

42. On the postwar litigation leading to Armstrong's death, see Tom Lewis, *Empire of the Air*, pp. 300-327.

Chapter Eight

AMMANN AND THE GEORGE WASHINGTON BRIDGE

A more closely interconnected civilization emerged from the new networks, processes, and machines that spread in the early twentieth century. New bridge structures supplied a different form of connection no less vital. By 1939, the bridges of New York, Philadelphia, Washington, St Louis, and San Francisco were essential to the everyday life of those cities and their surrounding areas. The need for new and larger bridges was a natural outgrowth of the demand for more and better roads in the 1910s and 1920s. The availability of inexpensive steel in the late nineteenth century gave civil engineers a new material with which to design and build bridges of much greater size and strength than traditional structures of wood and stone.

Steel bridge engineering made a spectacular advance in the George Washington Bridge, completed in 1931 over the Hudson river between New Jersey and New York. Designed by Othmar Ammann, the structure was almost twice the span of any previous bridge and it became a model for the design of other long-span bridges. The structure was innovative in two ways. First, Ammann employed a new and daring theory to estimate the weight of traffic that achieved dramatic economy in the cost of the bridge. Second, he relied on a new theory that justified minimizing the vertical depth of the
roadway deck. This theory led to great danger when engineers relied on it to design less massive suspension bridges later in the 1930s.

Bridges from Iron to Steel

As a bridge-building material, iron was far stronger than wood and far less costly than stone. Modern techniques improved the quality and quantity of iron and gave structural engineers the freedom to bridge longer spans. The first great designer of iron bridges, Thomas Telford (1757-1834), built a graceful arch of cast iron in his 1814 Craigellachie Bridge in Scotland. Telford's Menai Straits Bridge in Wales, completed in 1826, used wrought iron chain-link cables to suspend a roadway of unprecedented length, 580 feet between its two towers. With maintenance, these bridges proved durable and economical. Telford's two bridges along with many others that he built are still in use.

The coming of the railroad in the mid-nineteenth century created a demand for iron bridges of greater size and strength. The French engineer Gustave Eiffel (1832-1923) built wrought iron arch bridges, such as his 541-foot Garabit Viaduct in southern France, to carry trains around mountains and over gorges. The pylon towers supporting his elevated railway at Rouzat anticipated the design of Eiffel's famous 1889 tower in Paris. John Roebling (1806-1869) built a number of iron suspension bridges in the United States, culminating in his 1866 Cincinnati Bridge, which spanned 1,057 feet. With the development of structural steel in the 1850s and 1860s, civil engineers designed
bridges that could span longer distances and carry heavier loads. James B. Eads (1820-1889) completed the first steel arch bridge in 1874; it spanned the Mississippi river at St.
Louis. John A. Roebling's Brooklyn Bridge, finished by his son and daughter-in-law in
1883, was the first suspension bridge in steel. The Brooklyn Bridge used treated
("galvanized") steel wire to prevent rust and achieved a record span of 1,595 feet.

A bridge has to carry two kinds of weight: Its dead load is the static weight of
the structure itself. Its live load is mainly the weight of traffic crossing it. Live loads
also include any additional dynamic pressures acting on the structure, such as wind. Arch
bridges work in compression: the arch under the roadway supports the weight of the
bridge and the traffic going across it. Cable bridges work in tension: vertical wires
suspend a roadway deck from cables, which are strung over towers and anchored on each
side of the bridge. In an arch, the two abutments or end points have to resist the weight
of the bridge in two directions, horizontally and vertically (Fig. 8-1). A cable has to
resist the same forces, the vertical being greatest at the tower tops.

Bridging the Hudson

The Brooklyn Bridge connected Manhattan to Brooklyn and facilitated the union
of the five boroughs of New York City in 1898. By then, New York was drawing
commuters from a wide area, including Long Island, southern Connecticut, southern New
York State, and northern New Jersey. The city needed to be supplied from even greater
**Arch Bridge**

Arch and cable suspension bridges must carry their own weight, called *dead load*, and the weight of traffic, or *live load*.

An arch bridge carries these loads by *compression*: the weight presses down on the arch and is transmitted to the two abutments (the two end points of the arch). The abutments must resist this pressure horizontally and vertically.

