> Washington Bridge, the writer came to the conclusion that the arrangement of nearly flexible trusses in the finished bridge, and the omission of trusses in the initial stage of a single highway deck, were perfectly permissible and would secure a degree of rigidity at least equivalent to that of any of the aforementioned large modern bridges. (Ammann 1933)

The George Washington Bridge was initially designed as a double-deck bridge, as shown in Fig. 4-14. With an 8.8-m truss depth and a corresponding depth-to-span ratio of 1:120, the truss was much shallower than that of the Williamsburg Bridge (a bridge of approximately half the span with a 12.2-m deep truss and a depth-to-span ratio of 1:40). Therefore, it is not as stiff, and this is why the George Washington Bridge is described as "a semi-flexible truss."

But Ammann and Moisseiff reached the conclusion that even this was unnecessary, and only the upper deck to carry the initial stages of traffic was built as shown in Fig. 4-15 and in the photo in Fig. 4-16. It stood as nothing more than an unstiffened suspension bridge. The only attribute that made this feasible was the stiffening effect of the dead load; as weight increased, the stiffness of long-span suspension bridges was enhanced, thus rendering a truss unnecessary, as Ammann and Moisseiff claimed.

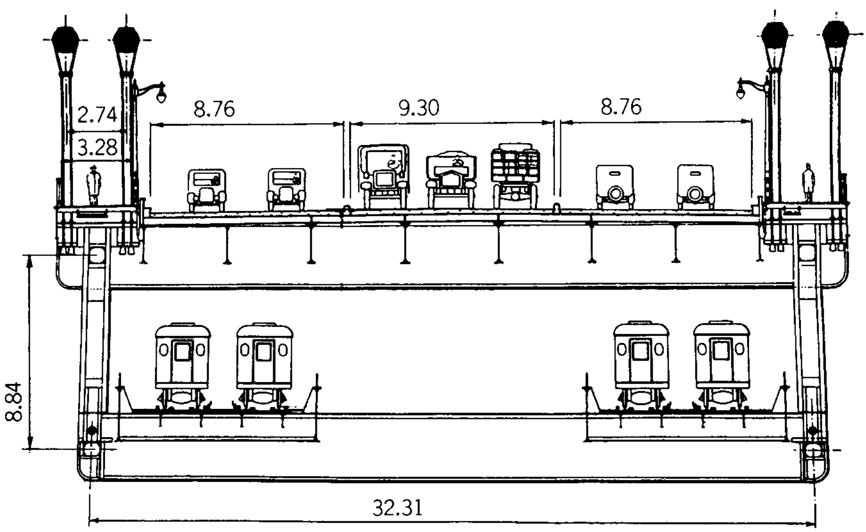

Figure 4-14. Ammann's and Moisseiff's original design for the George Washington Bridge truss.
Source: Ammann (1933).

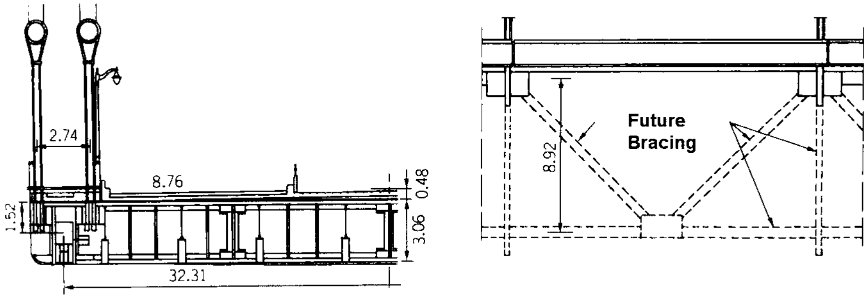

Figure 4-15. As-built suspended structure of the George Washington Bridge in 1931. *Source:* Dana et al. (1933).

As a matter of interest, a total of about 95,000 tonnes of steel were used in the George Washington Bridge, and four cables 91.4 cm in diameter—larger than those of the Delaware River Bridge—were used; they weighed 30,000 tonnes.

The views of Ammann and others were in this sense correct. Until the George Washington Bridge was transformed into a double-deck structure in 1962 as per the original plans, the unstiffened suspension bridge had been in service essentially problem-free for 30 years.

Two Large Projects in San Francisco

With the completion of the George Washington Bridge in 1931, engineers had succeeded in building a 1,000-m span without any intermediate supports. The suspension bridge as a structural type had made this achievement possible.

