A reprint from
American Scientist
the magazine of Sigma Xi, The Scientific Research Society

THE BAY BRIDGE

Henry Petroski

San Francisco and the Golden Gate Bridge are inextricably linked in the minds of tourists, but to many a commuter across San Francisco Bay, the most significant fixed crossing in the area is the San Francisco–Oakland Bay Bridge, popularly known as the Bay Bridge. It was this bridge that was visibly damaged in 1989, when the Loma Prieta earthquake caused a 50-foot section of the upper roadway to fall onto the lower. A motorist who drove into the gap was killed, and the entire structure had to be closed to traffic while it was being repaired. The loss of the bridge, which carries Interstate 80 across the bay, emphasized the obvious—that the crossing is a vital link in the area's infrastructure, upon which the regional economy relies greatly. Uncommonly rapid repairs reopened the bridge in about a month, but damage and risk assessments made it clear that the entire structure had to be updated to make it more earthquake resistant. Thus began a saga of design and construction that, more than 15 years later, has yet to fully play out. In the meantime, because of the attention focused on the structure, the history of the Bay Bridge has rightfully regained a place of distinction in both public and professional memory.

Emperor Norton's Vision

Talk of a bridge across San Francisco Bay dates back at least to the middle of the 19th century, when suspension bridges with main spans exceeding 1,000 feet had become reality. In 1849, one such span was completed over the Ohio River at Wheeling, West Virginia, and another over that same river was soon under construction at Cincinnati. Proposals to span even greater distances were being bandied about in New York, Philadelphia, St. Louis and elsewhere, including in the San Francisco Bay area, where it had become a topic of discussion even among individuals who were neither engineers nor architects. That is not to say that they were not visionaries.

The Gold Rush attracted a lot of fortune seekers to the West Coast, and Joshua Abraham Norton proved to be one of the more colorful. Norton was a Scottish businessman who struck it rich in California—and then lost it all, including his grip on reality. He declared himself Emperor of the United States, Protector of Mexico and Sole Owner of the Guano Islands. As Emperor Norton I, he issued proclamations in the royal "We" and printed his own money, which some sympathetic local eateries are said to have honored. Among his proclamations was one dated 1869, in which he ordered and directed "that a suspension bridge be constructed from … Oakland Point to Yerba Buena, from thence to the mountain range of Saucilleto." At the time, San Francisco was known as Yerba Buena, a name that has since come to designate the island in the middle of the bay, so it appears that Norton was proposing a bridge that would have been a combination of the San Francisco–Oakland Bay and the Golden Gate bridges. Since he is not known to have had any special technical expertise, it is likely that Norton's proclamation repeated, and perhaps expanded on, proposals put forth by contemporary engineers for suspension bridges in the Bay Area. Still, such proposals were really quite ahead of their time and beyond the state of the art of even the late 19th century.

By the early 20th century, suspension bridges spanning 1,600 feet were common, and cantilever bridges of even longer span had been built or were under construction. In fact, in the early 1920s, a plan to bridge the Golden Gate with a structure spanning 4,200 feet was moving forward, and so many proposals had been put forth to cross the bay between San Francisco and Oakland that a committee was appointed to recommend the one best way. The way chosen went from the vicinity of the preexisting earthenwork pier known as the Oakland Mole across to Goat (now Yerba Buena) Island—through whose rock the world's largest-diameter tunnel would eventually be bored—and thence followed the route of an underwater ridge of bedrock on to San Francisco.

Construction on both the Golden Gate and Bay bridges began in 1933—at the height of the Great Depression—and for almost four years work on them was under way simultaneously. The independent Golden Gate Bridge and Highway District was created especially to fund and build that crossing, but the Bay Bridge was a common state highway project, albeit the most expensive to date.

Henry Petroski is Aleksandar S. Vesic Professor of Civil Engineering and a professor of history at Duke University. Address: Box 90287, Durham, NC 27708-0287.

petroski@duke.edu

Adapted from map courtesy of U. S. Geological Survey, 1942

Figure 1. San Francisco–Oakland Bay Bridge was completed in 1936 and damaged by the Loma Prieta earthquake in 1989. The need for seismic upgrades have led to the construction of a replacement span east of Yerba Buena Island.

