Chapter 1

Manhattan Bridge

Bojidar Yanev and Brian Gill

CONTENTS

1.1 DESIGN AND CONSTRUCTION

After the Brooklyn (1886) and Williamsburg (1903) Bridges, the Manhattan was the third East River suspension bridge to provide vehicular and rail traffic between the New York City boroughs of Brooklyn and Manhattan. It was opened officially on December 31, 1909, by Mayor George B. McClellan, Jr., whose term was expiring on that date. About 30 m (100 ft) of the bridge lower roadway over Division Street in Manhattan consisted of temporary planking to allow the passage of the mayor's motorcade

(*New York Times*, January 1, 1910). The Second Avenue elevated portion of the subway had to be lowered 6 ft over a length of 244 m (800 ft) to accommodate the bridge clearance (*New York Times*, December 5, 1909) in that area.

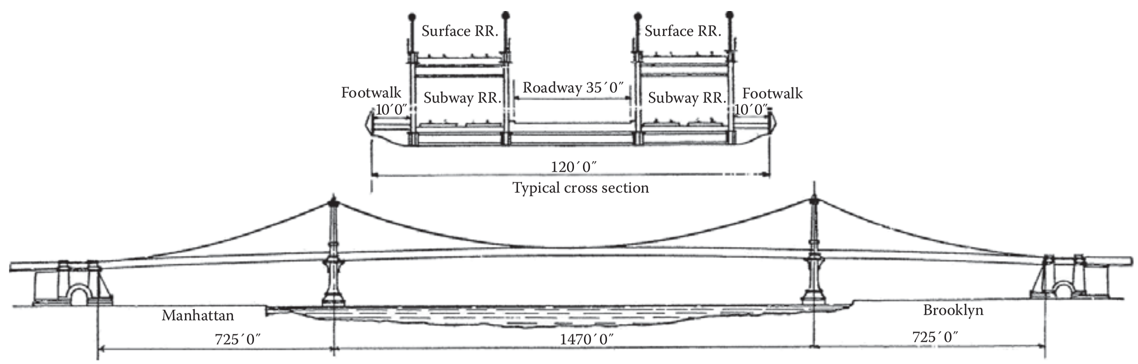
The Manhattan Bridge is 1761.4 m (5779 ft) long between abutments at the lower level and 1855 m (6086 ft) between portals on the upper levels. Both approaches are supported by three- and four-span continuous Warren trusses. Several stringer and floor beam spans support the upper roadways between portals and abutments. The main suspension bridge is 890 m (2920 ft) long, with a main span of 448 m (1470 ft) and two 221 m (725 ft) side spans. Four 7.3 m (24 ft) deep stiffening trusses (designated as A, B, C, and D from south to north) run between abutments. These are supported by piers on the approaches and by the four main cables on the suspended spans. Their spacing is 8.5 m–12.2 m–8.5 m (28 ft–40 ft–28 ft). The Brooklyn and Manhattan bound upper levels rest on trusses A–B and C–D, respectively. All other traffic is at the lower chord level. Figure 1.1a shows the original elevation and cross section of the bridge along with some details related to its construction. Figure 1.1b illustrates its location across the East River relative to the Brooklyn Bridge downstream.

As illustrated in Figure 1.2, the bridge has always carried the most people of any East River crossing. Originally, it was designed for railroad on the upper level, trolley cars underneath, and vehicular traffic on a wood-block deck in the center of the lower level. The structure now supports four vehicular lanes on the upper level, three lanes of vehicular traffic, four subway transit tracks, and a bikeway and a walkway on the lower level. Recent traffic counts surpass 500,000 commuters on weekdays (110,000 passengers in 85,000 vehicles, 390,000 mass transit riders, and 6000 bikers and pedestrians). Figure 1.3a and b shows general views of the bridge.

1.1.1 The transportation demand

The need for an all-railroad bridge was first suggested in the summer of 1895 by James Howell, former New York City mayor and later president of the Brooklyn Bridge Board of Trustees, as a measure to relieve congestion on the Brooklyn Bridge (Nichols, 1906). At the time, rail travel had much more influence on public policy than vehicular travel had. Manhattan Bridge would be the first railroad bridge to connect Long Island, the most populated island in the United States, with the mainland in a combination with a Hudson River crossing. The latter would be Gustav Lindenthal's 869.25 m (2850 ft) long suspended braced-eyebar bridge carrying several railroad tracks crossing the Hudson River first at Canal Street, then at 10th Street.

John Mooney, Secretary for the Board of Public Improvements noted (New York City Department of Bridges, 1904, pp. 341–342), "By removal of comparatively few buildings of poor quality and low cost, the solving of the problem of a straight line thoroughfare from the junction of Atlantic



Construction commenced October 1st 1901	
Const. of cable comm. Aug. 1, 1908, finished Dec. 10, 1908	
Opened to traffic	December 31, 1909
Total length	6855 feet
Length of main span	1470 feet
Length of each of the four cables	3224 feet

Diameter of each cable	24¼ inches
Total number of wires in each cable	9462
Total length of wire in the four cables	23,132 miles
The clear height over river channel is 135 ft. above mean high water	
Height of steel towers above mean high water	336 feet
Total weight of structural steel in bridge and approaches	60,000 tons

Cost of construction	$16,698,188.98
Cost of land	$14,386,516.40
Total cost	$131,084,705.38

Commissioner

Estimated travel during year 1916

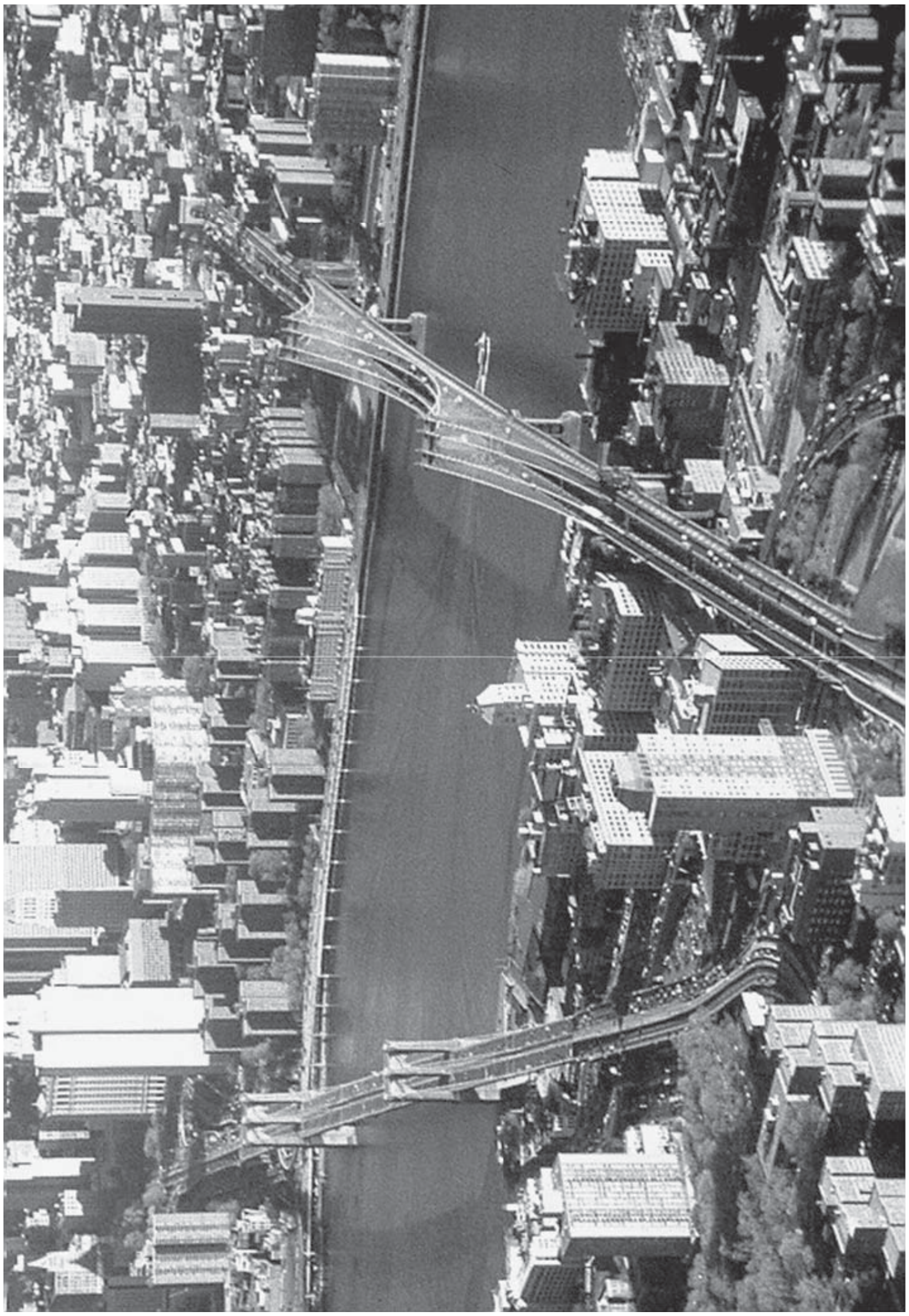
Subway trains	837,651 cars	43,248,000 passengers
Surface railroads	447,454 ”	12,605,000 ”
Vehicles	4,030,867	7,664,000 ”
Pedestrians		412,000

Total number of people crossing bridge during 1916–63,929,000

(a)

Figure 1.1 (a) Manhattan Bridge, 1909.