Figure 4-16. George Washington Bridge upon completion in 1931. *Source:* Courtesy of the Port Authority of New York & New Jersey.

The success of the George Washington and Delaware River bridges on the East coast proved a decisive influence over two major projects in California that had been pending for many years, the Golden Gate Bridge and the San Francisco-Oakland Bay Bridge. Two huge projects, similar in scale to the Akashi Kaikyo Bridge and the Seto Ohashi Bridge in Japan's Honshu-Shikoku Bridge project, were begun simultaneously in 1933 in the San Francisco Bay area (Fig. 4-17) (Kawada 1990).

The first span was the exceptionally famous Golden Gate Bridge, to which Joseph Baermann Strauss (1870–1938) as chief engineer devoted his life. Since 1921, Strauss had planned a hybrid structure consisting of a can-

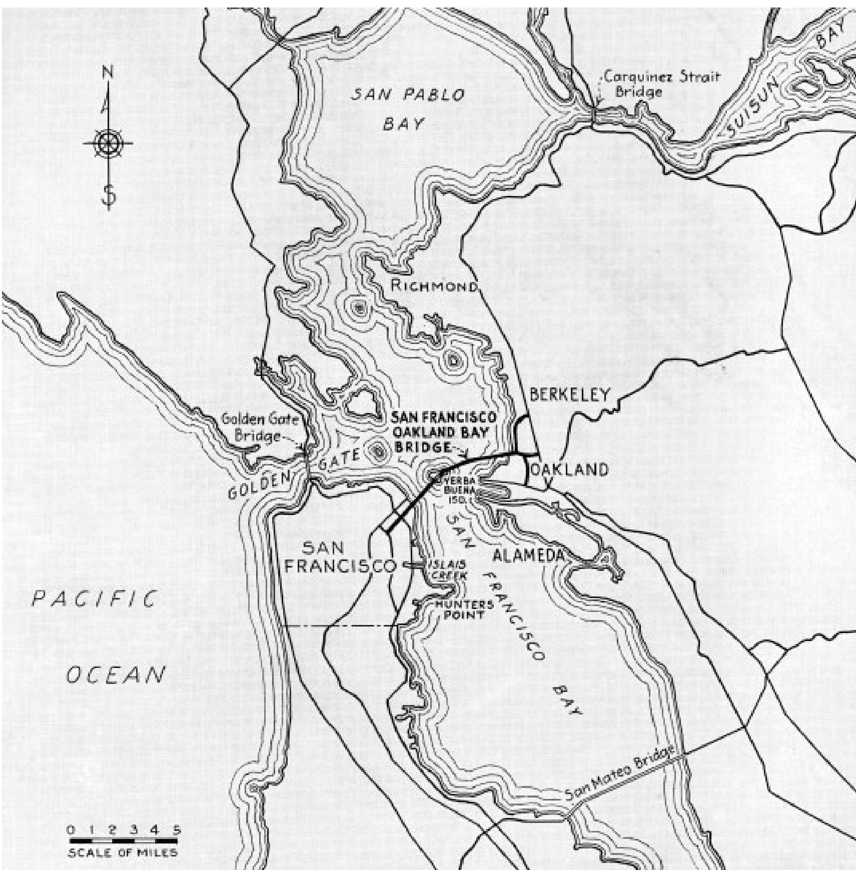

Figure 4-17. San Francisco Bay and the location of the Golden Gate Bridge and the San Francisco-Oakland Bay Bridge.
Source: U.S. Steel (1936), with permission of American Bridge Co.

tilever truss and suspension bridge spanning 1,200 m, as shown in Fig. 4-18. He obtained a patent for the concept and energetically campaigned for its construction (Petroski 1995, 277). However, when it became apparent that the George Washington Bridge would be completed successfully, Strauss abandoned his patented concept and designed the crossing as an orthodox suspension bridge. Figure 4-19 shows the new design, in which Ammann, Moisseiff, and Derleth were deeply involved as the three members of the Advisory Board of Engineers established by the Bridge District's Board of Directors. A peculiarity was its art deco-style tower design developed by consulting architect Irving F. Morrow.