A civil engineer can calculate the vertical and horizontal resistances or *reactions* with the help of two formulas. The vertical reaction \( P \) is the product of the load \( q \) and the length or span of the arch \( L \) divided by two. The division by two reflects the fact that one-half of the total weight goes to each abutment. The horizontal reaction \( H \) is equal to the product of the load per unit of length \( q \) and the total length \( L \) squared, divided by the arch's vertical rise \( d \) times eight.

![Arch bridge forces](image)

\[ P = \frac{qL}{2} \]
\[ V = \frac{qL^2}{8d} \]

**Cable Bridge**

Where an arch bridge works by compression, a cable bridge works in *tension*: vertical wires suspend the roadway deck from cables, and the cables must resist the weight as a pulling force. The cables go over towers and are anchored to the abutments.

The vertical and horizontal reactions on a suspension bridge are calculated at the tower tops rather than at the abutments. But the formulas are the same for cable bridges, except that \( d \) stands for the vertical sag of the cable instead of the rise of the arch.

distances. Steel bridges eventually connected Manhattan to the boroughs of the Bronx and Queens, and linked Staten Island to New Jersey. But New York's greatest need was to cross the Hudson River between Manhattan and New Jersey.⁶

Plans to bridge the Hudson began soon after the Civil War and the States of New York and New Jersey jointly authorized a bridge in 1890. Financing did not materialize, though, and after 1900 the Pennsylvania Railroad built tunnels under the river instead. But the growth of motor vehicle traffic following the introduction of the Model T and other cars made new road crossings urgent. Ferry service could not accommodate the volume of traffic and interest in a great bridge over the Hudson River revived after the end of the First World War in 1918.⁷

In 1888, the engineer Gustav Lindenthal (1850-1935) had proposed a suspension bridge to carry railway traffic over the Hudson from mid-Manhattan to New Jersey. As bridge commissioner of New York in 1902-3, he initiated several great bridge projects to connect the boroughs of the city. After these, his most important project was the Hell Gate Bridge between Ward's Island and the Borough of Queens. The 1917 Hell Gate was the longest-spanning steel arch bridge in the world and was designed to carry a railroad. In 1920, Lindenthal revived and expanded his earlier proposal for a Hudson River bridge near 57th Street in Manhattan.⁸
Lindenthal's 1920 design (Fig. 8-2) called for a steel suspension bridge. A single span 150 feet above the water at its center would extend 3,240 feet in length between two giant towers on the river embankments. The design was dramatic and would have spanned a distance twice as long as the Brooklyn Bridge. But Lindenthal believed that the principal use of his bridge would be to carry railway traffic, and he designed the bridge to carry the enormous weight of twelve fully loaded freight trains as well as four lighter rapid transit lines and sixteen lanes of motor-vehicle traffic. The estimated cost of his bridge, $180,000,000, was far higher than the $11,000,000 that a motor vehicle tunnel was estimated in 1913 to cost. In 1919, the States of New York and New Jersey authorized a vehicular tunnel between Manhattan and New Jersey. The Holland Tunnel, named for its designer Clifford Holland on its completion in 1927, proved difficult to construct, and with only two lanes it was not the answer to the need for a major new Hudson river crossing.

**Ammann as Public Entrepreneur**

Lindenthal's chief assistant on the Hell Gate Bridge, Othmar Ammann (1879-1965), realized that motor vehicles were replacing railroads as the mainstay of twentieth century transportation. Ammann came to the United States from Switzerland in 1904, two years after graduating from the Federal Technical Institute in Zürich (Fig. 8-3). He had learned structural design in Zürich from Professor Wilhelm Ritter (1847-1906), who had made the analysis of loads on suspension bridges more rigorous. Ritter also taught
In 1920, Gustav Lindenthal proposed a steel suspension bridge across the Hudson river from 57th Street in Manhattan. Lindenthal believed that railroads would continue to be as important as they had been in the nineteenth century. He designed his bridge to carry twelve fully-loaded freight trains on a lower deck and four lighter transit rail lines, sixteen lanes for motor vehicle traffic, and two pedestrian walkways on an upper deck. The estimated cost of his design was $180,000,000.

Othmar Ammann's 1923 design for a steel suspension bridge across the Hudson at 179th Street in Manhattan did not support heavy freight trains. Ammann proposed instead a bridge with eight lanes for motor vehicles and two pedestrian walkways on an upper deck and four lanes for light rapid transit trains below the deck. Ammann's bridge was estimated to cost $60,000,000. In fact, the bridge would cost only half this amount, about $31,000,000.

