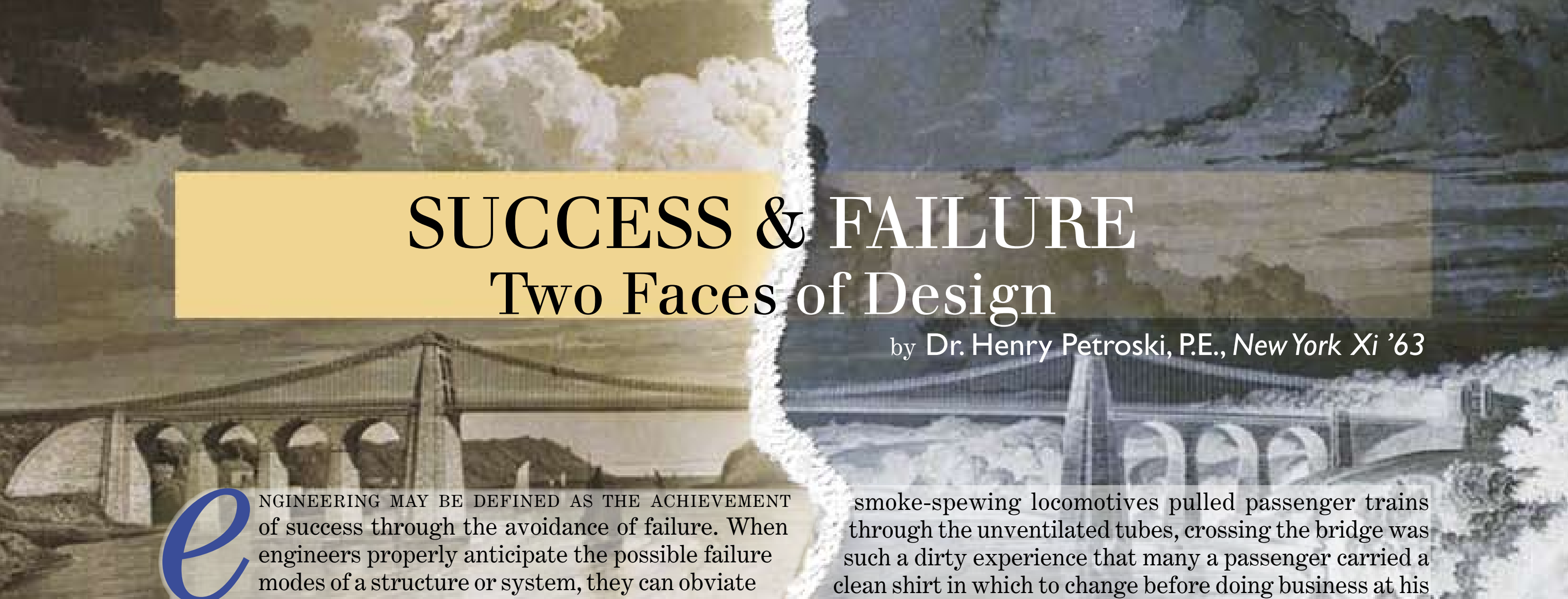


SUCCESS & FAILURE
Two Faces of Design

by Dr. Henry Petroski, P.E., *New York Xi '63*

ENGINEERING MAY BE DEFINED AS THE ACHIEVEMENT of success through the avoidance of failure. When engineers properly anticipate the possible failure modes of a structure or system, they can obviate them by design. There is thus a strong interrelationship between success and failure in engineering. This has always been the case and will continue to be so, for such a fundamental principle of engineering is independent of the state of the art or the sophistication of the tools available for design and analysis.

In the mid-nineteenth century, long-span bridge engineering was in crisis. Suspension bridges in Britain and on the Continent were notoriously unreliable, for their roadways were susceptible to being destroyed in the wind and under the feet of marching soldiers. At the same time, the developing railroads were in need of increasingly daring structures to carry the tracks across ever wider rivers, gorges, and valleys. Many an engineer thus sought an alternative to the failure-prone suspension bridge.

When faced with the problem of designing a railroad bridge to cross the strategic Menai Strait, *[top of page]* in northwest Wales, the British engineer Robert Stephenson (1803-59) came up with the idea of using a series of wrought-iron tubes—what we today would call box girders. Stephenson's longest tube had to span almost 500 feet, and so it had to be very deep. In fact, it was so large that trains could be driven through it. However, the tube's great size also meant that it was heavy, so that it might need supplemental chains to keep it from deflecting too much.

