of-the-art for construction.
- Consider the possibility of unusual loadings and misuse of the structure and machinery during the design process.
- Provide redundant paths for transmitting the applied loads to the foundations wherever feasible.
- Robustness of the structure and machinery is important.

Bandhauer, the designer, was acquitted of all charges in a judicial proceeding by the Law Faculty of the University of Göttingen. No single cause for the failure could be isolated. The collapse investigation records were likely lost in World War II, but information about the bridge and its collapse published by Bandhauer is accessible (Bandhauer 1827). As it turned out, if he had not published material related to the design, construction, and collapse of the bridge there would be little technical information extant about the structure and its collapse.

ACKNOWLEDGMENTS

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