Benjamin Franklin Bridge

Henry Petroski

Cities and water go together. It was natural to establish early camps, settlements and forts beside streams, rivers, lakes and bays. Such locations provided ready access not only to the substance essential to life but also to fishing, transportation and security. It is no accident that the nucleus of New York City was at the tip of lower Manhattan, which commands a strategic view of the harbor, or that the U.S. Military Academy sits on West Point, which is located at a double turn in the Hudson River, where enemy ships were forced to navigate slowly, thus making them easy targets.

As forts grew into towns and cities, waterways were both blessing and curse. Chicago's location on Lake Michigan gave it what at first must have seemed a nearly inexhaustible source of fresh water, and the Chicago River that flowed into the lake provided a natural sewer. However, the refuse eventually polluted the drinking water, producing a serious health hazard. The situation drove the city to undertake the enormous task of reversing the flow of the river, sending Chicago's sewage westward into the Des Plaines River and, eventually, into the Mississippi River, which supplied water to other cities, including St. Louis. Fortunately, as predicted, the water was purified in the course of the long and turbulent journey.

Swift-running rivers and streams not only cleaned themselves, but they also provided power for mills. Yet the same rapids that drove waterwheels obstructed up-, down- and cross-stream traffic, which was essential for distributing the products of the mills. The continued development of a mill town into a city necessitated the construction of canals, locks and especially bridges, the last of which was relatively easy for narrow crossings but a technological challenge for wider waterways. The growth of many a city was hampered as much by its lack of adequate bridges as by anything else.

The development of the railroad in the 19th century threatened the economic future of cities that could not provide bridges across wide rivers. Had the Eads Bridge not been built at St. Louis, virtually all long-haul rail traffic crossing the Mississippi River might have been routed through Chicago, leaving the more-southern city without significant commerce. The development of the automobile in the early 20th century presented new challenges for bridge builders, requiring increasingly long spans to move traffic across previously unbridged waters.

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Bridges, Real and Imagined

Every river city has at least one bridge story, and Philadelphia is no exception. Philadelphia sits at the confluence of the Schuylkill and Delaware rivers. The former being a tributary of the latter, the smaller Schuylkill was naturally the first to be bridged. The most famous of its early 19th-century crossings were located at Fairmount, now a part of the city but then a bit outside Philadelphia proper. In 1813, Louis Wernwag completed a combination arch-and-truss covered bridge there, which had a clear span of 340 feet. At the time, it was the longest wooden bridge in America. According to David B. Steinman and Ruth Watson, writing in their classic Bridges and their Builders, "it was a beautifully and originally designed bridge, worthy in all respects of its nickname," the Colossus. The great bridge has also been described by Donald C. Jackson, in his indispensable guidebook, Great American Bridges and Dams, as "the most stunning and visually compelling engineering structure built in the early United States." Unfortunately, like many a contemporary wooden bridge, the Colossus was destroyed by fire— in its case in 1838.

The Schuylkill was also spanned by two historically significant early suspension bridges, whose engineers were the pioneers of the form in America. The first was the design of James Finley, who is generally acknowledged to have built the earliest iron-chain bridges. The second significant suspension bridge at Fairmount was the first of that type built by Charles Ellet, Jr. His bridge, with a 358-foot span suspended from wire cable passing over stone towers, was completed in 1842. It provided a replacement for the Colossus.

The much wider Delaware River was bridged neither so early nor so readily. An 1818 proposal for a bridge between Philadelphia and Camden was unusual in that the span did not go all the