(*Continued*)



(b)

Figure 1.1 *(Continued)* (b) Brooklyn and Manhattan Bridges across East River.

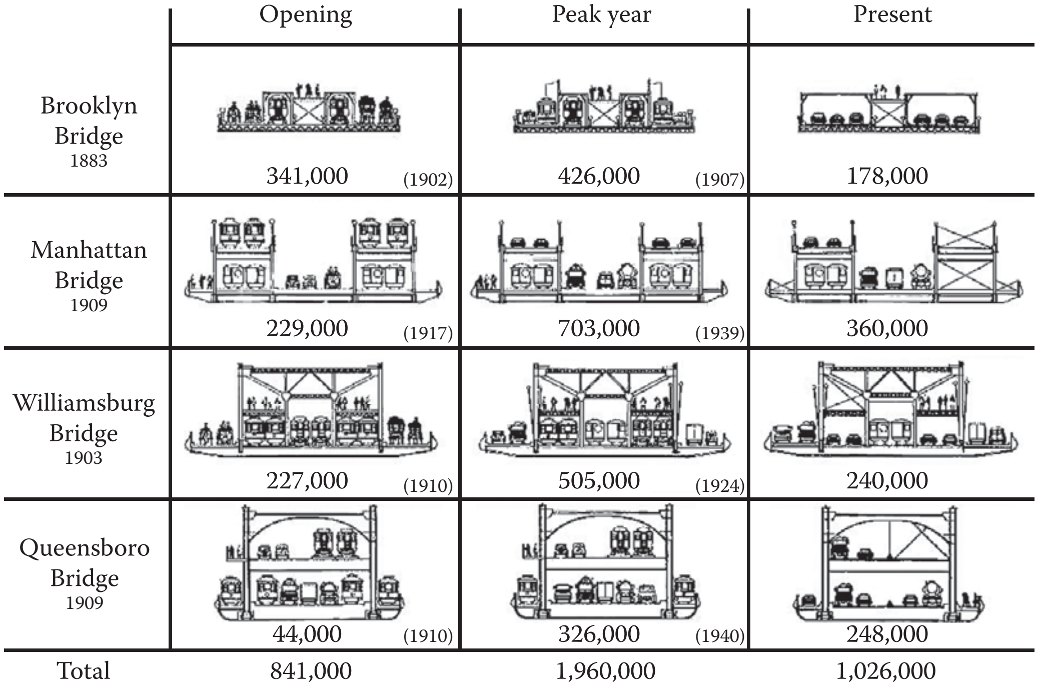


Figure 1.2 Use of the East River crossings from their opening to 1988.

and Flatbush Avenue and the station of the Long Island Rail Road (LIRR), long contemplated … and from the end of the bridge at Canal Street … and thence uptown or to the North (Hudson) River." The rail link never materialized and Long Island would have to wait until 1916 for the completion of Lindenthal's signature Hell Gate arch for its only direct rail link to the mainland.

1.1.2 Preliminary designs

By 1898 there were 15 to 20 alignments plotted and six proposed designs for what was called the third East River bridge. Four of these designs featured cantilevered main bridges and two were suspended wire cable bridges, one with a 55 ft high stiffening truss and the other with a 35 ft high truss (Richard S. Buck's design), evoking debates over the most efficient and aesthetic bridge type for the location and intended purpose.

In addition to the cantilever/suspension debate for the best design of long-span bridges unfolding during this period, another debate was playing out between the use of braced eyebars versus wire cable–supported suspension bridges. This debate, heated at times, resulted in three separate design proposals between 1899 and 1904 and, along with changes to user funding, delayed the construction of the bridge by several years.

In November 1899 Mayor Van Wyck met with the Board of Public Improvements and noted that "after mature deliberation, it was decided

(a)

(b)

Figure 1.3 (a) Manhattan and Williamsburg Bridges across East River and (b) Manhattan Bridge viewed from the Brooklyn Tower, 2012.

to adopt the suspension bridge. The location is so close to the present New York and Brooklyn Bridge that any departure in style or type of structure would not be pleasing or commendable" (New York City Department of Bridges, 1901, p. 336).

The first design proposal was for a wire cable suspension bridge with 10.67 m (35 ft) high stiffening trusses. It was designed by Richard S. Buck, chief engineer in charge of the newly created New York City Department of Bridges, and approved by the Board of Public Improvements in November 1899. The bridge was to be 2813.3 m (9230 ft) long from Canal Street and the Bowery in Manhattan to Willoughby and Price Streets in Brooklyn (New York City Department of Bridges, 1901, p. 266), with a 2.8% maximum grade (4% was the built design). If constructed, it would have eliminated about one-half of the length of the Flatbush Avenue Extension that ended at LIRR's Atlantic Terminal.

Work on the first approved design actually began. The tower foundation contracts were advertised and constructed based on this plan (Nichols, 1906). The tower foundations were later adapted to accommodate the newer design by additional masonry (Johnson, 1910, p. 22).

Richard S. Buck (New York City Department of Bridges, 1901, p. 363) noted, “No attempt has been made to complete plans of any part of the work much ahead of the time they are to be executed. It has been thought best rather to cover as much ground as possible in careful studies of all controlling features of the design in order that all parts of the work may be harmonized as thoroughly as possible.”

The second design was advanced by G. Lindenthal after he was appointed commissioner by Mayor Seth Low in 1902. Lindenthal proposed changing the entire character of the bridge to a braced eyebar suspension bridge in March 1902 (Nichols, 1906, p. 23). The capacity of the bridge was also increased by adding two elevated tracks (New York City Department of Bridges, 1904, p. 133). Lindenthal’s eyebar design was demonstrably feasible, as the 290 m (951 ft) main span of the Elisabeth Bridge in Budapest was being constructed. In 1903 that was the longest chain-supported span in the world. Saint Mary’s, built in 1929, was the last chain bridge built in the United States. The last European chain bridge was built in Cologne in 1915 (Griggis, 2008, p. 277). The longest suspended eyebar span at 340 m (1115 ft) is the Florianópolis Bridge, which was completed in 1926 (currently closed to traffic).

Lindenthal noted that using the eyebars would save months, if not years, in reduced construction time based on previous performance of time needed to spin the wire cables (Reier, 1977, pp. 52–53). The eyebar substitute was approved by the Art Commission in March 1903 (New York City Department of Bridges, 1904, p. 22). The length of each eyebar was about 13.7 m (45 ft), compared with 15.25 to 17.7 m (50 to 58 ft) long bars for the cantilever truss of the Quebec Bridge (Nichols, 1906, p. 40).

Lindenthal’s eyebar design may have sought justification in Roebling’s perceived slow fabrication and spinning on the Williamsburg Bridge, Roebling’s largest bridge contract to date (Winpenny, 2004, p. 85; Zink and Hartman, 1992). More to the point, Lindenthal, as much as Waddell, of whom he was dismissive, demonstrated a lifelong preference for eyebars over cables. Thus, the East River bridges in the 21st century testify to the superiority of Roebling’s 19th-century vision over the skill of some top early-20th-century professionals.

To compete more effectively with eyebars, the Roeblings were expanding production of their high-strength wire and had started construction of a new plant that would employ 300 workers. During the spinning of the Williamsburg Bridge cables, the Roeblings were not producing their own steel and had to rely on others for delivery of the billets (Zink and Hartman, 1992). There had been inexperience in working the special steel into the dimensions and length described (Nichols, 1906, p. 27). At the time, there were 11 companies in the United States that could produce nickel steel eyebars, but Roebling & Sons was the only producers of the wire specified (Reier, 1977, p. 53).

Opponents to the eyebar design noted that the Elisabeth Bridge eyebars were cut from plate and not forged as they would have to be for the larger and heavier Manhattan Bridge span, making comparison of the two designs less valid. Calculations show that there are 10,000 tons more steel required for the eyebar design (New York City Department of Bridges, 1904) Richard S. Buck challenged Lindenthal's arguments about the wire cable design costs and about additional construction time requirements (Griggis, 2008).

Upon his appointment as commissioner of the Department of Bridges in 1904, George Best took note of Roebling's increased production capacity (New York City Department of Bridges, 1904, p. 12): "I am convinced that the wire cable suspension bridge can be built in one-half the time, and at very much less the cost, than the eyebar bridge … and that a wire cable bridge was anticipated in the original authorization."

Commissioner Best also noted (Nichols, 1906, p. 29), "I am well aware that a commission of celebrated engineers passed favorably upon the design for the eyebar chain bridge, and I am far from denying that a structure of that type can be built at this site. However, this commission made no technical comparison between the two types of bridges and their incidental remark that a chain bridge could be built more cheaply than a cable bridge must be regarded as mere expression of personal preference, because there are absolutely no data in existence from which to determine with the remotest degree of accuracy what the cost of the chain bridge will be in either time or money."

Although much has been written about the eyebar/wire rope design debate, resulting bidding controversy, and the politics of selecting the design, time has shown that wire cables are more redundant and their safety factor more reliably calculated during service. The collapse of the nonredundant eyebar chain–supported Silver Bridge over the Ohio River in 1967 closed the debate.