Fig. 1 When its roadway was twisted by winds and it collapsed in 1940, the Tacoma Narrows Bridge became an icon of engineering design failure.

The resulting Britannia Bridge *[Fig. 2]* was a structural success, in that its tubes barely deflected under their own weight and the added weight of a line of locomotives assembled for a proof test. Thus chains were not needed, and the tall towers built for the contingency are structurally inexplicable to those unfamiliar with the structure's design history. There were also other aspects of the bridge—such as the hundreds of thousands of rivets needed to assemble the tubes—that made it expensive to build.

In spite of its being a structural success, the Britannia Bridge was an economic and environmental failure. Because smoke-spewing locomotives pulled passenger trains through the unventilated tubes, crossing the bridge was such a dirty experience that many a passenger carried a clean shirt in which to change before doing business at his destination. In addition, the tubular bridge—effectively a tunnel in the sky—became uncomfortably hot under the summer sun.

But had it been the only way to bridge great distances, the tubular concept would no doubt have continued to be applied in spite of its expense and inconvenience. However, only a half dozen or so tubular bridges were ever built worldwide, in large part because the feasibility of alternative designs was soon demonstrated. One notable British example was the Royal Albert Bridge at Saltash *[Fig. 3]*, in southwest England, designed by the versatile engineer Isambard Kingdom Brunel (1806-59). This structure spanned about the same distance as did the Britannia Bridge; however, it did so not by employing a tubular concept but by combining the principles of an arch and a suspension bridge to produce with less iron a structure that was open to the air—hence being less expensive to build and more comfortable to use. However, like the tubular bridge, the Brunel hybrid was not to be widely emulated.

The British were led to devise these unusual structures, which proved to be dead ends in bridge design, because of their belief that pure suspension bridges were unsuitable for carrying the heavy loads of railroad locomotives. Because early suspension bridges had such flexible decks, it was thought that trains using them would cause deflections so large that the locomotives would effectively have to climb out of a valley of their own creation. Furthermore, because such bridges were prone to having their roadways destroyed in the wind, the British railways did not wish to invest in using them along their rights of way.

The German-American engineer John A. Roebling (1806-69) had a different reaction to the failure of suspension bridges. After having studied engineering at Berlin's Polytechnic Institute (and philosophy under Hegel), the young Roebling had worked at road building,

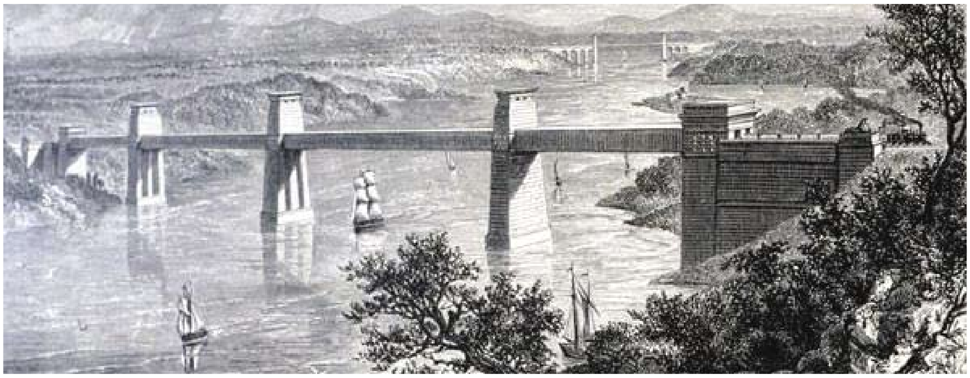


Fig. 2 The 1850 Britannia Bridge (above), was innovative in its use of a wrought-iron tubular structure. The railroad bridge remained in service until 1979, when a fire damaged its tubes beyond repair. Today, a section of one of the original structures (above right) stands beside the bridge rebuilt as an arch.

and it was during this period that he first saw a suspension bridge, which he considered a miraculous form. In 1832 he had emigrated to America to lead an agrarian life, but the image of the "miracle bridge" and his desire to build such a structure seem never to have been far from his mind. Fortunately for us all, Roebling failed miserably as a farmer, which drove him back to being an engineer and pursuing his dream.