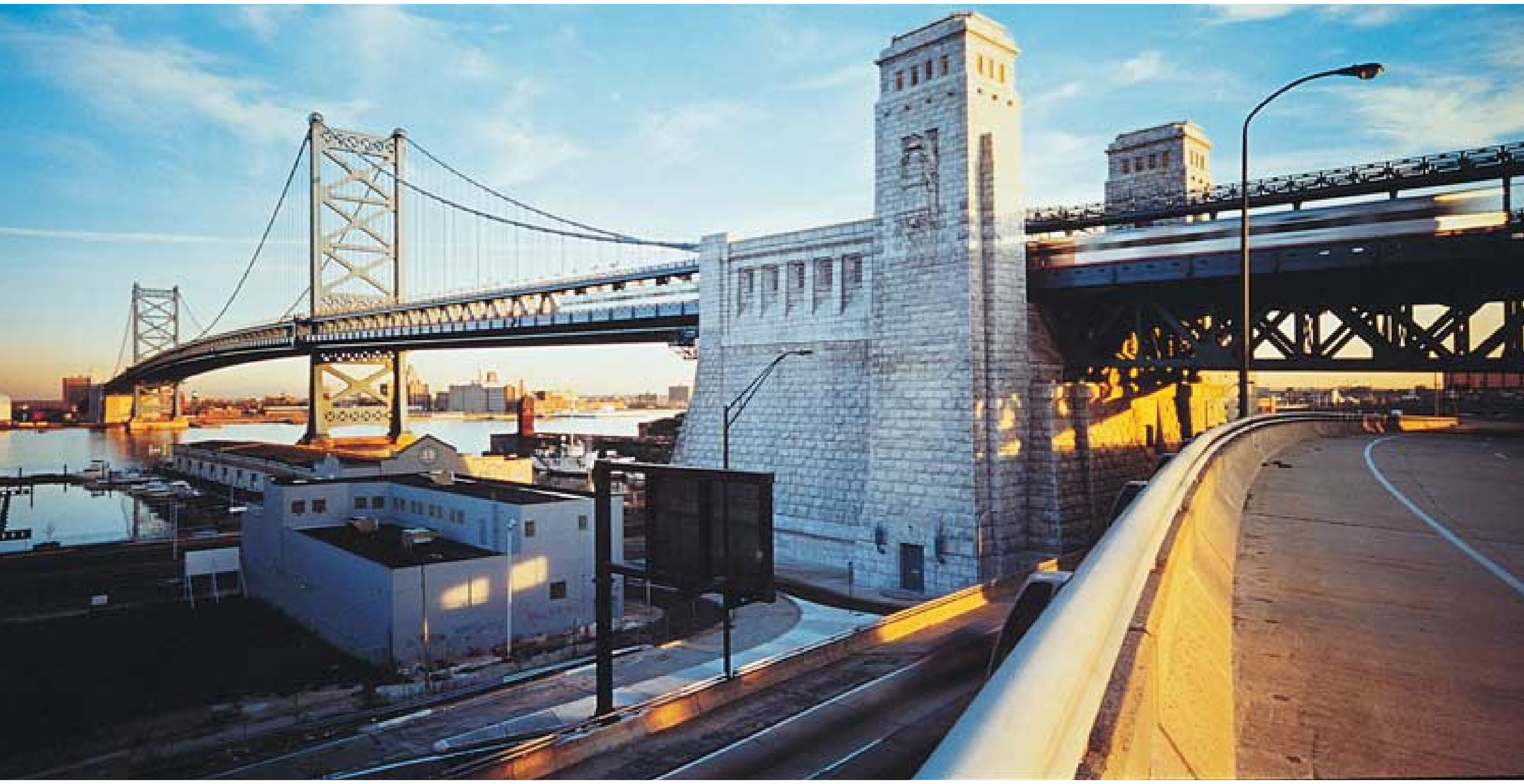

Figure 1: Benjamin Franklin Bridge held the distinction of being the world's longest-span suspension bridge at 1,750 feet from its completion in 1926 until 1929, when the Ambassador Bridge between Detroit and Windsor, Ontario, exceeded its span by 50 feet. (Photograph courtesy of James B. Abbott.)

way across the river. The scheme consisted of a bridge from New Jersey to Smith Island, which then existed close to the Pennsylvania shore, in combination with a ferry connecting the island and the foot of Market Street. The island itself was removed in 1893 to improve navigation, but even before then other bridges reaching across the entire river were proposed.

There is always more than one way to cross a river, of course, and a multi-span suspension bridge was proposed in 1851 by the Philadelphia-born engineer John C. Trautwine. Trautwine had gained extensive experience on railroad and canal projects, including surveying work on a railroad across the Isthmus of Panama, prefiguring the route of the future canal. His proposal for a bridge with four spans of 1,000 feet each would have been a daring stretch of the state of the art. Just two years earlier, Ellet's 1,010-foot suspension bridge had been completed over the Ohio River at Wheeling, West Virginia. Unfortunately, the roadway of that bridge was destroyed in a windstorm in 1854 and had to be reconstructed. Such a structural failure would naturally give pause to any community then contemplating a similar bridge.

The collapse of the Wheeling span might have struck an even more severe blow to suspension bridge building in America had not another bridge, designed by John A. Roebling, been completed at about the same time. His Niagara Gorge Suspension Bridge, with a clear span of 851 feet, was the first of that genre to carry railroad trains. Roebling's unique structure owed much of its success to the engineer's having studied in detail the effects of wind on large bridges. It was only by understanding how earlier suspension bridges had failed, Roebling believed, that he could design ones that would withstand the forces of nature.