Construction of the Golden Gate Bridge began on January 5, 1933. The most difficult and time-consuming task was the construction of the marine foundation for the San Francisco tower pier. It was planned to build this foundation 20 m under the water and about 340 m offshore, where the strait meets the open waters of the Pacific Ocean. Fortunately, an extended sheet of rock was relatively shallow, and therefore it was planned to install a trestle to the pier site. However, because the actual rock surface had been polished by the action of strong tides, it was extremely difficult to install the trestle on the exposed rock. Then the original trestle was immediately destroyed by wave action, but was rebuilt to a much more robust design.

Construction of the San Francisco tower foundation itself proved even more difficult. The magnitude of the challenge was amply demonstrated by

Figure 4-18. Strauss's original plan for the Golden Gate Bridge, a hybrid structure consisting of a cantilever truss and suspension bridge.
Source: Derleth Collection, Water Resources Center Archives, University of California, Berkeley. Reproduced with permission.

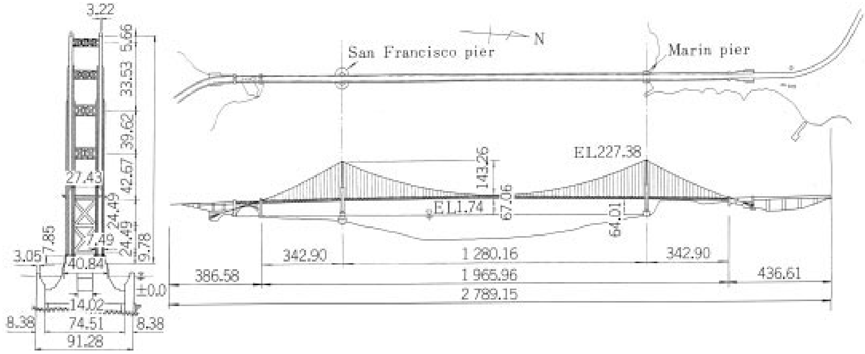

Figure 4-19. Strauss's final design of the Golden Gate Bridge, which was strongly influenced by Ammann and Moisseiff.
Source: Ito et al. (1999), courtesy of Tadaki Kawada.

the fact that its design underwent significant change four times. The original plan was to float a steel caisson into a concrete fender that would serve as a breakwater and provide protection from ship collision; the pier would then be built after excavating to a depth of 33 m (Golden Gate Bridge and Highway District 1970).

Construction progressed to the point that the 10,000-tonne steel caisson was towed to the site and pulled inside the fender. However, the mooring ropes broke immediately because of direct exposure to surging waves from the open sea that entered the fender. The caisson then swayed and struck the fender, exposing it to danger as well. In the end, the enormous caisson had to be pulled out of the fender and was scuttled in the open sea. Work to close the fender proceeded so as to eliminate damage from surging waves, and the design was subsequently changed to transform the fender itself into a foundation. With several design changes to the fender, the bearing area of the tower foundation increased to 2.4 times the size of the original plans (van der Zee 1986, 210–213).

The construction of the San Francisco tower foundation and tower was the most difficult challenge of this project. They required 2 years and 4 months to complete, which encompassed more than half of the span's overall construction period of 4 years and 3 months. The remaining work was completed in just under 2 years, including construction of the cables, stiffening trusses, and other tasks. On May 27, 1937, the 1,280-m span Golden Gate Bridge was opened, and so began its reign of about a quarter-century as the world's longest span bridge (Fig. 4-20).

Figure 4-20. Golden Gate Bridge and bronze statue of Joseph B. Strauss.
Source: Author.

Although in span not equaling the Golden Gate Bridge, the San Francisco-Oakland Bay Bridge was unquestionably the world's largest bridge to date in terms of the scale of its construction. As shown in Fig. 4-21, the bridge's double-deck structure initially accommodated two interurban tracks and nine road lanes. It now accommodates 10 road lanes. In addition to twin 704-m-span suspension bridges, this major bridge complex includes a 164-m-long tunnel on Yerba Buena Island and a 427-m-span cantilever truss. Its total length of 13.2 km, including the 8.1-km over-water section and approaches, is no less impressive than Japan's Seto Ohashi route between Kojima and Sakaide in the Honshu-Shikoku Bridge project. The latter's combined highway-railroad bridge features a 9.4-km-long over-water section and a total length of 13.1 km when approaches are included. Moreover, the San Francisco-Oakland Bay Bridge was built before the Second World War, a half-century earlier than the Japanese bridge.