Othmar Ammann at work at the Port Authority circa 1930. (Courtesy Margot Ammann.)
that structures could carry their weight by means of efficient and elegant form and not simply be utilitarian structures.10

Ammann saw that New York needed crossings primarily for automobiles and trucks. He believed that a cable suspension bridge to carry motor vehicles and light rapid transit lines (Fig 8.2) could be built at far less cost than Lindenthal’s structure. By not carrying heavy freight railroad trains, such a bridge would have no need to connect to the freight terminals of midtown Manhattan. The bridge could be located at the northern end of the island, where the inflow of bridge traffic and the approaches to the bridge would also be less disruptive to the city.

Ammann tried to persuade Lindenthal to adopt a less costly bridge over the Hudson to carry mostly motor vehicle traffic, but Lindenthal was unwilling to abandon his vision of a great railroad bridge. Bankers in New York refused to finance the Lindenthal bridge, and Manhattanites worried that traffic from a bridge at 57th Street would worsen midtown congestion. In March 1923, Ammann resigned from Lindenthal’s office and began to seek backing for a less costly motor vehicle bridge that he intended to design himself. To build what would become the George Washington Bridge, Ammann realized that a structure of this scale was necessarily a public concern and that political support could be crucial to achieving his vision. He sought political support and became an entrepreneur whose goal was to create a public rather than private enterprise.11
After finishing the Hell Gate Bridge in 1917, Lindenthal's office lacked work, so at Lindenthal's suggestion, Ammann occupied himself for three years managing a clay factory in New Jersey whose directors included Lindenthal and George P. Silzer, an attorney. In 1922, Silzer won election to a three-year term as Governor of New Jersey, serving from 1923 to 1926. An activist Wilsonian Democrat, Silzer wanted to improve the highway system in New Jersey and build bridges to New York City. Ammann approached Silzer after his election and won the governor's support for a great motor vehicle bridge over the Hudson from Fort Lee, New Jersey, to 179th Street in Manhattan.

Ammann and Silzer faced an obstacle, however, in the fact that Fort Lee was part of Bergen County, New Jersey, a Republican stronghold. A great bridge backed by a Democratic governor would encounter opposition in the county most likely to benefit from the bridge. In his January 1923 inaugural address, Silzer called for a bridge across the Hudson from New Jersey to New York, but over the next year Silzer stayed in the background, leaving Ammann to generate public support for the bridge. Local business interests on both sides of the river, and the major daily newspaper in Bergen County, The Bergen Record, favored a tunnel to connect New Jersey and northern Manhattan. Over the summer and fall of 1923, local fund-raising for a tunnel began. Ammann was unable to persuade local leaders on either side of the river to support a bridge.

In November 1923, however, the Port Authority of New York and New Jersey announced a public hearing on December 5 to hear proposals for additional tunnels to
accommodate motor vehicles. Formed in 1921 by the Governors of New York and New Jersey as a bi-state planning agency, the Port Authority’s mandate was to relieve railway congestion in the New York metropolitan area. The agency proved unable to develop a workable plan for railways. Silzer and Ammann urged the Port Authority to consider new motor vehicle bridges at its hearing and the agency’s board of commissioners agreed.

In the month prior to the December hearing, Ammann prepared the case for a span across the Hudson, estimating that a motor vehicle bridge could be built for $30,000,000, or $25,000,000 without transit rail lines. He argued that a bridge could support itself through tolls At the hearing, most speakers agreed on the need for more vehicular crossings. While some supported tunnels, others supported a bridge on the northern end of Manhattan. Dwight Morrow, a partner in the J. P. Morgan Bank of New York, informed Governor Silzer that private funding for a bridge was unlikely but that the Port Authority might raise the money itself. Silzer and Ammann pressed the agency to construct and operate its own bridges and tunnels. On December 17, Ammann submitted a report to Silzer. The Governor sent it to the Port Authority staff, and on December 21, the commissioners agreed to carry out a study of a great bridge between 179th Street and Fort Lee.