John Roebling went on to design the great bridge across the Ohio River at Cincinnati. Although its construction was interrupted by the Civil War, the 1,057-foot span was completed and opened to traffic by 1867. The bridge at Cincinnati set the structural stage for Roebling's masterpiece, the Brooklyn Bridge, whose construction was approved only because he proposed a high bridge that gave ample clearance to tall-masted river traffic. To achieve this, however, the Brooklyn Bridge required long and expensive approaches to carry traffic from street level to the high central span across the river and then back down to street level.

Nevertheless, plans to cross the East River in New York with a span of about 1,600 feet appear to have rejuvenated talk of a crossing of the Delaware River. An 1868 joint report by committees representing the interests of Philadelphia and Camden put forth what they considered an improvement on the span planned for Brooklyn. The proposed Delaware River structure eliminated the need for long approaches by allowing the bridge to remain a low-level crossing throughout, incorporating a roadway that split into two draw-bridge spans.

The idea was for the bridge to operate somewhat like a canal lock. When a ship wished to pass the bridge, traffic would be diverted to the far draw span, which would remain in the closed position. The closer draw span would be raised, allowing the ship to pass into a wide pool between the two roadways. Then the raised span would be closed behind the ship, bridge traffic redirected once again, and the second draw span opened to give the ship free passage out of the pool. Sketches of the extravagant scheme were published, but not surprisingly the bizarre structure was never built.

That is not to say that engineers did not continue to dream up new schemes to bridge great distances. John A. L. Waddell was one of the most flamboyant personalities among bridge engineers of the time, and he produced an equally flamboyant design for crossing the Delaware. It called for a unique suspension bridge that answered the objections normally raised against bridges of this type. In order to avoid long land-based approaches requiring the acquisition of expensive land in established neighborhoods—as was the case with the Brooklyn Bridge—Waddell employed compact helical approaches, not unlike the kind we encounter in some multilevel parking structures today. Such an unusual scheme won little support, however, and in 1919 Pennsylvania and New Jersey established a bistate Delaware River Bridge Joint Commission, under which careful and thoughtful planning would begin again in earnest.

Commissioning a Bridge

The commission interviewed bridge engineers from around the country, and a three-member Board of Engineers was appointed. The board included George S. Webster, who had long been associated with public works in Philadelphia; Laurence A. Ball, who had extensive experience with railroad and subway work in New York City; and Ralph Modjeski, whose wide-ranging bridge-building experience made him one of the premier bridge engineers of the time. It was Modjeski who chaired the board and who came to be named chief engineer of the project. The bridge was effectively to become Modjeski's bridge.

Ralph Modjeski, who was born in Poland in 1861, first visited America with his mother, Helen Modjeska, the actress who was hailed as the "premiere tragedienne of her time." The family visited New York and Philadelphia, where they took in the Centennial Exposition. Young Ralph no doubt noticed that there was no bridge across the Delaware, just as he noticed that there was no canal across the Isthmus of Panama, which they crossed by rail. His mother later recounted that the teenage Modjeski declared that "someday he would build the Panama Canal."

After being educated at the prestigious École des ponts et chaussées, in Paris, Modjeski returned to America in 1885 to begin his engineering career. He first worked under George S. Morison, who is considered by many the "father of bridge building in America," but soon opened his own office in Chicago. Modjeski's name would eventually be associated with more than 50 major bridges, including bascule, truss, arch, cantilever and suspension types. If he would not build the Panama Canal, he would strive to build bridges that were also world-class achievements.

Modjeski became a member of the board of engineers charged with overseeing the redesign of a massive St. Lawrence River bridge at Quebec, the first version of which collapsed during construction in 1907. The Quebec Bridge, an enormous cantilever structure, was finally completed in 1917, and at 1,800 feet between piers, it then had the longest single span of any bridge of any kind anywhere in the world. But the failure of the first Quebec Bridge so shook the bridge-building community that the cantilever form soon fell out of fashion, and the Quebec remains to this day the longest bridge span of its kind ever built.

No doubt Modjeski's association with such an ultimately successful record-setting achievement made him an attractive candidate to lead the effort to build a bridge across the Delaware River. Although the collapse of the Quebec Bridge had called for a closer look at every new cantilever design, the form was still considered an attractive option to cross the Delaware, especially with Modjeski in charge. In the end, however, a suspension bridge was determined to be the less expensive alternative. According to *Engineering News-Record*, the leading chronicler of the construction industry, in an article reviewing engineering studies for a Philadelphia-Camden Bridge,

> The advantage of superior rigidity possessed by the cantilever bridge was believed to be negligible in highway service. The cantilever saves a large item of cost in simpler anchorages and approach construction. The suspension bridge, on the other hand, is not only very much lighter, but was considered to involve less risk in construction, to be adapted to subdivision of contracts, to require less time to build, and to be cheaper in maintenance on account of having less metal exposed. It was also considered to have the esthetic advantage over the cantilever bridge.