For this bridge, Modjeski, Moisseiff, and Moran again served on the Board of Consulting Engineers. The largest problem in this project was how to connect the 3-km section between San Francisco and Yerba Buena Island. With the state of engineering at that time, this distance was too great to

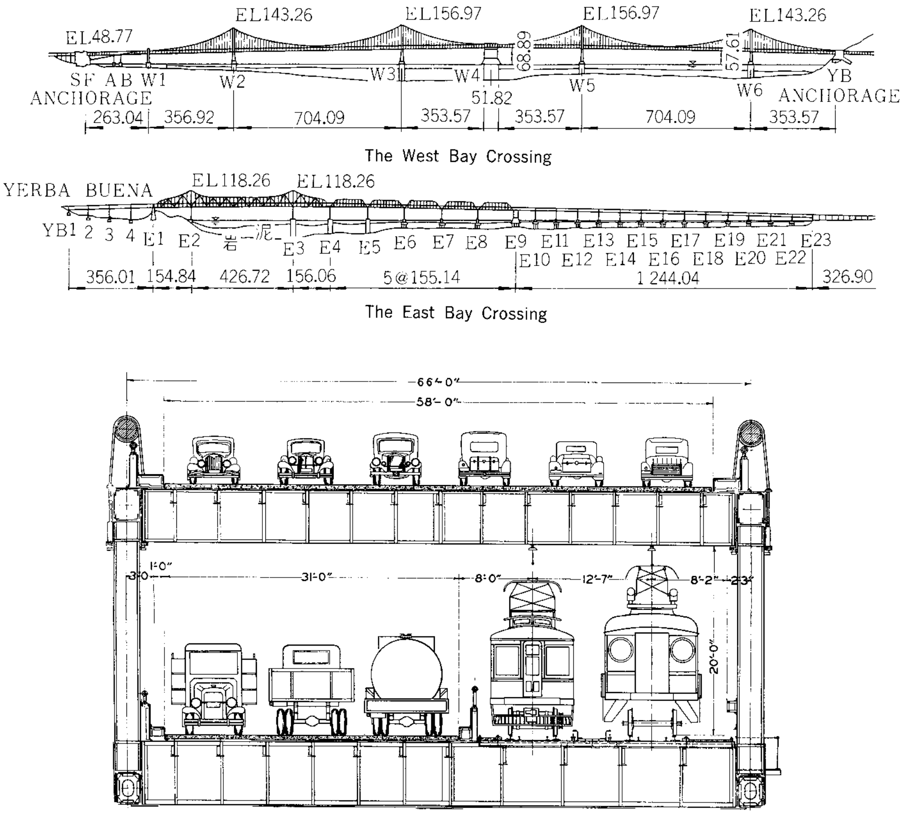

Figure 4-21. San Francisco-Oakland Bay Bridge, original plan and cross section.
Source: U.S. Steel (1936), with permission of American Bridge Co.

envisage spanning with a single suspension bridge. However, the resulting concept—to align two suspension bridges end-to-end—generated the new problem of constructing a huge artificial island for a common anchorage (*W4* in Fig. 4-21). This artificial island was of an extraordinary scale and had to be embedded in rock at the unprecedented depth of 65 m to resist the several thousand tonnes of horizontal pull from the cables, which entered the anchorage at a height of 84 m above sea level.

It was Daniel Moran who resolved this problem brilliantly. As a foundation consultant, Moran had demonstrated his abilities in the George Washington and Delaware River bridges. From the standpoint of workability, the pneumatic caisson method at that time was limited to depths of only 38 m. For the San Francisco-Oakland Bay Bridge, Moran developed the concept of the multiple-domed caisson that integrated the best features of both dredging and pneumatic caissons. With this concept, global tilting could be controlled by adjusting the buoyancy of each dome by means of compressed air (Fig. 4-22).

An assembly of 55 steel tube caissons, each 4.5 m in diameter and assembled in a 5 × 11 arrangement to form a gigantic 27.6-m-long × 59.1-m-wide block, was floated under its own buoyancy and towed to the site. After positioning at the site, concrete was cast in openings between the steel tubes. This gradually lowered the caisson, expelling air from the steel tubes in the process (Fig. 4-23). As the large caisson sank, each steel tube was extended upwards through the addition of more sections. Before the caisson reached deep bedrock at a depth of 65 m, the caps of the steel tube caissons were removed, allowing excavation to continue through layers of sedimentary rock and mixed boulder-clay soils, which were dredged by grab buckets. Frequently the caisson cutting edge struck boulders, causing the caisson to tilt, and this required divers to enter the caisson to remove them by underwater blasting.