1.1.3 The third and final design

When Lindenthal was replaced as Commissioner, the eyebar design was replaced with a second wire cable design as the latter was more efficient. In a 1904 letter to the City Art Commission, Commissioner Best wrote (Nichols, 1906), "It is well known that steel reaches is greatest strength when drawn into wire (the weight of the eye bars would be twice the wire cable weight yet only about half the strength) and this combined with the uncertainty in the performance of each eyebar due to the inability to test production pieces makes the wire cable design the preferred design for the new Manhattan Bridge."

The calculations for the redesign were performed by Leon S. Moisseiff, who graduated from Columbia University in 1895 and worked as a draftsman under R. S. Buck on both the Queensboro Bridge and the first Manhattan Bridge design. During the third design, Moisseiff worked under R. S. Buck (who was employed again by the Department of Bridges after

George Best was appointed commissioner) and O. F. Nichols (Griggis, 2008, p. 271). Moisseiff later designed the infamous Galloping Gertie—the original Tacoma Narrows Bridge that collapsed 4 months after opening in 1940. Some features of the tower designed by Lindenthal were retained, but the pinned bases and much of the bracing were removed between the center columns (Griggis, 2008, p. 271).

Moisseiff designed the wire suspension bridge in 6 months by using the newly developed deflection theory to reduce steel weight and cost. This was the first application on a bridge, let alone an eccentrically loaded railroad bridge. Prior suspension bridges were designed with elastic theory, emphasizing deeper trusses (Winpenny, 2004, p. xvii).

The deflection theory, or the "more exact theory," is due to Josef Melan (1888). For further reference, see the other chapters in this book. Prior suspension designs had used the elastic theory developed in 1826 or the Rankine theory developed in 1858. A Fourier series treatment of deflection theory was added in 1930 (Steinman and Watson, 1941). David B. Steinman, another Columbia graduate (1908), noted that the values of the bending moments and shears produced by the elastic theory are too high, thus satisfying safety, but not economy, and that the elastic theory is generally sufficient for short spans with deep rigid stiffening systems (Steinman, 1922). Melan theorized that the maximum span of 4694 m (15,400 ft) was obtainable if the bridge carried only its own weight (Steinman, 1913, p. 17).

According to the deflection theory, the work performed by the truss from dead and live loads equals the total internal work expended in stretching the cable and suspenders and in deflecting or bending the stiffening truss throughout the span. The stiffening truss is erected and adjusted at mean temperature so that the dead load does not produce bending in it (Burr, 1913, p. 212). The moving load is distributed into two parts, the much smaller producing deflections in the stiffening truss and the other a uniform pull on the suspenders, producing cable stresses; these stresses are used in the initial equations (Burr, 1913). Unlike the elastic theory, the deflection theory does not assume that the ordinates of the cable curve remain unaltered under live loads and the lever arms of the cable forces are taken into account (Steinman, 1922, p. 248).

The revised wire cable design was submitted and approved by the Art Commission in September 1904 (New York City Department of Bridges, 1904). The Art Commission noted that it did not have adequate guidelines for accepting bridge designs as it would seem they must consider engineering, economic, and aesthetic factors to make a total comment approving one design over the other. Either was acceptable as long as the new bridge adhered to the architectural effects in Lindenthal's design (Reier, 1977, p. 54).

Fabrication for the superstructure steel for the main bridge began in August 1906. One year later, toward the end of the workday on August 29, 1907, the south arm of the cantilevered Quebec Bridge collapsed, sending 83 workers into the Saint Lawrence River, killing 75 (Winpenny, 2004,

p. 90). The company supplying steel for the Quebec Bridge, Phoenix, happened to be the same as the one that was awarded contracts for steel fabrication and erection of the superstructure of the Manhattan Bridge. Phoenix had the contracts to provide the structural steel for the anchorages, towers, and trusses (Winpenny, 2004, p. 16). Memories also held that Phoenix was involved in construction of the Louisville Bridge, which collapsed in December 1893 during high winds, killing 20 (Winpenny, 2004, p. 27).

Although the construction of a suspension bridge is inherently safer than that of a cantilever bridge, there were justifiable calls for precautions, and in response, the Department of Bridges retained Ralph Modjeski to investigate the Moisseiff design. This included investigating the type of the foundations, stresses in the cable and stiffening truss, corrected dead-load values, and conductivity of heat in the main cables. At the time, the maximum theoretical loading for structural steel was 27,226 kg/m (18,300 lb/ft), which was considered as the practical maximum.

In his report, Modjeski (1909) noted that this rare maximum loading would not reach 80% of the elastic limit stress. The towers and floor system are of carbon steel and the trusses are of nickel steel. This was the first use of nickel alloy steel on a major bridge in significant amounts, including for the riveting. Investigation showed that the first slip of the plates detected 650 to 1000 kg/cm^2 (9500 to 14,670 pounds per square inch [psi]) for field-riveted joints (by pneumatic hammer) and 720 to 1260 kg/cm^2 (10,500 to 18,000 psi) for shop-riveted joints (by a pressure machine). Modjeski observed that had these higher values been known, no doubt some allowance would have been made for stress reversals, resulting in a more efficient design. He concluded that "the structure as a whole has been carefully designed, and when complete will be amply strong to carry the heaviest traffic … as well as any reasonable increase in weight of properly regulated traffic it may be called upon [to support] for many years to come."

The original design loads assumed four lines of crowded LIRR cars, four lines of Brooklyn Rapid Transit cars, four vehicular lanes, and two pedestrian walkways. At an average of 2812 kg/cm^2 (40,000 psi), the yield stresses for the fabricated carbon steel used in the towers were 20% higher than specified. The yield stresses for the fabricated nickel steel trusses averaged at 4289 kg/cm^2 (61,000 psi), or 10% higher than specified.

The suspended structure was designed for dead load, including the cables of 37,180 kg/m (25,000 lb/ft) and a working live load of 11,672 kg/m (8000 lb/ft) or congested live load of 2722 kg (6000 lb) (Perry, 1909, p. 51).

The cables stretch 3 ft due to the maximum dead loading of 29,743 kg/m (20,000 lb/ft), which results in a factor of safety of 2. The cables would have to stretch 9 to 10 ft before the elastic limit was reached (Perry, 1909, p. 65). "The maximum stress on the tower and stiffening truss would occur at congested loading and maximum temperature … Snow loading is offset by the lower temperatures … this principle would not apply to cantilevered bridges."

1.1.4 Construction firsts

The Manhattan Bridge was originally referred to as the third East River bridge, but because of the redesigns and rebidding of contracts, it became the fourth East River bridge to be completed. Even though the construction timeline shows 17 years from the beginning of the tower foundations in 1901 to opening for full service on the Brooklyn Rapid Transit lines in 1918, once the steel tower work started, construction of the towers and superstructures set records and the bridge was substantially completed in 3 years, totaling 42,000 tons between anchorages. Many of the modern construction techniques for suspension bridges were developed and used for the first time on the Manhattan Bridge.

The speed of constructing the main bridge was partially attributed to the fact that the steel towers, cables, suspenders, and suspended superstructure were included in one contract, thereby "eliminating multiplicity of plant, friction between contractors and possible consequent litigation with the City" (Johnson, 1910, p. 28) There had been three contracts let for the main bridge steel of the Williamsburg Bridge. The single contract facilitated orderly fabrication and building of the towers, cables, and suspended spans in an overlapping sequence, without intervals of lost time.

1.1.4.1 Caisson construction

The foundation contracts for the Manhattan and Brooklyn Towers were advertised separately. The caisson for the Brooklyn Tower's foundation was floated into place in February 1902 and the cutting edge rested at an average depth of 27.75 m (91 ft) below mean high water (MHW) or about 18.9 m (62 ft) below the river bottom. The material was described such that it required a pick ax to loosen and was a perfectly reliable foundation. A few cases of the bends developed, two of which were fatal (New York City Department of Bridges, 1904, p. 141).

The $23.8 \times 43.9\ m^2$ ($78 \times 144\ ft^2$) timber caissons were constructed 13.7 m (45 ft) high in Manhattan for the tower foundation and 17 m (56 ft) high for the Brooklyn foundation to accommodate the plans showing an anticipated depth of 24 m (79 ft) below MHW to a bed of gravel in Manhattan and 28.7 m (94 ft) below MHW in Brooklyn (New York City Department of Bridges, 1901, p. 363).

The Manhattan Tower caisson was floated into place July 1903 and the foundation reached "course sand with fine gravel being very firm in character" at –28.2 m (–92.5 ft) in December 1904 (Modjeski, 1909, p. 4). Attempts were made for weeks to force grout into this material, which was useless, and the pressure of up to 3.2 kg/cm^2 (47 psi) caused the death of several men (Johnson, 1910, p. 26). A study of the conditions resulted in the decision to fill the caissons some 6 m (20 ft) above rock (Nichols, 1906).

1.1.4.2 Towers

In contrast to the Brooklyn and Williamsburg Bridges, which combine relatively rigid towers and sliding saddles, the Manhattan was the first to combine fixed saddles and flexible towers, braced only in the transverse and vertical directions. Moisseiff eliminated Lindenthal's pivot at the tower base. Instead of relying on the rollers under the saddles at the towers, which were largely ineffective on previous bridges, the slender towers resist elastically the varying longitudinal forces caused by ambient service conditions. Under maximum loading and temperature, the actual towers can accommodate a movement of 61 cm (2 ft) each way from the tower tops. Under ordinary conditions the movement was estimated at less than 15 cm (6 in), producing stress in the extreme fiber under 7258 kg (16,000 lb) (Perry, 1909).