(The final cost was $77 million, compared to the Golden Gate's $33 million.) Remarkably by today's expectations, it was the Bay Bridge, arguably the more challenging engineering task, that was completed first, in October 1936; the completion of the Golden Gate followed in May 1937. In 1939, the Golden Gate International Exposition—that year's West Coast "world's fair"—opened on the purposely man-made Treasure Island, located just north of Yerba Buena Island, to celebrate the completion of "the world's two greatest bridges," a defensible assertion by contemporary standards.

Indeed, at 4,200 feet between its towers, the Golden Gate Bridge was the longest single span of any kind in the world, and the Bay Bridge's total length of more than eight miles (about four-and-a-half of which are over water) made it the longest overall. One booklet, published in the year of its completion, exclaimed that "the San Francisco–Oakland Bay Bridge is predicted to stand for a thousand years as the longest and largest bridge in the world!" Not surprisingly, the claim proved to be overly optimistic. Within two decades, the Lake Pontchartrain Causeway, near New Orleans, spanned 24 miles over water. The Golden Gate would hold its record until 1964, when the Verrazano-Narrows Bridge opened across New York Harbor.

In the mid-1950s, when members of the American Society of Civil Engineers were polled to determine the seven modern civil-engineering wonders of the United States, the Bay Bridge was named one of them. In 1994, however, when a similar poll was conducted worldwide, it was the Golden Gate, "one of the world's most revered and photographed bridges," that was listed among the Seven Wonders of the Modern World. Still, one record that the Bay Bridge does maintain is its claim to carrying the most traffic of any bridge in the United States—at last count, an average of 280,000 vehicles daily—and it is that distinction that has been among the factors complicating the bridge's recent history and future form.

In the meantime, Emperor Norton has not been forgotten. The Emperor Norton Inn, a small hotel that no doubt has seen better days, is located within a few blocks of Union Square; the San Francisco Brewing Company in North Beach serves Emperor Norton lager; and until recently the ice cream parlor at Ghirardelli Square offered an Emperor Norton sundae. Just last year, a movement to rename the Bay Bridge for Norton, whose proclamations not only proposed bridges but also defended minorities and championed civil rights, fell on sympathetic ears in a city known for those values today. According to supervisor Aaron Peskin, "Emperor Norton was a model San Franciscan, extolling the virtues of tolerance, compassion and embracing diversity in our community." Last December, to much derision by less appreciative citizens, the San Francisco Board of Supervisors voted—whimsically, it was later said—to rename the bridge for Norton. If approved by the mayor, the proposal was to have been forwarded to the Oakland City Council and then on to the California Legislature. What the legislature might have done would have been anyone's guess, given the animosity that had developed between downstate and Bay Area politicians over what to do about the East Bay crossing.

petroski@duke.edu

Form or Function?

The rift between the Bay Area and the rest of California was not opened up by the Loma Prieta earthquake, but it has grown since that event revealed weaknesses in the Bay Bridge. After the 1989 temblor, the vulnerability of the bridge, which is located within 10 miles of both the San Andreas Fault and the Hayward Fault, could no longer be talked about in the context of geological and engineering theory alone. Something definitive clearly had to be done to protect the structure against the future "big one," and the California Department of Transportation, known as Caltrans, undertook a study to determine exactly what. The study, which took seven years to complete, concluded that reinforcing the eastern portion would be so expensive (the better part of a billion dollars) and so disruptive to traffic, that it made more sense to replace it. At the time, it was estimated that building a new bridge adjacent to the old, which traffic could continue to use during construction, would cost little more than a retrofit.