During the winter and spring of 1924, Ammann held meetings with civic groups in Bergen, Passaic, and Morris Counties in New Jersey; in Washington Heights, Harlem, the Bronx, Westchester, and Yonkers in New York; and in southern Connecticut.
Success finally began to come when a state senator from Bergen county backed the bridge that spring. The New Jersey and New York state legislatures approved the Port Authority's decision to conduct a study and authorized two bridges to Staten Island. Governor Al Smith of New York, like Silzer a Democrat, favored public control of bridges and tunnels and supported a more active role by the Port Authority. The Harlem Board of Commerce then switched its support from a new tunnel to the Ammann bridge. Finally, the New Jersey state senate passed a bill in January 1925 authorizing a bridge over the Hudson river at Fort Lee, and the state assembly agreed. The New York state legislature concurred in March.14

Ammann submitted a bid for the contract to design the two Staten Island bridges. He lost to the more experienced private bridge design firm of J. A. L. Waddell. But the Port Authority soon began a tradition of relying on its own engineers for design work, and Ammann offered himself as a staff engineer. With Silzer's backing, the Port Authority hired Ammann and entrusted him with the design and supervision of the construction of the great Hudson river bridge.

**Ammann as Engineering Designer**

Since the early nineteenth century, the U.S. Army Corps of Engineers has regulated navigable rivers in the United States. The Corps required a bridge across the Hudson to have a clearance of at least 200 feet above water at its midspan and 185 feet
above water near the towers. The Army and private navigation interests opposed the use of piers in the middle of the river. For his bridge, Ammann envisioned a single long span with a midpoint 210 feet above the water and a length of 3,500 feet between two towers, one near each embankment. To build such a bridge at a substantially lower cost than Lindenthal's structure, however, Ammann had to rethink some fundamentals of bridge design.

Ammann first questioned the assumptions of what traffic loads a motor vehicle bridge would carry. A theoretical maximum would fill every lane with heavily-loaded trucks traveling end to end. This loading would resemble railroad trains in the weight they would exert on a bridge. But in fact this kind of end-to-end loading of heavy trucks was unlikely. Cars and trucks usually traveled with one or two vehicle lengths of space between them and there were usually more cars than trucks. In 1916, the engineer J. A. L. Waddell had argued that for motor vehicle bridges, long spans over 800 feet should be designed for one-half the weight of heavily-loaded trucks laid end to end.

Ammann knew that the estimated live load would have a large influence on the amount of steel the bridge would need; and the amount of steel was crucial to the cost of the bridge. He designed the George Washington Bridge to have an eighty-foot wide roadway with eight lanes for motor vehicles, which he believed would need to support 20,000 pounds of live load per foot of span length. Two pedestrian walkways would need 2000 pounds per foot. On two narrower parallel decks underneath, he designed four
lanes for rapid transit trains with a capacity for 24,000 pounds per foot. Adding all the traffic gave a total live load of 46,000 pounds per foot. Taking Waddell's safety factor of one-half suggested a design for 23,000 pounds per foot of span length.

The Delaware River Bridge (now the Ben Franklin Bridge) in Philadelphia was designed to carry one-half of its estimated total live load. But engineers knew that as the span length of a bridge increased, the heaviest vehicles decreased as a percentage of the overall traffic, and a traffic analysis showed that the 1,750 foot span of the Philadelphia bridge could have been designed for one-third, not one-half, of the maximum live load. Ammann decided that the percentage of heavy trucks would be even less on his own much longer span of 3,500 feet. He concluded that the bridge could be designed for an even greater reduction of the maximum load in any one of the lanes reserved for motor vehicles and rapid transit trains.

Ammann developed an estimate of the traffic load from several simple formulas that he devised (Fig. 8-4). He calculated that a span of 3500 feet for an eight-lane bridge could be designed for about seventeen percent of the maximum live load, or about 8,000 pounds per foot instead of 46,000 pounds per foot. Seventeen percent was a dramatic reduction in the estimated live load for a bridge and it was a stunning reduction for a bridge span that would be twice as long as any in existence. Few drivers who cross the George Washington Bridge today are aware of the fact that the bridge is only designed to carry about one-sixth of its estimated maximum traffic weight. But traffic studies in the
Ammann’s Traffic Load Estimate

Before the George Washington Bridge, structural engineers estimated the maximum traffic load on a bridge by imagining what it would weigh with every space filled by heavily-loaded trucks laid end-to-end. For the George Washington Bridge, this maximum live load would have been 46,000 pounds per foot of span length. Engineers recognized, however, that motor vehicles usually traveled with one or two vehicle lengths between each vehicle and that more vehicles would be cars than trucks. Engineers before Ammann designed bridges on the assumption that a long-span bridge would need to support fifty percent of its estimated maximum traffic load.