Previously unseen in bridge design were also the cellular spaces within the tower legs, replacing exposed elements (such as, for example, at the Williamsburg Bridge). This design allowed construction of the tower columns without falsework. An ingenious derrick could advance vertically up each leg after each 62-ton section was installed (Steinman, 1922, p. 337). The derrick had a platform supported by two struts; the tip moment was resisted by a pair of wheels engaging the vertical edges on the tower. When the 62-ton full section had been added, blocks were added to the top and falls attached to the derrick platform, by which it then lifted to the next level. In addition to the two stiff-leg derricks, each tower had two hoisting engines, a power plant with air compressors, 30 pneumatic riveting hammers, six forges, and a workforce of 100 men and six rivet gangs. This system allowed erecting a record 2000 tons of steel at one tower in 16 working days (Steinman, 1922, p. 165).

In order to offset the deformations caused by congested live loads, the towers were pulled 10 cm (4 in) toward the shores when the cables were completed and prior to placing the dead load (Perry, 1909).

1.1.4.3 Cable spinning

With diameters of 54.2 cm (21 1/4 in), the four main cables were the largest in the world when spun and remained so for 17 years. The two 76.5 cm (30 in) diameter cables on the Benjamin Franklin Bridge were completed by 1926, but only the four cables of the George Washington Bridge, completed in 1931, had greater carrying capacity. At 105 years, the Manhattan Bridge still carries the most traffic and has the largest capacity of all six East River suspension bridges.

Roebling & Sons made good on their marketing promise that the wires for the largest cables in the world would also be spun in record time. In the spring of 1908, the contractor was claiming that the cables would be completed within 12 months of stringing the first wire and at "far greater celerity than the Brooklyn and Williamsburg Bridges." Stringing would be done by late spring 1909 and the bridge would be ready to open by the summer of 1911 (*Scientific American*, 1908).

All cable work was performed by Glyndon Contracting (Perry, 1909). Preparations began with four reels of 4.45 cm (1 3/4 in) wire ropes for the footbridge cables towed across the East River by barge with other traffic stopped. The free end of each rope was hauled up by line over the tower tops, placed on temporary saddles, and adjusted with hoist engines at the Brooklyn anchorage (Perry, 1909, p. 55).

The inner and outer cables were braced by working platforms, and hauling rope towers were stationed every 76.25 m (250 ft). The work platform was stayed against wind vibration, with four 4.46 cm (1 3/4 in) storm cables connected to the footbridge at 16.8 m (55 ft) intervals (Perry, 1909, p. 56).

Guide wires were adjusted to the designed deflection and slippage in the tower and anchorage saddles prior to loading (Hool and Kinne, 1943, p. 350). The four hauling wire ropes featured 1.9 cm (3/4 in) diameter endless loops with two traveling sheaves. The hauling rope at the Manhattan anchorage passed around two 0.915 m (3 ft) diameter deflecting wheels and one 1.525 m (5 ft) diameter idler wheel that could adjust the tension (Perry, 1909, p. 57).

The wires for the main cables were delivered in 24,384 m (80,000 ft) continuous length, wound on a reel. Four reels were placed at each anchorage, eight total on the bridge, allowing for eight traveling sheaves at a time (Hool and Kinne, 1943, p. 352).

Strands were supported at the anchorages and tower saddles by cast iron sheaves bolted temporarily to the saddles on each side of the groove, several inches above the tops of the saddles and 30.5 to 61 cm (1 to 2 ft) above their final position (Perry, 1909, p. 56). Movement of the traveling sheave was monitored. A system of electric bells and telephone notified controllers at the break wheels, greatly assisting all operations and adjustments (Perry, 1909).

A loop placing two wires was pulled by 91.5 cm (3 ft) diameter traveling sheaves, which made the round trip from anchorage at anchorage in 15 min. The traveling sheave on the opposite side for each cable also carried a loop, allowing placement of 16 wires at a time (Steinman, 1922, p. 339). Since the length of each cable is 983.3 m (3224 ft), the eight sheaves were laying wire at a rate of 64.4 km/h (40 mi/h). The 37,224 km (23,130 mi) of wire, 7% shy of the earth's circumference, were spun in less than 4 1/2 months—a record speed which inspired others to pursue more efficient spinning methods. For comparison, the amount of wire spun on the best day at the Brooklyn Bridge was 20 tons and 75 tons at the Williamsburg Bridge. The maximum amount of wire spun in one day on Manhattan Bridge was 130 tons (Steinman, 1922, p. 190).

Mayor McClellan was present at the start and end of the spinning, showing that Tammany Hall was capable of building public works in an efficient manner (Reier, 1977). He pulled the lever to lay the last wires on December 10, 1908. "As the wire was drawn over the Brooklyn tower, the spectators below cheered and passing river craft blew their whistles in salute. At the same time flags were unfurled on the towers of the bridges" (*New York Times*, December 11, 1908).

The Manhattan cables required the first hydraulic squeeze rings adaptable for different diameters: for the 7 strands in the first stage and for the entire 37 strands in the second stage. The method was replaced with flat band seizings on later bridges (Steinman, 1922, p. 340).

Holton D. Robinson was the Engineer in Charge of the Department of Bridges for the Manhattan Bridge in 1905 and worked for the contractor during the wire spinning. He designed and patented the cable-wrapping machine. This machine used an electric motor and was self-propelled for the first time. The 454 kg (1000 lb) wrapping machine used a 1.5 hp electric motor and pressed the wires against the preceding coil at 13 revolutions per minute with two spools at the same time advancing at a rate of 5.5 m/h (18 ft/h) (Steinman, 1922, p. 183; Hool and Kinne, 1943, p. 355). In 1921 Robinson and Steinman started a consulting firm.

The total length of the loaded cable between the pins of the anchor chain is 983.4 m (3226.35 ft) and for the unloaded anchor chains, it is 982.25 m (3222.61 ft). Thus, the extension due to the dead load of the trusses and floor is 1.14 m (3.74 ft) (Perry, 1909, p. 52). The lengths and dead-load forces were computed for parabolic curves.

Upon galvanization, the cable wires demonstrated outstanding ductility. They could bend cold around a rod 1.5 times their own diameter without signs of a fracture (Perry, 1909, p. 52). For protection from the weather and facilitation of handling and stringing, the wires were covered with grease during all operations (Perry, 1909, p. 66). The wire surfaces retain remnants of an oily coating 105 years later. In an early demonstration of sustainable economy, the 4.45 cm (1 3/4 in) footbridge cables were cut and used for the short suspenders (Perry, 1909).

1.1.4.4 Stiffening trusses

Manhattan was the first suspension bridge to use the lighter Warren truss. Erection proceeded at four separate points, simultaneously working from both directions of the each tower. The first pass was started in March 1909 and connected at midspan a little more than a month later (*New York Times*, December 5, 1909). In it, the lower chords of the truss and floor system were temporarily connected to the suspenders. The truss diagonals were installed on the second pass, followed by the upper decks and transverse bracing. For the trusses, 300 men were employed, erecting a record 300 tons per day (Steinman, 1922, p. 181). To achieve proper profile of the travel way and the cables, the chord members of the truss were closed only after the dead load was on the structure and adjustments were made to the suspender lengths.

The slender design of the bridge, apart from the deflection theory, is also due to incorporating nickel steel with a working stress of 2812 kg/cm^2 (40,000 psi) in the upper and lower truss chords. The working stress of the nickel rivets was 1406 kg/cm^2 (20,000 psi) (*Scientific American*, 1908). In all, 8100 tons of nickel steel was used for the trusses, and 44,000 tons of steel was used for the entire bridge (Steinman and Watson, 1941, p. 367).

Not half a dozen men lost their lives during construction (*New York Times*, December 5, 1909). The construction cost estimate in 1908 was US$26 million (Winpenny, 2004, p. 18; *Scientific American*, 1908) and the structure was completed for US$32 million.

1.1.4.5 Design and construction timeline

1897	Bills are introduced in the state legislature.
November 1898	The Board of Public Improvements authorizes preparation of the plans to construct an all-railroad bridge (New York City Department of Bridges, 1904).
November 1899	The Board on Public Improvements approves a wire cable suspension bridge.
January 29, 1900	Construction is approved by the municipal assembly, the mayor, and the War Department.
December 1900	Bids are opened for the foundation.
April 22, 1901	"Final bids for the construction of the Brooklyn Tower foundation for the bridge were opened, and the contract was awarded to John C. Rodgers, the lowest formal bidder, at a contract price of $US 471,757. This contract was executed on May 1, 1901, and the actual work was begun on August 20, 1901. The estimated cost of this structure, including approaches, is $US 15,833,600. The amount of money expended on this bridge to November 30, 1901, is $US 89,283.42" (Shea, 1901).
March 1902	Commissioner Lindenthal proposes changing the design to eyebar suspension bridge (Nichols, 1906, p. 23).
March 10, 1903	Eyebar substitute is successively approved and rejected by the Art Commission.
August 1904	The foundations of Manhattan and Brooklyn Towers are completed (New York City Department of Bridges, 1904, p. 22).
September 1904	Revised wire cables are approved by the Art Commission (New York City Department of Bridges, 1904).
August 1906	Phoenix begins receiving contracts for the superstructure between the towers (Winpenny, 2004, p. 11). Tower fabrication begins.