The existing East Bay crossing is undistinguished except for the steel cantilever that towers over the shipping channel just east of Yerba Buena Island. When first built, the cantilever's 1,400-foot span made it the longest in the U.S., the second longest in North America and among the longest in the world. Today, it is the fourth largest cantilever in the U.S. The rest of the East Bay crossing consists of a series of relatively modest truss spans leading to and from the area of the Oakland Mole. (By contrast, the West Bay crossing consists of a dramatic pair of tandem suspension bridges that share a common center anchorage, which because of the water depth in which it is located is in itself a most remarkable engineering feat. When built, the 2,310-foot twin structures were the second-longest suspension spans in the world. Only the 3,100-foot George Washington Bridge had a longer span, since the Golden Gate had yet to be completed.) From the Bay Bridge's earliest days, its East Bay crossing was overshadowed by the more dramatic and graceful West Bay one.

Caltrans's initial design for a new East Bay crossing did not do much to change perceptions of the relative aesthetic importance of the two parts of the bridge. When the new design failed to gain broad support, the idea for a signature span—one that would be eminently distinctive and so raise the status of the East Bay crossing (and Oakland)—was put on the table. A unique structure is generally incompatible with a quick, low-budget solution, however, and it usually engenders considerable debate over technical, aesthetic and financial matters. To sort through all the complexities, the area's Metropolitan Transportation Commission, which serves as the region's planning agency, established an Engineering Design Advisory Panel, whose members included engineers, architects, seismologists and representatives of Bay Area counties that would foot the bill for the incremental cost of building a more-than-utilitarian structure. The panel recommended that an open design competition be held to generate ideas, but Caltrans did not fully embrace the proposal.

The transportation department determined that the signature span should be either a cable-stayed or a self-anchored suspension bridge, and it issued a contract to a joint-venture team to establish which design would be more appropriate. The team consisted of T. Y. Lin International, a distinguished San Francisco-based firm, and Moffatt and Nichol, which is based in Long Beach, thus involving both local and downstate economies. As is often the case in large projects, specialty firms were also involved as subconsultants, and the New York-based Weidlinger Associates, which has considerable experience with suspension bridges, became the team's structural engineer for that option. The charge from Caltrans was to develop for each bridge type preliminary designs to about one-third completion, so that they could be compared as to how they would look, how they would be constructed, how they would behave in an earthquake and what they would cost. The limited competition was managed by the regional planning commission's Engineering Design Advisory Panel.

And the Winner Is …

A self-anchored suspension bridge is one in which the pull of the cables is opposed by the push of the deck, much the way the tension in a rubber band is resisted by the compression of the objects it binds together. Most such bridges look very much like a conventional suspension bridge, with its cables draped over two towers, but without the massive anchorages that bookend it. The winning Bay Bridge design eliminated not only both of the anchorages but also one of the towers, resulting in a unique structure.

According to one of the principal designers at Weidlinger, the specification of a single tower was driven mainly by underwater conditions, which would have required that a premium be paid for a second tower. Among the other constraints was that no bridge tower could be higher than the 518-foot-tall ones of the West Bay suspension spans. Also, unlike the existing crossing, in which westbound traffic uses a lower deck, the new bridge had to carry all traffic on a single level. Finally, the cost of the signature structure was not to be any greater than that of viaducts of the kind it would link up with. Since a cable-stayed bridge generally requires a taller tower than a suspension bridge of the same span, the latter had an advantage. In the end, the self-anchored suspension bridge appears to have won out mainly on aesthetic grounds. One of its principal designers has described it as being "envisioned as a 'white line' across the Bay."

Not all structural critics agree with either the motivation or the choice. Some believe that because San Francisco has, in the Golden Gate and the West Bay crossing, two world-class suspension bridges, Oakland thought it was time that it had one also. Christian Menn, the distinguished Swiss bridge

Figure 2. Construction of a replacement bridge for the East Bay is proceeding parallel to the original span, which remains open to traffic. (Photograph courtesy of John Huseby/Caltrans.)

designer who is responsible for the new signature span of Boston's Central Artery, terms the East Bay suspension-span solution an "architectural bridge," one whose design is driven by form, as opposed to an engineering one, whose design should be driven by structural and constructional considerations. While admitting that "the appearance of the bridge is certainly very good," Menn presciently remarked in early 2003 that "the costs will be much higher than originally planned."