Ammann realized that as the span length of a bridge increased, the likelihood of maximum traffic load would diminish. To calculate this reduction, he invented a formula \( K = 0.2 + \frac{160}{(200 + L)} \), to calculate the percentage of maximum load in one lane \( K \) on a bridge. For a span \( I \) of 3500 feet, he estimated \( K \) to be 0.24 or 24 percent:

\[
K = 0.2 + \frac{160}{(200 + 3500)}
\]

\[
K = 0.2 + 0.04 = 0.24
\]

Ammann also reasoned that the more lanes the bridge had, the less likely it was that all would carry the same load per foot at the same time. Ammann calculated this likelihood as a percentage by a second formula, \( C = 0.5 + \frac{2}{(n + 3)} \), in which \( n \) was the number of lanes on the bridge. For one lane, \( C \) was 1.0; for eight lanes \( n = 8 \), it was 0.6818 (rounded to 0.682):

\[
C = 0.5 + \frac{2}{(8 + 3)}
\]

\[
C = 0.5 + 0.182 = 0.682
\]

Multiplying the maximum traffic load of 46,000 pounds per foot by 0.682, and then multiplying the result by the 0.24 estimated for one lane, gave a figure of 7,529 pounds per foot, or about 16 percent of the maximum. This was the amount of live load for which Ammann believed the bridge would need to be designed. He rounded this figure up to 8,000 pounds per foot (about 17 percent) in his final design.

1920s confirmed Ammann's safety factor, which became standard practice. The steel used in the George Washington Bridge represented about $23,000,000 of bridge's total cost of $57,000,000. Had the bridge been designed to withstand one-half of its maximum traffic load, the steel would have likely cost an additional $7,400,000.

To complete his safety estimate, Ammann also calculated the stresses in the steel cables (Fig. 8-5). Steel reaches a yield point under stress, at which it deforms before reaching its breaking point. For the steel wire that he planned to use in his cables, the breaking point was about 220,000 pounds per square inch (psi) of stress and the yield point was about 150,000 psi. Engineers normally allow a stress of about one-half the yield point in steel and Ammann took this allowable stress ($f_a$) in the cables to be 82,000 psi. From this number, he calculated the cross-sectional area needed in the steel cables to be 3200 square inches. If he had instead calculated the stress under the full maximum traffic load of 46,000 pounds per foot, the allowable stress in 3200 square inches of cable would have been 148,000 psi. Under this maximum load, the bridge still would have held, although with almost no margin of safety. Responsible public officials would have never tolerated a safety factor so thin, but they accepted Ammann's factor of 150,000/82,000 psi as a reasonable compromise. Technical needs thus depended on a social choice between safety and economy.

Ammann's traffic-load estimate was daring but successful. His embrace of a new design theory, however, proved dangerous. The deck of a suspension bridge hangs from
Ammann calculated the total load for the George Washington bridge by adding his estimate of the traffic or live load to the estimated dead load. He then computed the horizontal and vertical reactions in the structure (1,000 lbs = one kilopound or kip):

- **Live load:** 8,000 lbs/ft
- **Dead load:** 39,000 lbs/ft
- **Total (q):** 47,000 lbs/ft

Length (L): 3,500 ft
Depth (d): 325 ft

\[ H = \frac{qL^2}{8d} = \frac{(47,000)(3500)^2}{8(325)} = 221,442 \text{ kips} \]

\[ V = \frac{qL}{2} = \frac{(47,000)(3500)}{2} = 82,250 \text{ kips} \]

Four parallel cables would hold up the roadway and tension in the cables would be greatest near the tower tops. This maximum tension (T_m) near the tops is the square root of the squares of the horizontal and vertical reactions: \( T_m = \sqrt{H^2 + V^2} \)

For the cables (T) inside the two towers, maximum tension was 236,223 kips. The cables leading to the abutments (T_I) had different values for maximum tension: on the New Jersey side, \( T_I = 260,000 \text{ kips} \), and on the New York side, \( T_I = 261,000 \text{ kips} \). Since the cable had to be the same size from end to end, Ammann took 261,000 kips as the maximum tension (T_m) for deciding how strong to make the cables.