June 15, 1904	(New York City Department of Bridges, 1904, p. 22).
July 1908	Towers are completed (Hool and Kinne, 1943, p. 357).
June–July 1908	Temporary cables are strung and footbridge is constructed.
August–December 1908	All cables are laid (New York City Department of Bridges, 1912).
February–December 1909	Suspended-span steel is erected. Approaches are completed.
December 31, 1909	Official opening is held.
January 1913	The first coat of structural paint is applied.
1918	The bridge is fully opened to subways.

1.1.5 Traffic

Surface trolley started in 1912; light rapid transit, in 1915 (Steinman, 1955, p. 2). In 1918 the number of motorized vehicles in New York City surpassed that of horse-drawn vehicles. In July 1922 the Manhattan Bridge was closed to horse-drawn vehicles that had to cross via the Brooklyn Bridge (Winpenny, 2004, p. 40) and the Manhattan Bridge became much cleaner. In 1929 New York City Mayor Jimmy Walker bought the franchise ridges and rolling stock of the trolley line operating on the Bridge (south side), which was converted for bus use (Winpenny, 2004). Daily vehicular traffic increased from 65 000 to 110 000 cars (Winpenny, 2004). Pedestrians were banned from the East River bridges at night starting December 17, 1941 (Winpenny, 2004).

1.2 LIFE-CYCLE PERFORMANCE

The loads and responses are uniquely dynamic in suspension bridges. In that respect, they resemble mechanical devices more closely than they do "rigid" structures. With the Manhattan this is especially true, and as a result, the bridge has been a foremost subject of bridge management studies (Birdsall, 1971). The live loads on the bridge are exceptionally high in both frequency and amplitude and cause a similarly extreme structural response. To begin with, the bridge not only moves with seasonal and daily thermal changes but also can deflect over 0.3 m (1 ft) at center span every time one of the more than 900 daily trains crosses. This change in profile translates to frequent movement in the expansion joints at the towers and differential vertical movement most pronounced between the inner trusses. Figure 1.4 shows a 36 cm (14 in) sliding bearing under a subway track stringer, extended almost beyond its pedestal as a result of regular movements caused by service loads and temperature. Figure 1.5 illustrates a typical live load configuration producing the torsional response that has been questioned, investigated, and mitigated throughout the life of the bridge.

Figure 1.4 Overextended sliding bearing under the subway tracks.

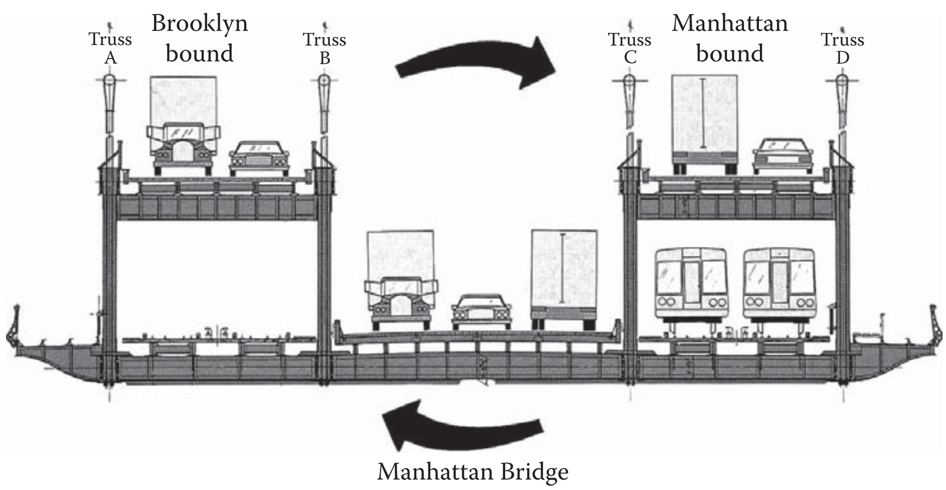


Figure 1.5 Typical cross section with asymmetric loading.

1.2.1 Torsion

"For reason unknown, Moisseiff placed the heaviest live loads, the subway trains and elevated-car traffic, outside rather than inside… resulting in excessive torque…" (Winpenny, 2004, p. ix). The effects of the differential deflection became apparent within 6 years of the bridge opening, as the bracings between the top chords of the inner trusses (B and C in Figure 1.5) cracked. Originally intended as support for traffic signs, the bracings were removed in 1924.

The three approved designs for the Manhattan Bridge may have contributed to a gap between the originally anticipated and the actual use of the bridge. Complicating this was the fact that the commissioner of New York City Department of Bridges was not in control of the transit facilities, as had been the case at the Brooklyn and Williamsburg Bridges. Under the new charter (*New York Times*, December 5, 1909), control had passed to the Public Service Commission, which succeeded the Rapid Transit Commission. Thus the bridge acquired a "split personality," responding to vehicular mode of transportation in a predominantly flexural mode of deformation and to rail traffic in a different mode, most significantly, a torsional one.

The original suspenders passed through the upper truss chords without centering devices. As each passage of one or two adjacent trains tilted the bridge to one side, the suspenders moved toward the upper chord webs, engaging in friction midspan. To improve the clearance and reduce chaffing against the upper chord, the original two-part suspenders were replaced with single-part suspenders near center span in 1937.

Measures mitigating the torsional movements were implemented between 1930 and 1940. In 1938, two-part suspenders near midspan replaced the lower portion of the four-part suspender ropes. Torsional displacements had caused damage to the original suspenders when they came in contact with the top chord and the two-part suspenders reduced this problem by providing more clearance. By the 1980s it had become obvious that the two-part suspenders were also engaging the upper truss chord. In 1938, the stiffening truss connections at the towers were changed from rockers to pinned hangers along with expansion joints in the lower deck.

Commissioner Zurmuhlen in 1952 noted that the Brooklyn–Manhattan Transit trains placed "a terrific strain on the cables and all structural parts." With six cars weighing 40 tons each, a train weighs 240 tons. It was estimated that passengers add up to 44% to that load, or 105 tons of human weight. Thus, the total weight of a loaded train was 345 tons. The trains crossing the bridge since the 1980s are composed of eight R68 cars, weighing 42 tons each, or 336 tons unloaded and 484 tons loaded. Thus, the new train loads exceed those of the 1950s by at least 40%. Added passenger capacity may have raised that ratio to as much as 60%.

In 1955 the city retained the firm Steinman, Boynton, Gronquist & London to conduct an extensive study of the bridge. As one option, Steinman's (1955) report recommended relocating the subway train to a new US$90 million tunnel. This was rejected by Mayor Wagner as financially impractical. The second option—to relocate three tracks to the center for US$30 million—was also never pursued due to operational difficulties. Many of the actions preceding the recent rehabilitation program have aimed at reducing the torsional rigidity, under the assumption that no stiffness is better than inadequate stiffness (Birdsall, 1971). Consistently with the original premise of the deflection theory, this logic produces excessively flexible structures. The 1955 study established that torsional stresses were responsible for cracks in the floor systems. The upper floor systems were replaced with a system supposedly less sensitive to twist during 1959 to 1962.

During a subsequent study in 1971, Steinman, Boynton, Gronquist & London tested a two-dimensional model at Columbia University in order to determine the spring constant of the cable truss system, acknowledging that the perfect dimensional model was the bridge itself. The study concluded that side-span supports, combined either with transverse stays at the main-span quarter points or with tower stays, and four panels of diagonals at the main-span centerline would most efficiently and economically reduce deflections and, hence, the torque. It was noted that the torsion had not compromised the performance of the primary members, namely, the cable, towers, and foundations (Birdsall, 1971). Several schemes to reduce the torsion were recommended, including tie cables and diagonals in the main and side spans and tower and transverse stays. None of these schemes were adopted.

The early 1980s' in-depth inspection found widespread and severe deterioration in the floor beams and stringers under the joints and at the fascias. Track bearings were worn out and laterals were broken. On at least one occasion in 1988, all nine stringers supporting the lower roadway were found broken at the same floor beam.

The central finding of the inspection was unexpected and serious: the upper roadways of the suspended spans, floor beams, and stringers, installed in 1962, had cracked extensively. Cracked members were clustered near anchorages, towers, and the center span. Figure 1.6 shows a typical crack in a stringer, propagating beyond a 2.5 mm hole, drilled in an attempt to arrest it. Figure 1.7a shows a crack through the entire bottom chord of truss D. A typical crack in the bearing of a stringer supporting the subway tracks is shown in Figure 1.7b. Advanced corrosion and poor bearing details contributed to an unquantifiable degree to the crack initiation and propagation.

New studies of potential stiffening schemes were conducted in two phases. As a foremost constraint, any structural modification had to increase the dead load on the cables and towers within acceptable margins of safety. In the first phase, a two-dimensional computer model analyzed 14 stiffening schemes, including those considered in 1955 and 1971. Figure 1.8a through c shows 11 of them.

Figure 1.6 Typical crack in roadway stringer, propagating beyond a hole.

(a)

(b)

Figure 1.7 Cracks in (a) bottom chord, truss D and (b) stringer bearing.