Sign Here for Signature Span

The decision about the East Bay crossing was no doubt influenced by the distinctiveness of the design. By the end of the 20th century, cable-stayed bridges had become almost commonplace, but self-anchored suspension bridges were rare. In fact, there are only 20 in the whole world. (The first three in the U.S. were Pittsburgh's Sixth, Seventh and Ninth Street bridges, built in the late 1920s.) Furthermore, the one proposed for the East Bay would be the longest of its type and the first asymmetrical one to be built in the U.S. But with uniqueness also comes uncertainties—of complications during construction and of cost, as Menn had predicted. The initial estimated cost for the signature span was $740 million, which was almost as much as the $866 million that one Caltrans engineer estimated in 1997 that it would cost for replacing the entire East Bay crossing with a viaduct. (At the time, the additional cost of demolition of the existing crossing was put at $40 million.) In 1998, when the design had been selected, the overall cost estimate had reached $1.4 billion. Governor Pete Wilson wanted Bay Area residents to shoulder the bulk of the cost, with only $500 million coming from the state's transportation budget. The project was expected to be completed by 2004.

Once the decision was made to go ahead with the signature span, its design could proceed to completion, which meant looking more closely at details, which usually means making changes. Among the design changes that had to be implemented was the incorporation of a bicycle path. Since no traffic lanes were to be sacrificed to do this, the bike lane was designed to be cantilevered off the south side of the deck structure. This destroyed the symmetry of the deck and introduced a large eccentric load. To balance that load, a heavy counterweight had to be incorporated along the north side of the deck. The overall design loads on the bridge structure were increased also by revised predictions of ground motion in the event of an earthquake. Since the deck of a self-anchored suspension bridge reacts against the cables, which it anchors, the greater the tensile forces in the cables, the greater the compressive forces in the deck. And the greater the forces along the deck, the more it must be stiffened, lest it buckle. But additional stiffening means additional weight, which in turn increases the tension in the cables, which then increases the compressive force in the deck, which consequently requires more stiffening. Breaking such a vicious circle naturally complicates the solution to the structural design problem—and increases the cost of design and construction.

In the meantime, construction on the much more conventional part of the crossing, which has come to be known as the Skyway, was to proceed—even though in 2001 the estimated cost of the East Bay crossing had risen to $2.6 billion. At groundbreaking ceremonies, which took place in early 2002, Governor Gray Davis pointed out that the concrete viaduct, which was more than a mile long, was designed to survive an earthquake as great as the one that hit San Francisco in 1906. The alignment of the new one-level dual viaduct parallels the existing double-decker one, and so nearby construction cranes have been a looming presence to travelers. The high cranes have been especially visible from vehicles traveling on the (westbound) upper deck, and they provided a strikingly regular arrangement

petroski@duke.edu

when they were idle during a period of inactivity last Christmastime, when the structure was said to be 65 percent complete. The tower cranes, which are used to erect the piers on which the segments of the skyway will rest, stood in formation, and their booms looked not unlike the shouldered arms on a line of Brobdingnagian soldiers rising out of the bay and serving as an honor guard pointing the way to the future location of the signature span.

The Price of Uniquity

A call for bids to construct the unique signature structure went out in early 2003. By this time, the estimated cost of the entire East Bay crossing had risen to about $2.5 billion, a level that if known early on would surely have favored retrofitting the original bridge. By this time, however, things had gone too far to turn back—or so it was argued—and so the term of a toll surcharge instituted to help pay for the project was extended by 30 years. (Thus, today, a $3.00 toll is collected but only from westbound traffic.) In spite of all the warnings, Caltrans continued to maintain, publicly at least, that bids for the signature structure would come in close to the original estimate—that is, around $750 million. Unfortunately, only one bid was submitted—by a joint venture comprising American Bridge Company, located in Pennsylvania, Nippon Steel Bridge of Tokyo and Fluor Enterprises of Aliso Viejo, California—and it was for a whopping $1.4 billion. Needless to say, there was considerable shock and much subsequent speculation on what accounted for the difference. The rising cost of steel was blamed, as was the increased cost of risk insurance after September 11, 2001, but neither of these could be blamed entirely.