Ammann chose a cable with a breaking point of 220,000 psi (pounds per square inch) and a yield point of 150,000 psi. An engineer normally designs the cable to withstand about one-half of the yield point, a factor known as the allowable stress (f_a). By dividing the maximum tension by it, Ammann was able to calculate the total cross-sectional area of the four cables (A). He took 82,000 psi as the allowable stress:

\[ A = \frac{261,000 \text{ kips}}{82 \text{ psi}} = 3190 \text{ sq. in. (rounded to 3200 sq. in.)} \]

\[ = \frac{800 \text{ sq. in. in each cable}}{284} \]

a flexible cable. To prevent excessive motion of the deck, engineers usually strengthen the deck of a suspension bridge with trusswork underneath. But a new idea in bridge design called *deflection theory* (Fig. 8-6) argued mathematically that the stiffer the cable was relative to the deck, the less would be the effect of live load on the deck. The theory persuaded Ammann to think that if the cable carried a great dead load, the deck would need almost no stiffness and could be designed to have a very light and slender form.²³

The deflection theory encouraged Ammann to reduce the vertical trusswork on the two decks in his original design (Fig. 8-7). He soon eliminated the lower deck and vertical truss altogether in the final 1931 bridge, so that the cables suspended only a single thin roadway for cars, trucks, and pedestrians (Fig. 8-8). Estimated use of the bridge made the lower deck unnecessary and the deflection theory provided a structural reason for not building it. The final cost of the George Washington Bridge was three million dollars less than the $60,000,000 in bonds sold by the Port Authority to pay for the project.²⁴ Ground-breaking began on September 21, 1927, and the bridge opened for traffic on October 25, 1931.

Suspension bridges in the United States began to be designed to have lighter decks in 1909 but the George Washington Bridge set a new standard in the design of large-scale bridges.²⁵ Later cable bridges in the 1930s followed its example of suspending very thin decks over very long spans.²⁶ The decks of the later structures soon ran into trouble. On a suspension bridge, the cables resist only vertical loads. The deck
The Deflection Theory

The deflection theory relates the live load on the cable and the deck of a suspension bridge \((P)\), the vertical distance that the cable and deck "deflect" or descend under this weight \((v)\), and the stiffness of the cable and deck \((S)\). The presentation below simplifies the mathematics in the theory in order to explain its basic idea:

\[
P_1 \quad \quad \quad P_2
\]

\[
v_1 = P_1/S_1 \quad \quad \quad v_2 = P_2/S_2
\]

Cable with deflection \(v_1\) \quad \quad \quad Deck with deflection \(v_2\)

The total live load \((P)\) consists of the proportion carried by the cable at its midpoint \((P_1)\) and the proportion carried by the deck at its midpoint \((P_2)\). The deflection of the cable \((v_1)\) and the deck \((v_2)\) occur at the same point and so descend the same distance: thus \(v_1 = v_2\). The cable and deck also possess stiffness, which for the cable can be designated \(S_1\) and for the deck \(S_2\). The amount of deflection equals the weight divided by the stiffness: \(v_1 = P_1/S_1\) and \(v_2 = P_2/S_2\).

In place of \(v_1 = v_2\), we can substitute the equation \(P_1/S_1 = P_2/S_2\). Multiplying each side by \(S_1\), we can then say that \(P_1 = P_2 (S_1/S_2)\). Substituting \(P_2 (S_1/S_2)\) for \(P_1\), the total live load, \(P = P_1 + P_2\), can be rewritten as \(P = P_2 (S_1/S_2) + P_2\), or \(P = P_2 (1 + S_1/S_2)\). Dividing each side by \((1 + S_1/S_2)\) gives us the formula: \(P_2 = P/(1 + S_1/S_2)\).

From this formula, \(P_2 = P/(1 + S_1/S_2)\), it can be seen that if the deck stiffness \((S_2)\) is 100 times more than the stiffness of the cable \((S_1)\), then \(S_1/S_2 = 1/100\), and \(P_2 = P/(1 + 0.01)\). The live load on the deck \(P_2\) amounts to all but about one percent of the load. But if the cable stiffness is 100 times more than the deck, then \(S_1/S_2 = 100/1\) and therefore \(P_2 = P/(1 + 100)\). The cable carries all but about one percent of the load.