In 1982 Weidlinger Associates first recommended creating what is called twin torque tubes to reduce the differential deflection between the trusses due to eccentric train loading. Three-dimensional models of schemes C1 and C2 (Figure 1.8) were studied analytically and validated through results of a load test. The high-friction forces in the stringer bearings of the upper roadways were identified as the key factor in causing widespread floor beam cracking. Failure of the stringers to slide over the floor beam could magnify the stress caused by the torque eightfold.

Scheme C2 was selected. It included stiffening the suspended torque tubes connected by strengthened floor beams at the lower level and providing eight rigid end frames around the transit envelopes adjacent to the towers for each suspended span, by installing diagonals between the outer and inner trusses of the upper level and diagonals between the outer trusses of the lower level. The partial upper laterals, removed in 1924, were replaced with stronger members. All sliding bearings under the stringers were replaced with elastomeric bearings, thus isolating the stringers from the torque tubes. Along with its structural benefits, the torque tube solution retained the appearance of the bridge. Each torque tube ends with a new rigid frame, as shown in Figure 1.9.

1.2.2 The stiffer performance

The torque tube and lower roadway stiffening system has performed under actual loadings only since 2008. The projected fatigue life of the stiffened structure has yet to be demonstrated. Meanwhile, its dynamic response is measureable.

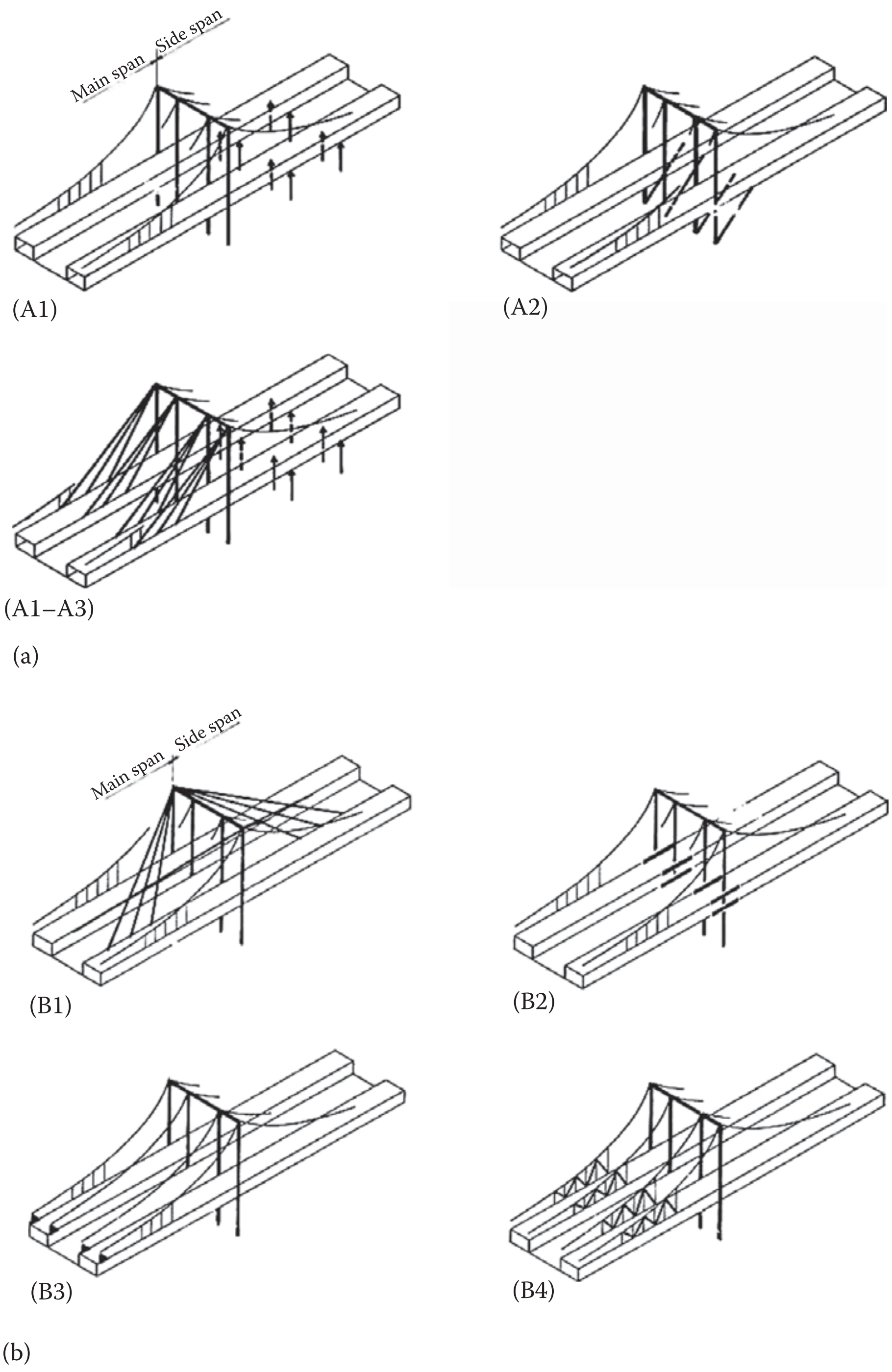


Figure 1.8 Stiffening schemes. (a) Category A: schemes that stiffen the category load; (A1) side span supports, (A2) underdeck cables in side spans, and (A1–A3) side span supports and stay cables in main span. (b) Category B: schemes that selectively stiffen the category load; (B1) crossed stay cables, (B2) interconnected hydraulic cylinders in truss chords, (B3) center span cable to truss connections, and (B4) diagonals between trusses and cables.

(*Continued*)

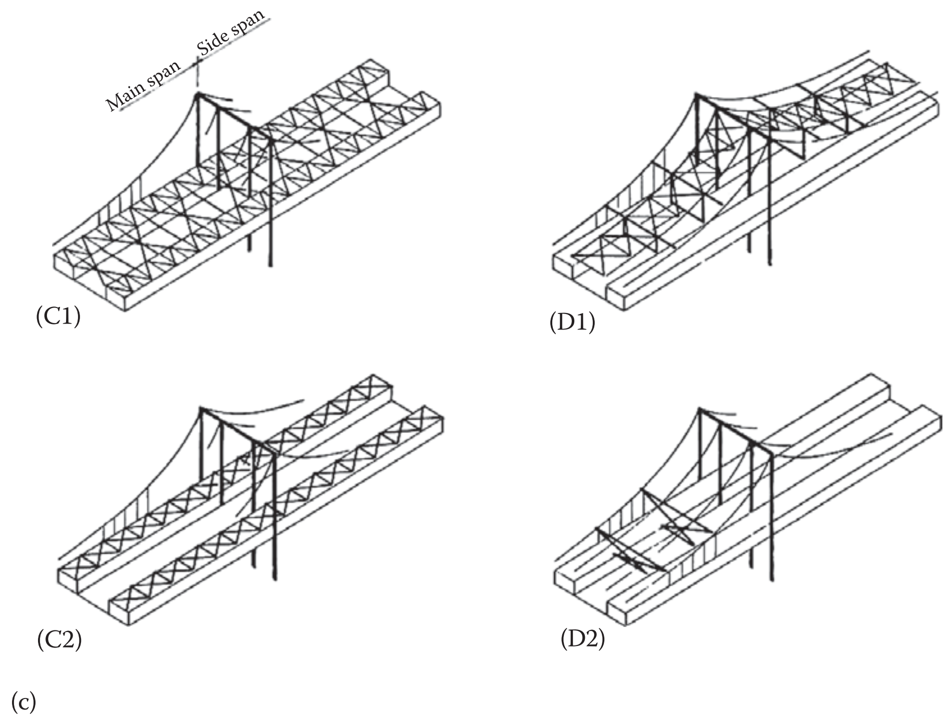


Figure 1.8 (Continued) Stiffening schemes. (c) Category C: schemes using torque tubes; (C1) full upper laterals and (C2) partial upper laterals and category D: schemes involving shear on the plane of the cable; (D1) torsional posts and (D2) transverse cables between suspenders.

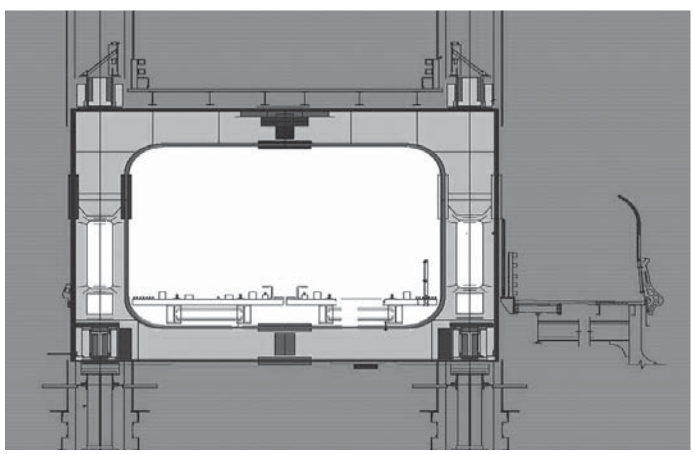


Figure 1.9 Rigid frame constraining the end of each torque tube.