Indeed, when completed, at 1,750 feet it would be the longest suspension span in the world. It should not be surprising that an engineer with the background, talents and ambitions of Modjeski would enthusiastically embrace the opportunity to build another record-breaking bridge of its type.

Regardless of experience or talent, no single engineer or board of engineers, no matter how distinguished, can alone build a world-class bridge.

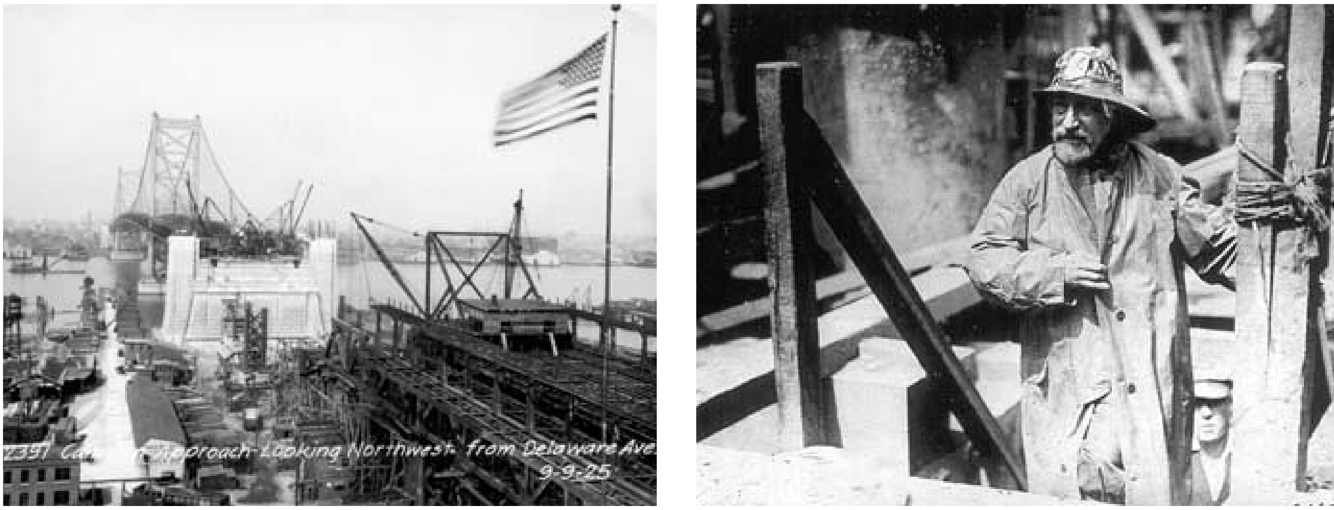

Figure 2. Delaware River Bridge (left), as it initially was called, was innovative in many ways and was said by some to embody the answers to the last significant questions in building suspension bridges. The bridge's chief engineer, Ralph Modjeski (right), was involved in more than 50 bridge projects during his career. (Photographs courtesy of the Delaware River Port Authority.)

There is too much specialized knowledge required, there are too many design alternatives to be considered, and in the final analysis there are simply too many details to be worked out. Even with the decision made to build a suspension bridge, there remained many subsidiary technical choices to be made before construction could begin. These included exactly where the bridge should cross the river, where the towers should be founded and how high they should be, where the anchorages should be placed, what the line of the cables should be and whether they should be made of eyebars or wire, what the configuration and proportions of the roadway should be, where train tracks and walkways should be located, what the exact dimensions of each piece of stone and steel should be, and what kinds of architectural details should be included. Consulting engineers and architects are engaged to help address such issues. Among the principal consultants for the Delaware River Bridge were Leon S. Moisseiff and Paul P. Cret.

Leon Moisseiff served as consulting designing engineer to the board and later as engineer of design for the project. He was, in fact, to have a hand in the design of virtually every major suspension bridge built in the three decades after the 1909 completion of the Manhattan Bridge, to which he applied the so-called deflection theory. This theory, by taking into account the interaction of the cables and roadway of a suspension bridge, enabled design engineers to make a more accurate determination of how forces were distributed among the various parts of the structure. By knowing more accurately the distribution of these forces among the parts of the structure, the steel components could be designed more optimally and hence the bridge built more economically.