Whatever the reasons for the unexpectedly high bid, the cost of the overall project had now soared to more than $5 billion, which forced a reconsideration of the signature span. After months of speculation, the extraordinary bid was rejected on the day that it was to expire, September 30, 2004. Governor Arnold Schwarzenegger announced in December that he preferred to scrap the self-anchored steel suspension span and substitute an extension of the concrete skyway. This would enable the entire project to be completed by 2012, the date at which the signature span was to be finished, according to supporters of the governor's position. But others warned that switching to a viaduct design at this stage would entail additional design and environmental reviews, which would threaten to delay the project further. Opponents believed that the governor's move was intended to force the Bay Area politicians to increase the region's portion of the project's funding, if it wanted to maintain the signature span. A suggestion that was a compromise of sorts—namely, to change from a self-anchored suspension bridge to a more conventional cable-stayed bridge, which had already been partially designed and which could use the foundation that was already under construction—was not taken by the state government.

The repeated escalation of costs and slippage of completion date have been an embarrassment for Caltrans. The embarrassment became especially acute in the closing days of 2004, when it was reported that an audit ordered by the state legislature found that the transportation department had "concealed cost overruns … mismanaged the project and consistently underestimated expenses."

At about the same time, news of the opening of a new bridge in France begged for comparison. The Millau Bridge is a strikingly beautiful and graceful cable-stayed structure, which closes the last gap in the superhighway between Paris and Barcelona. The overall concept should be credited to Michel Virlogeux, the engineer who designed the Pont de Normandie. However, news reports of the Millau Bridge's completion attributed its design to its more visible and more widely known architect, Sir Norman Foster. The 1.6-mile-long structure, whose tallest pylon is higher than the Eiffel Tower, is said to appear to float above the mist and clouds that can fill the Tarn Valley in southern France. Just as spectacular is the fact that the bridge was built in less than three years at a cost of $522 million, all financed privately. Investors expect to recoup their investment—and more—out of income from tolls, which for automobiles will be as high as $8.60. In contrast to the Millau Bridge, which proud locals are calling "the most beautiful bridge in the world," the East Bay crossing may turn out to be an undistinguished viaduct that will, according to contemporary estimates, take three times as long to build and cost almost ten times as much. It has been called "the most expensive bridge in the world."

Acknowledgment

I am grateful to the many Bay Area residents—especially Bob Piper of Berkeley, Peter Neumann of Menlo Park and Karen Petroski of San Francisco—who have kept me posted, via e-mail messages and newspaper clippings, on the ongoing saga of the East Bay Crossing.

Selected Bibliography

Bryant, Elizabeth. 2004. A tale of two bridges. *San Francisco Chronicle,* December 24, pp. A1, A9.

Camo, Sante. 2004. The evolution of a design. *Structural Engineer,* January, pp. 32–37.

Princeton University. 2004. *Teaching and Scholarship in the Grand Tradition of Modern Engineering: A Symposium in Honor of David P. Billington at Seventy-Five and Forty-Five Years of Teaching at Princeton University.* Princeton, N.J.: Department of Civil and Environmental Engineering.

Dillon, Richard, Thomas Moulin and Dan Denevi. 1979. *High Steel: Building the Bridges across San Francisco Bay.* Millbrae, Calif.: Celestial Arts.

Herel, Suzanne. 2004. Emperor Norton's name may yet span the Bay. *San Francisco Chronicle,* December 15, p. A1.

Mladjov, Roumen V. 2004. The most expensive bridge in the world. *Modern Steel Construction,* September, pp. 53–55.

Plummer, John W. 1936. *The World's Two Greatest Bridges.* San Francisco, Calif.: Personal Stationery Company.

Powers, Mary B. 2004. California scraps sole bid for signature span. *Engineering News-Record,* October 11, pp. 10–11.

petroski@duke.edu