For the Steinman, Boynton, Gronquist & London (1971) study, Professor R. B. Testa of Columbia University measured up to 2.44 m (8 ft) in differential vertical movement between the bridge fasciae in the uneven loading case of two trains, on either the north or south tracks, as in Figure 1.5. Since the retrofit, measurements have been obtained by a laser tiltmeter

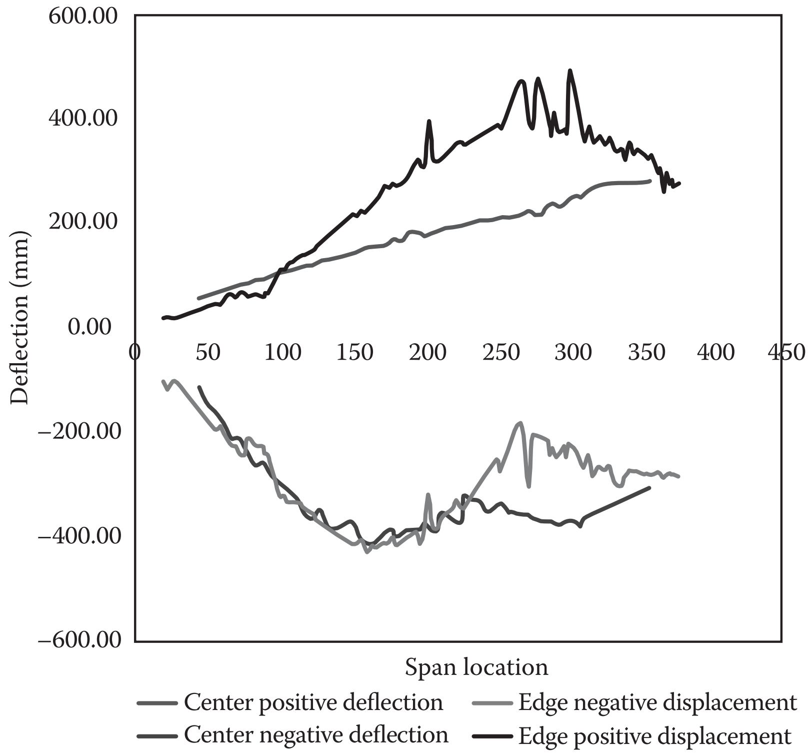


Figure 1.10 Laser tiltmeter measurements of deflection versus span location.

midspan (Figure 1.10), by an interferometric radar scanner by Ingegneria Dei Sistemi, Pisa, Italy (Figure 1.11), as a demonstration of the preceding system; and by a global positioning system (GPS) from the tops of the bridge towers (Figure 1.12), as part of the dynamic reanalysis of the bridge for seismic retrofitting (Mayer et al., 2010).

The three methods consistently indicate maximum differential movement of roughly 60 cm between the fasciae. Thus, the reduction in the original displacements by 50%, projected in 1981, has been exceeded.

1.2.3 Rehabilitation/reconstruction

By 1980, for structurally different reasons, the three great suspension bridges over the East River underwent major rehabilitation/reconstruction through multiple contracts. Between 1981 and 2020 the expenditures for the various capital projects on Brooklyn Bridge will reach US$936 million–US$956 million. The suspenders and stays, the decks, and some of the approach spans have been replaced. In 1988 the total replacement of the Williamsburg Bridge was considered. The cost of its rehabilitation/reconstruction (1983–2002) eventually amounted to US$1086.66 million. At Manhattan Bridge between 1999 and 2009, state and city inspectors

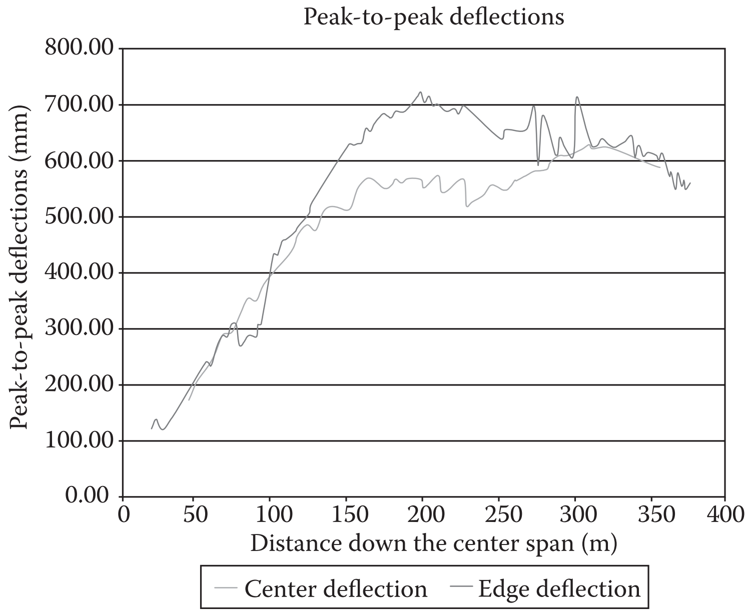


Figure 1.11 Results of interferometric radar scan of half the main span.

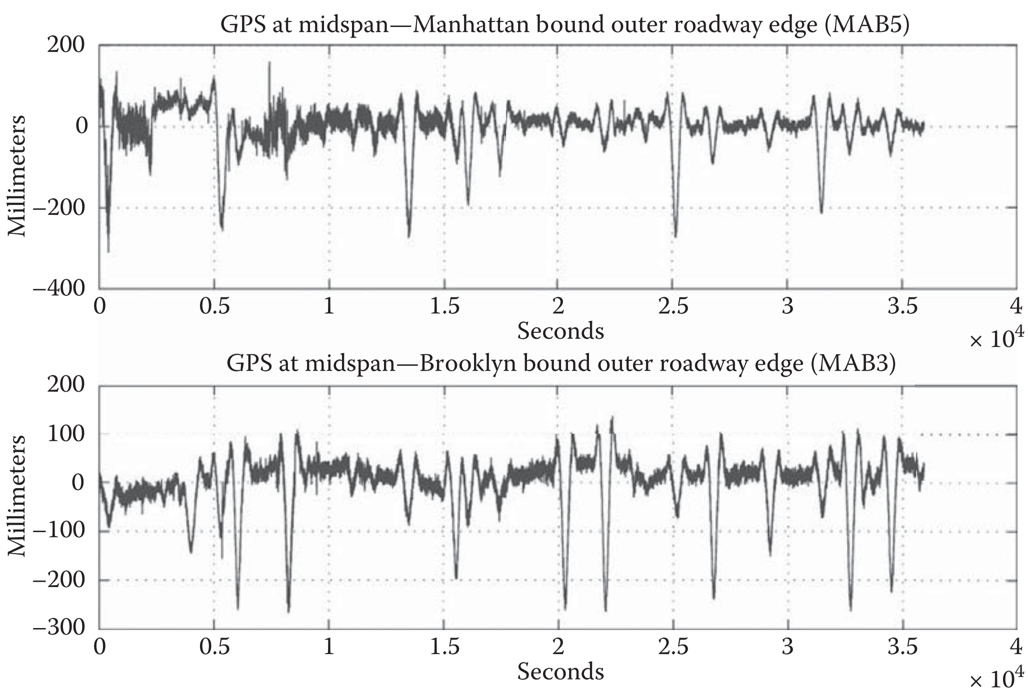


Figure 1.12 GPS receiver data showing outer roadway edge deflections.

issued 691 structural and safety flags. Of those, 206 were addressed by in-house forces and 485 were routed to various contracts. The following summary describes the scope and cost of the reconstruction/rehabilitation contracts from on Manhattan Bridge 1982 to 2012 (New York City Department of Transportation, 2012).

Rehabilitation items	*Total estimated cost (million US$)*
Repair of floor beams (1982)	0.70[a]
Replacement of inspection platforms, subway stringers on approach spans (1985)	6.30[a]
Installation of truss supports on suspended spans (1985)	0.50[a]
Partial rehabilitation of walkway (1989)	3.00[a]
Rehabilitation of truss hangers on east side of bridge (1989)	0.70[a]
Installation of antitorsional fix (side spans) and rehabilitation of upper roadway decks on approach spans on east side; replacement of drainage system on approach spans; installation of new lighting on entire upper roadways' east side, including purchase of fabricated material for west side of bridge (1989)	40.30[a]
Eyebar rehabilitation—Manhattan anchorage chamber C (1988)	12.20[a]
Replacement of maintenance platform in the suspended span (1982)	4.27[a]
Reconstruction of maintenance inspection platforms, including new rail and hanger systems and new electrical and mechanical systems; over 2000 interim repairs to structural steel support system of lower roadway for future functioning of roadway as a detour during later construction contracts (1992)	23.50[a]
Installment of antitorsional fix on west side (main and side spans) and west upper roadway decks; replacement of drainage systems on west suspended and approach spans; rehabilitation of walkway (installment of fencing and new lighting on west upper roadways and walkways); rehabilitation of cables in Brooklyn and Manhattan anchorage chambers; dehumidification of anchorages (1997)	141.82[a]
Installation of test panels (1982)	1.55[d]
Removal of existing suspender ropes and sockets in the suspended spans; replacement with new suspender ropes and sockets in the suspended spans and retensioning of suspender ropes bearing plates; retensioning of cable band bolts; removal of existing main cable wrapping; cleaning of main cables; new protective paste on main cables and new main cable wrapping; reinforcement of truss verticals and gusset plates; replacement of necklace lighting and multirotational bearings at trusses C and D; installation of access platforms at towers, rehabilitation of south upper roadway lighting (2010)	149.38[b]
Interim steel rehabilitation and painting—cable and saddle repairs lower roadway floor beams at panel point (PP) 37/38 on approaches and at anchorages; west side truss rockers and grillages on approaches; cable and suspender repairs; removal of parking deck; painting of entire west side, all four cables (2001)	127.98[a]