Function Follows Form

Before such calculations could be made, however, the overall proportions of the structure had to be established. There were no rigid formulas for doing this; it involved a combination of working within the constraints of the bridge location and local geology and of making aesthetic judgments about what just looked right. In taking this all-important design step of setting the proportions of a major structure, engineers act more like artists than scientists. And only after the overall defining geometry is set down can the theories and formulas of engineering science be applied to the details. Modjeski and Moisseiff were each masters of both the art and the science, but as chief engineer Modjeski would have the final word and responsibility for the way the bridge looked.

Although a suspension bridge is the purest of structural forms, needing no decorative treatment or façade to give it an aesthetic presence, architects are often involved to recommend finishing touches. Modjeski engaged Paul Cret as architect to provide advice on details large and small. Cret had considerable input on such aspects of the bridge as the exterior design of the enormous anchorages that it required and the stone pylons that frame the steel towers for everyone driving across the bridge. Yet for all of the thought that went into the materials, proportions and appearance of the structure, the artist Joseph Pennell would still call the bridge under construction over the Delaware "the ugliest bridge in the world." That judgment would be reinforced by the aging master bridge engineer Gustav Lindenthal, who considered the towers to be designed "too much on the utilitarian principle of braced telegraph poles or derricks, holding up ropes." Such opinions were disputed by many other observers who found the structure beautiful.

Whatever the aesthetic verdict on the bridge, from a purely engineering point of view it was to be an innovative and record-breaking achievement. Modjeski's board had submitted its defin-

Figure 3. Cables were spun in place, and each consisted of more than 20,000 individual steel wires—twice as many as any previous bridge. (Photograph courtesy of James B. Abbott.)

ing recommendation for the location and type of structure on June 9, 1921, and it was accepted by the Joint Commission just two weeks later. The total cost of the bridge was estimated to be almost $29 million, with the State of New Jersey responsible for about $12.5 million and the Commonwealth of Pennsylvania and the City of Philadelphia responsible for just over $8 million each. The board declared that the bridge could be finished for the country's sesquicentennial celebrations being planned for July 4, 1926. It would open three days early, almost 50 years to the day from when Modjeski first came to America. The opening took place as planned despite construction delays caused by a debate over whether tolls would be charged. In the end, tolls were used to pay for the project, which was believed to be the largest public-toll enterprise up to that time.

The span, width and traffic capacity of the bridge required cables of unprecedented size. Each cable was spun in place and was made up of 20,000 individual steel wires, which meant the spinning operation had to handle almost twice as many strands as on any previously built suspension-bridge project. When compacted, the finished cables measured 30 inches in diameter, which made them half again as large as any then built. The use of new and stronger materials in the cables and lighter materials in the roadway reduced the overall weight of the structure, as did the use of lightweight trusses. These things in turn kept the overall cost down.

For all the attention to technical innovations, the bridge was also designed with full regard for the people who would use it. Vehicle traffic lanes were located in the center of the bridge, flanked and guarded on either side by sets of train rails and trusses. One set of tracks ran inside and one outside each of the bridge's two stiffening trusses. Over the outside tracks, cantilevered out from the top of the trusses, was a pair of pedestrian walkways. The placement of these walkways was as thoughtful as that on any major bridge. As on the Brooklyn Bridge, the elevation of the walkway above the road and rail traffic improved safety and gave pedestrians spectacular views uninterrupted by passing cars or trains.

Engineering News-Record celebrated the completion of the Delaware River Bridge in an editorial entitled "An Engineering Monument." The bridge was said to be "worthy of admiration most of all as an embodiment of modern engineering skill." The editorial went on to note that, coming nearly half a century after the Brooklyn Bridge, the Delaware River Bridge in a sense represented the concluding chapter in the book of suspension-bridge building. Whatever open questions in engineering knowledge had remained since the completion of the Brooklyn Bridge, the Delaware River Bridge was believed to have closed them.

Its reign as the longest suspended span in the world lasted only three years—until 1929, when the main span of the Ambassador Bridge between Detroit and Windsor, Canada, reached across a distance 50 feet greater—but the Delaware River Bridge was by far the more attractive bridge and remains so. The 1931 completion of the George Washington Bridge, with a main span exactly two times that of the Delaware River Bridge, ushered in a new era—one of longer, sleeker and lighter structures. Unfortunately, within a decade engineers like Moisseiff had allowed their hubris to get the better of their judgment, and the nadir of suspension bridge building was reached in the 1940 collapse of the Tacoma Narrows Bridge in the state of Washington. Fortunately, the Delaware River Bridge had none of the inherent flaws of the Tacoma Narrows or related bridges. Now known as the Benjamin Franklin Bridge (and more familiarly as the Ben Franklin), the structure stands as a lasting monument to Ralph Modjeski and to the role of civil engineering in forging proud and vital links across the waters between neighboring cities.

Acknowledgment

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