Rather than taking the numerous examples of failed suspension bridges as a sweeping condemnation of the form, he took them as lessons from which he could learn how to build structures that would succeed in standing against the wind and other destructive forces. He concluded from the failure cases that he studied that "storms are unquestionably the greatest enemies of suspension bridges" and sought ways to combat their effects. He did this by designing a bridge whose roadway would have sufficient mass to stand steady against gusts of wind, sufficient stiffness to retain its shape, and sufficient constraint to check any motion that the wind might initiate in the structure.

When Stephenson learned that Roebling was building a suspension bridge to carry railroad trains across a windy gorge, the British engineer wrote to the American that "if your bridge succeeds, mine is a magnificent blunder," meaning, of course, that Roebling's achievement would provide a counterexample to the British hypothesis that a suspension bridge could not carry a heavy railroad train and withstand the force of the wind—and do so economically. The Niagara Gorge Railway Suspension Bridge *[Fig. 4]* opened in 1855 and thereby became the first of its type to carry railroad trains. In his final report, its engineer explained what made it work: "Weight, Girders, Trusses, and Stays." The weight provided the inertia, the girders and stays the stiffness, and the stays the means of checking unwanted motions.

Roebling went on to design the suspension bridge across the Ohio River at Cincinnati according to his rules for success learned from failures. This structure, begun just before and completed just after the Civil War, was rededicated as the Roebling Memorial Bridge in 1984. The river crossing served as a model for Roebling's masterpiece: the Brooklyn Bridge *[Fig. 5]*. Though he would not live to see it built, the father's design principles were faithfully followed by his son, Washington A. Roebling (1837-1926). And when Washington became incapacitated due to an accident, his wife, Emily Warren Roebling (1843-1903), effectively became his emissary on the construction site.

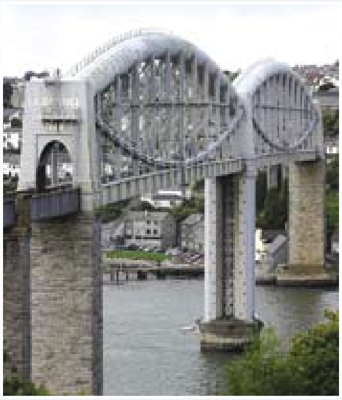


Fig. 3 The Royal Albert Bridge (above) at Saltash, in southwestern England, was designed by Isambard Kingdom Brunel as an alternative to the Britannia tubular form.