Ammann and other engineers of the time concluded that if almost all of the stiffness was in the cable, almost none would be needed in the suspension bridge deck. Unfortunately, deflection theory did not take into account the dynamic effects of winds on a deck with very little stiffness. After the Tacoma Narrows bridge failure of 1940, suspension bridges were designed with stiffer and more aerodynamically stable decks.
Artist's Sketch of Steel Tower with Protected Observation Platform

FIG. 8-8
is vulnerable to sideways motion and uplift from below caused by wind. Bridge engineers, following Ammann, regarded wind as a purely horizontal force that could be resisted by horizontally-placed trusses underneath the deck. But wind can attack a bridge from many angles. Winds can gust more strongly under the bridge than over it, and alternating gusts can lift and then depress the roadway. A very thin deck will gallop or undulate under severe wind conditions. Horizontal trusses are no protection against these dynamic wind effects.

Bridges built later in the 1930s with thin but narrower decks experienced dangerous problems with winds. Four months after its completion in 1940, the Tacoma Narrows bridge in Washington failed when moderate winds caused the structure to lift up, undulate, twist, and then collapse (Fig. 8-9). In the aftermath of Tacoma, structural engineers added vertical stiffness to suspension bridges that had such thin decks. The George Washington Bridge was so wide and so heavy that dynamic winds did not make its deck unstable. In 1962, a second lower deck was added to accommodate increased traffic, and this double deck (for which the cables were originally designed) added stiffness to the span (Fig. 8-10). Ammann went on to design a number of other large bridges, including an arch bridge between Bayonne, New Jersey, and Staten Island, New York. His last and greatest structure was a suspension bridge over the Verrazano Narrows between Brooklyn and Staten Island, completed in 1964. For the Verrazano Bridge, Ammann developed a tubular deck that provided greater stiffness without the
Fig. 8-9
Tacoma Narrows Bridge
1940
box-like appearance of a truss. Large suspension bridges since then have been built with aerodynamically-designed decks that are thin but safe against wind.

**History and Aesthetics in Design**

Nineteenth century bridges usually had masonry towers or were covered entirely in stone, because tradition demanded a stone appearance in public works. The steel towers on the George Washington Bridge were designed to be covered with concrete and then faced with stone. The final cost of $57 million did not include this masonry work. To keep down expenses, the Port Authority decided to leave the steel towers uncovered, and the public embraced the skeletal towers as a striking visual feature of the bridge. The George Washington Bridge thereby symbolizes an ambiguity. Its dense steel framework represented the structure required to support both the cables and the structurally unnecessary concrete and stone. Ammann's later bridges were free of such excess steel.

In the design of large bridges, twentieth century civil engineers shared with engineers in other industries the urge to make their work more scientific and mathematical. Amman's traffic estimate was strikingly simple but it was informed by experience. In embracing the deflection theory, however, Ammann revealed the danger of treating design purely as a matter of theoretical deduction. In writing about the George Washington Bridge, Ammann underlined the "structural simplicity" of its design. At the same time, he defended the design on aesthetic grounds, observing that English
suspension bridges of the early nineteenth century were elegant solutions to the problem of spanning long distances.\textsuperscript{29} Further historical study would have revealed to Ammann the experience of the earlier bridges with dynamic winds and the failure of some as a result. The Menai Straits Bridge had to be reinforced with vertical trusses under the deck. John Roebling built a different kind of reinforcement into the Brooklyn Bridge by using cable stays, diagonal wires extending from the towers to the deck. These stays were more elegant than trusses and appeared to many to be ornamental, but their real purpose was to help stabilize the roadway against wind. Recent suspension bridges have come back to the ideal of thinness in the roadway deck but engineers have learned to include aerodynamic stability as part of the design.\textsuperscript{30}

Many engineers hold the view that history and aesthetics are extraneous to their professional knowledge. Theory, in their view, is self-contained, and a work's elegance is an added feature with no necessary relation to its efficiency or economy. An ideal of aesthetic excellence was an important and laudable part of Ammann's vision that he brought with him from Switzerland. In 1931, he also completed the Bayonne Bridge connecting New York to New Jersey, which beat the George Washington Bridge for the aesthetics award that year of the American Institute of Steel Construction. But both bridges displayed Ammann's engineering ideal of bridges that were not only efficient and economical but also elegant.\textsuperscript{31}
In his successful effort to build what was at the time the world's longest-spanning bridge, Othmar Ammann operated as an entrepreneur of structure in steel. Another new building material, reinforced concrete, also opened new possibilities for structure in the first four decades of the twentieth century. Two engineers, John Eastwood and Anton Tedesco, explored the potential of reinforced concrete to achieve efficient, economical, and elegant engineering through new forms.