Moran's idea was successful. The cutting edge passed through the 30-m-thick sedimentary layer and reached bedrock in June 1934, about 1 year after

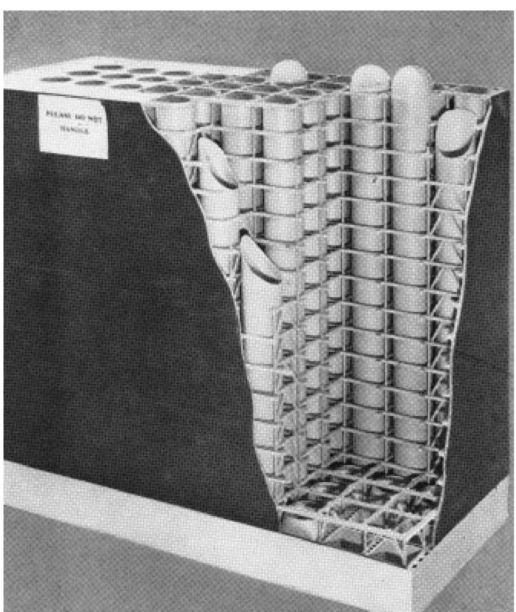

Figure 4-22. Mock-up, multiple-dome caisson conceptualized by Daniel Moran.
Source: State of California (1934).

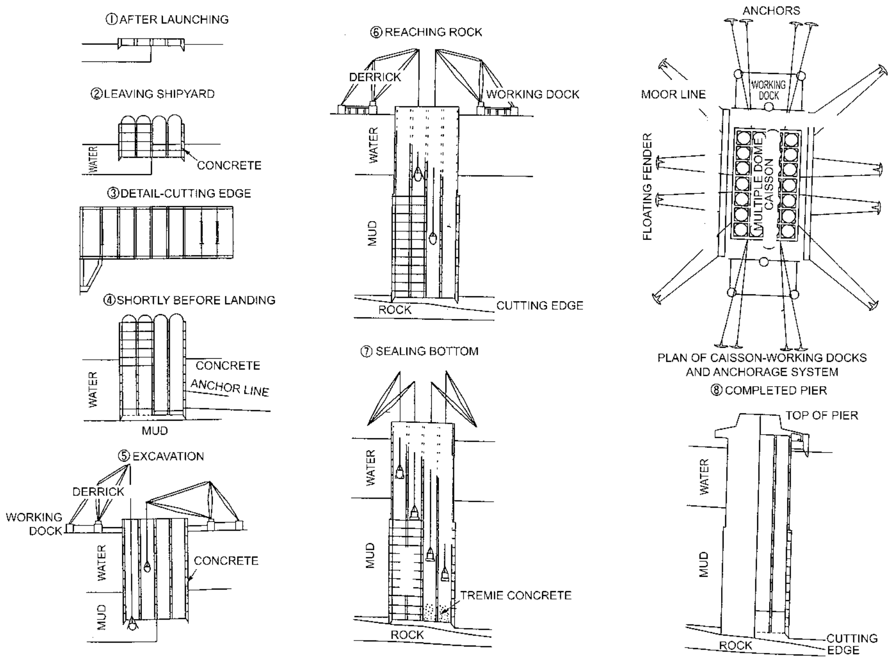

Figure 4-23. Construction procedure, multiple-dome caisson.
Source: State of California (1934).

sinking had begun (State of California 1934). Yet even after the caisson had settled on bedrock, other difficulties arose, such as leveling the rock and compacting the tremie concrete. Eventually, however, the gigantic middle anchorage, with a rectangular cross section measuring 59.1 m longitudinally and 27.6 m transversely, and standing 65 m deep and 84.3 m above water level, was completed (Fig. 4-24) (U.S. Steel 1936). This artificial island was created using the largest caisson built to that time, and was proudly reported by engineers to be larger than the pyramid for King Khufu, with more concrete than was used in the Empire State Building.

The construction of the middle anchorage *W4* was the most challenging aspect of building the San Francisco-Oakland Bay Bridge. Subsequent work steadily progressed, and all construction was completed and the bridge opened to traffic in November, 1936. With an amazingly short construction period of only 3 years and 4 months, this immense project was now finished (Fig. 4-25).

Figure 4-24. Middle anchorage *W4* of San Francisco-Oakland Bay Bridge.
Source: U.S. Steel (1936), with permission of American Bridge Co.