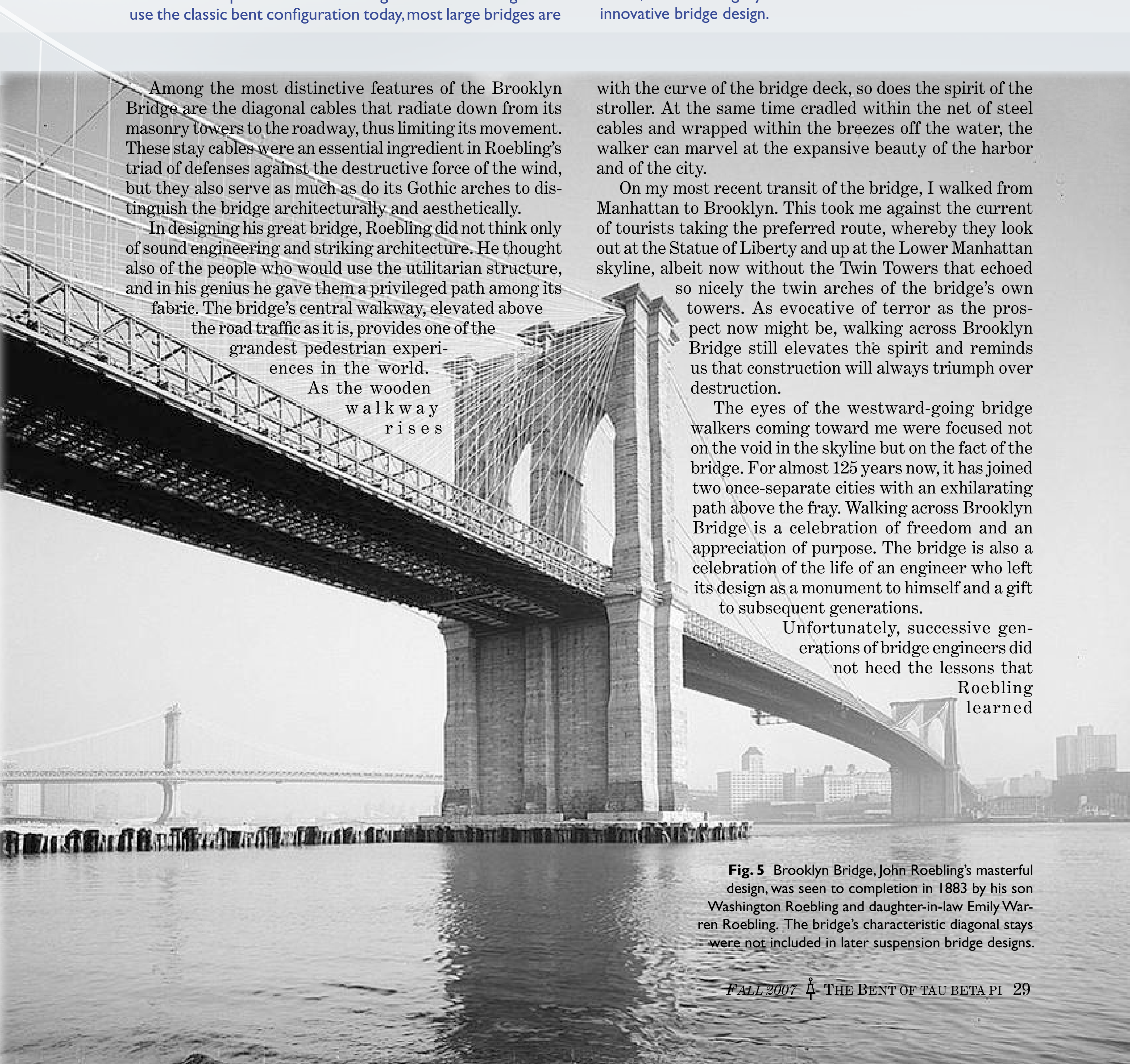
Fig. 4 John Roebling's Niagara Gorge Railway Suspension Bridge (below), which opened in 1855, was the first of its type to carry railroad trains. Roebling believed the structure owed its success to the weight and stiffness of the roadway and to the fact that it was fitted with stay cables.

“THE BENT” Origins in Bridge Design

THE CLASSIC “BENT” used by Tau Beta Pi as its symbol since 1885 holds a special place in bridge-building history. Bridges erected from long timbers became far more stable when their outermost supports were angled so their bases were farther apart than their tops (see sample photo above).

Bridges with members thus battered or ‘bent’ offered increased stability, especially regarding the serious risk of sideward collapse. While some designers of small bridges still use the classic bent configuration today, most large bridges are supported by vertical reinforced-concrete or steel elements, which are able to achieve lateral stability without the trapezoidal geometry. Yet even though the columns holding up a modern highway bridge may not be inclined, the assemblies are still referred to as “bents.”

The integrity offered by the classic bent is not gone; it has merely transmuted into new and equally important structural forms, and that integrity remains at the heart of even the most innovative bridge design.



Among the most distinctive features of the Brooklyn Bridge are the diagonal cables that radiate down from its masonry towers to the roadway, thus limiting its movement. These stay cables were an essential ingredient in Roebling’s triad of defenses against the destructive force of the wind, but they also serve as much as do its Gothic arches to distinguish the bridge architecturally and aesthetically.

In designing his great bridge, Roebling did not think only of sound engineering and striking architecture. He thought also of the people who would use the utilitarian structure, and in his genius he gave them a privileged path among its fabric. The bridge’s central walkway, elevated above the road traffic as it is, provides one of the grandest pedestrian experiences in the world. As the wooden walkway rises with the curve of the bridge deck, so does the spirit of the stroller. At the same time cradled within the net of steel cables and wrapped within the breezes off the water, the walker can marvel at the expansive beauty of the harbor and of the city.

On my most recent transit of the bridge, I walked from Manhattan to Brooklyn. This took me against the current of tourists taking the preferred route, whereby they look out at the Statue of Liberty and up at the Lower Manhattan skyline, albeit now without the Twin Towers that echoed so nicely the twin arches of the bridge’s own towers. As evocative of terror as the prospect now might be, walking across Brooklyn Bridge still elevates the spirit and reminds us that construction will always triumph over destruction.