References


3. On Roebling's Cincinnati Bridge, see John A. Roebling, *Report of John A. Roebling, Civil Engineer, to the President and Board of Directors of the Covington and Cincinnati Bridge Company* (Cincinnati, 1867).


19. For Ammann's traffic load analysis, see Allston Dana, Aksel Andersen, and George M. Rapp, "George Washington Bridge: Design of Superstructure," *ASCE Transactions*,...
No. 97 (1933), pp. 103-104. In the actual calculations, Ammann rounded $K$ from 0.24 to 0.25, and the figure 0.681 (0.681818) to 0.682. These gave a product of $K$ and $C$ as 7,843. He rounded this number to 8,000 pounds per foot.


22. For the cable strength, see Allston Dana, Aksel Andersen, and George M. Rapp, "George Washington Bridge: Design of Superstructure," *ASCE Transactions*, No. 97 (1933), pp. 109


Technology and Culture, pp. 558-559. The table below (ibid., p. 559), gives the deflection moment in the stiffening trusses at midspan and shows the effects of thinness:

<table>
<thead>
<tr>
<th>Kip Feet</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,390,400</td>
<td>Truss with no cable support</td>
</tr>
<tr>
<td>56,150</td>
<td>Truss with moveable cable support (deflection theory)</td>
</tr>
<tr>
<td>6,980</td>
<td>More flexible truss with moveable cable support (deflection theory)</td>
</tr>
</tbody>
</table>


26. The following table shows the trend toward lighter and thinner decks:

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Date Built</th>
<th>Width (ft.)</th>
<th>Span L (ft.)</th>
<th>Depth h (ft.)</th>
<th>Ratio of h/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Williamsburg</td>
<td>1903</td>
<td>118</td>
<td>1,600</td>
<td>40.0</td>
<td>1/40</td>
</tr>
<tr>
<td>Manhattan</td>
<td>1909</td>
<td>120</td>
<td>1,470</td>
<td>24.5</td>
<td>1/60</td>
</tr>
<tr>
<td>Bear Mountain</td>
<td>1924</td>
<td>55</td>
<td>1,630</td>
<td>25.9</td>
<td>1/63</td>
</tr>
<tr>
<td>Delaware R.</td>
<td>1926</td>
<td>89</td>
<td>1,750</td>
<td>27.8</td>
<td>1/63</td>
</tr>
<tr>
<td>Ambassador</td>
<td>1929</td>
<td>60</td>
<td>1,850</td>
<td>22.0</td>
<td>1/84</td>
</tr>
<tr>
<td>George</td>
<td>1931</td>
<td>106</td>
<td>3,500</td>
<td>10.0</td>
<td>1/350</td>
</tr>
<tr>
<td>Washington</td>
<td>1937</td>
<td>90</td>
<td>4,200</td>
<td>25.0</td>
<td>1/168</td>
</tr>
<tr>
<td>Golden Gate</td>
<td>1939</td>
<td>25</td>
<td>1,080</td>
<td>6.5</td>
<td>1/166</td>
</tr>
<tr>
<td>Deer Island</td>
<td>1939</td>
<td>75</td>
<td>2,300</td>
<td>10.9</td>
<td>1/210</td>
</tr>
<tr>
<td>Bronx-White-</td>
<td>1940</td>
<td>40</td>
<td>2,800</td>
<td>8.0</td>
<td>1/350</td>
</tr>
<tr>
<td>Narrows</td>
<td>1940</td>
<td>40</td>
<td>2,800</td>
<td>8.0</td>
<td>1/350</td>
</tr>
</tbody>
</table>

27. For the Tacoma Narrows collapse, see F. B. Farquharson, "Aerodynamic Stability of Suspension Bridges with Special Reference to the Tacoma Narrows Bridge," University of Washington Engineering Bulletin Experiment Station Bulletin, No. 116, Part 1, investigations prior to October 1941. No. 116 appeared in four more parts published in 1950, 1952, 1954, and 1955. Aware that the bridge was in danger, Professor Farquharson was on the bridge at the time of its failure.