The eyes of the westward-going bridge walkers coming toward me were focused not on the void in the skyline but on the fact of the bridge. For almost 125 years now, it has joined two once-separate cities with an exhilarating path above the fray. Walking across Brooklyn Bridge is a celebration of freedom and an appreciation of purpose. The bridge is also a celebration of the life of an engineer who left its design as a monument to himself and a gift to subsequent generations.

Unfortunately, successive generations of bridge engineers did not heed the lessons that Roebling learned

Fig. 5 Brooklyn Bridge, John Roebling’s masterful design, was seen to completion in 1883 by his son Washington Roebling and daughter-in-law Emily Warren Roebling. The bridge’s characteristic diagonal stays were not included in later suspension bridge designs.

Fig. 6 When completed in 1931, the George Washington Bridge had no truss and only a single deck, but its great width gave it mass and stiffness to stand steady against the forces of wind and traffic. A second deck, located below the original, was added in the early 1960s to accommodate increased traffic.

from early nineteenth-century suspension-bridge failures. His specifications of weight, stiffness, and stays for a successful bridge were systematically chipped away during the half century or so after the completion of the Brooklyn Bridge. In the early twentieth century, suspension bridges began to be built without stays of any kind. They did have wide (and thus heavy) roadways with deep trusses, however, which kept them steady in the wind.

A further erosion of Roebling's principles began with the completion of the George Washington Bridge *[Fig. 6]* in 1931. As originally built, its single wide deck had no stiffening truss, and this introduced a new aesthetic into the design of suspension bridges. Designs of the later 1930s had decks stiffened not by trusses but by plate girders, which produced the desirable slender look, but at the expense of stiffness. Furthermore, many of the bridges built during this period were located in remote areas, where two traffic lanes sufficed, thus making the bridge deck not only narrow but also light. The resulting unstayed, flexible, and light roadways were susceptible to being blown about by the wind—and they were.

The trend away from Roebling's failure-based design principles culminated in the Tacoma Narrows Bridge *[Fig. 1]*. At 2,800 feet between towers, this two-lane crossing had the third longest span in the world when completed in 1940. Like other light and slender bridges built to the same state of the art, its roadway undulated in the wind. Though such behavior took engineers by surprise, they did not feel that it threatened the bridges, which continued to carry traffic while their behavior was studied and a theoretical explanation sought.

As is well known, within months of its opening the Tacoma Narrows Bridge collapsed—before its behavior could be fully explained. The report of the board of engineers charged with studying the failure concluded that wind is the enemy of suspension bridges and that flexible decks are susceptible to forces of the wind. This report was issued exactly a century after Roebling had expressed the same conclusions. As the philosopher Santayana reminded us, "Those who cannot remember the past are condemned to repeat it."

The story of the ups and downs of suspension bridges provides a compelling argument for knowing our engineering history. Although there were considerable advances in theoretical models, methods of calculation, strength of materials, and construction methods in the intervening century, the Tacoma Narrows Bridge still had to be able to stand up to the same forces of the wind that destroyed the decks of early suspension bridges. The forgetting of the fundamental failure modes and the wind forces that excited them in those early structures are what condemned the Tacoma Narrows Bridge to behave as if it had been built a century earlier.

AUTHOR'S ADDENDUM: As this article was being produced in August 2007, an interstate-highway bridge spanning the Mississippi River in Minneapolis collapsed, costing several motorists their lives. When the cause of that tragic failure is determined, invaluable lessons for improving the safety of structures of its type will be learned. Let us hope that they will not be forgotten as easily as were those of historic suspension bridges.

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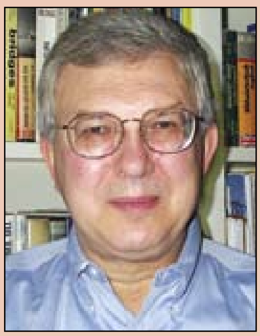

A member of the National Academy of Engineering and a fellow of the ASCE, ASME, American Academy of Arts and Sciences, and Institution of Engineers of Ireland, he has received the Ralph Coats Roe medal from ASME and the Washington Award from the Western Society of Engineers. He is the author of *Success through Failure: The Paradox of Design* and a dozen other books on engineering and design. His latest book, *The Toothpick: Technology and Culture*, is a history of the invention, development, mass production, and use of the wooden implement.