Rehabilitation items	*Total estimated cost (million US$)*
Stiffening of main span; reconstruction of North Subway framing; reconstruction of north upper roadway deck at suspended spans; rehabilitation of north approach span trusses; replacement of overlay on north upper roadway approach spans; rehabilitation of north elevated structures and subway tunnels; removal of railing on truss D in the north spans; painting of north side of bridge; new inspection platforms and debris protection in approach spans; construction of new north bikeway, replacement of approach span bearings and grillages; installation of intelligent vehicle highway system for north and south upper roadways as well as for lower roadway (in progress)	184.78[a]
Rehabilitation of lower roadway; rehabilitation of anchorage roofs under lower roadway; rehabilitation of substructures and retaining walls in Brooklyn and Manhattan approaches; installation of new signage on bridge and at plaza areas; installation of new lighting on lower roadway and plaza areas; cleaning and painting of lower roadway; installation of grating platform under towers at lower roadway; canopy lighting at towers (present)	143.80[a]
Seismic retrofit (2020)	40.00–60.00[c]
Total	880.78–900.78

[a] Complete.
[b] In construction.
[c] In design.
[d] Research and development (completed).

Major repair and construction of the torque tubes with full service closures were conducted at the south tracks from December 1990 to July 2001 and at the north tracks from July 2001 to February 2004. Figure 1.13 shows a new stiffening lateral member under the upper roadway. As during the original construction, the slip-critical bolted connections were tightened only after all laterals were installed.

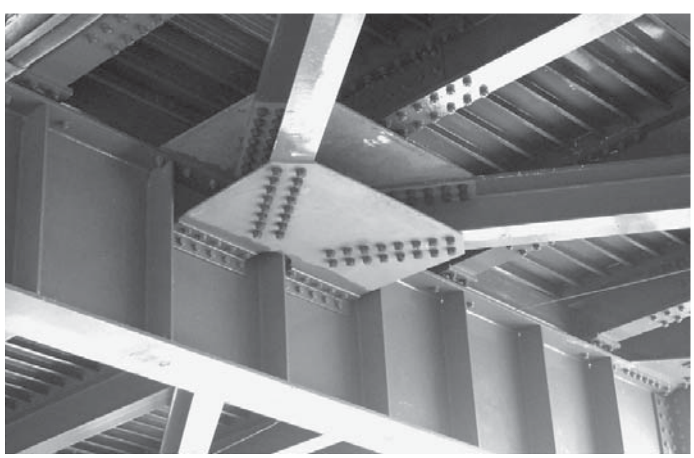
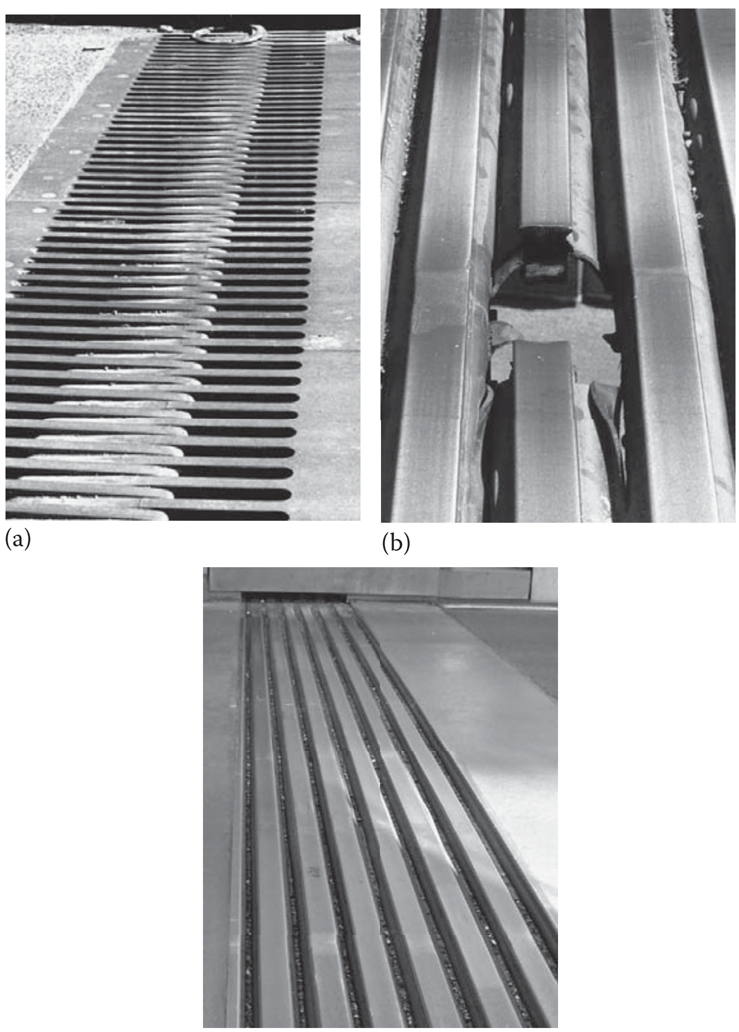


Figure 1.13 New lateral bracing under the upper roadway.

Modular joints and finger joints had been alternatively used in the old roadways (Figure 1.14a and b). New modular joints are as shown in Figure 1.14c. A future transition to modular joints only is anticipated.

The new decks are steel grids (Figure 1.15) with concrete overfill. The entire 18,600 m^2 (200,000 ft^2) of lower roadway deck, 2344 stringers, and 305 floor beams were replaced between October 2006 and August 2007 by introducing the following innovations:

- The work plan developed by the contractor (Koch Skanska) maximized access to the work zones by providing for delivery of equipment and materials from both the Manhattan and Brooklyn approaches. The construction began with two crews at the Manhattan anchorage with one crew working westerly toward the Manhattan abutment and one



(a) (b) (c)

Figure 1.14 Roadway expansion joints: (a) finger, (b) modular, with broken spacer bar, and (c) new modular joint.

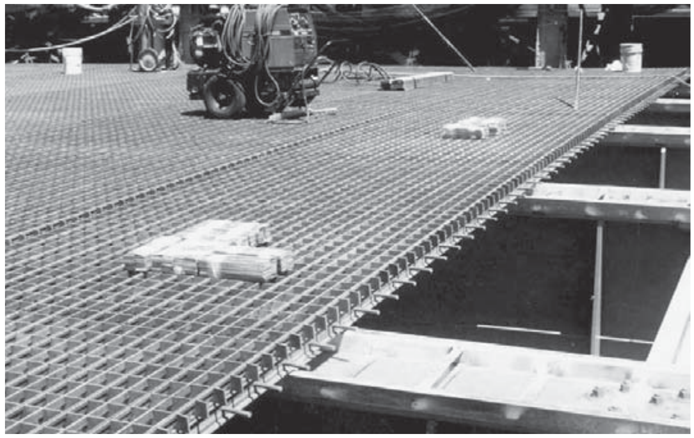


Figure 1.15 Lower roadway steel grid deck under construction.

crew working easterly toward the Brooklyn abutment. As a time-saving measure, the existing deck and stringers were removed in panels.

- The new stringers were preassembled in groups of two in the shop. The floor beams came to the site with the elastomeric pads preinstalled. This preassembly allowed for quick erection of the structural steel.
- To ensure that the contractor met the 12-month closure schedule, the contract specification required that 50% of the grid deck and structural steel be fabricated prior to closure. To minimize the risk, the contractor fabricated 100% of the main steel elements prior to the closure. The described measures not only lessened the impact on traffic but also improved the quality of the final product and reduced the duration of construction.
- Full closure of the lower roadway eliminated the need for construction joints in the grid deck and concrete placements were made from deck joint to deck joint—no cold joints were required.
- The grid deck panels (Figure 1.15) run the complete width of the roadway with no need for splicing of the main bars.
- The maximum incentive (US$65,000/day × 60 days) resulted in reopening the lower roadway 60 calendar days early.

All East River bridges were repainted with full containment, without traffic interruption. Seismic evaluation and retrofit are planned on all of them.

1.3 ANCHORAGES

Along with the towers, the anchorages render the cables load resistant and must precede their construction. The Manhattan Bridge ones are particularly monumental. With age, they became the center of uniquely innovative rehabilitation measures as well. By the early 1980s, the eyebars anchoring cable C in the Manhattan anchorage had lost so much cross-sectional area to corrosion that their elastic elongation was beginning to affect the tension of the strands. Weidlinger Associates designed the reanchoring of the cable, shown in Figure 1.16, and Karl Koch Construction was the contractor (Mayrbaurl and Good, 1988).

Two new transfer girders were anchored into the monolith by two drilled shafts, posttensioned and grouted. Nine strands were transferred to each girder (Figure 1.17). The sockets were filled with molten zinc. On a smaller scale, strands were subsequently reanchored in the Brooklyn anchorage, by using polyester raisin for the sockets. The anchorages are now actively dehumidified.

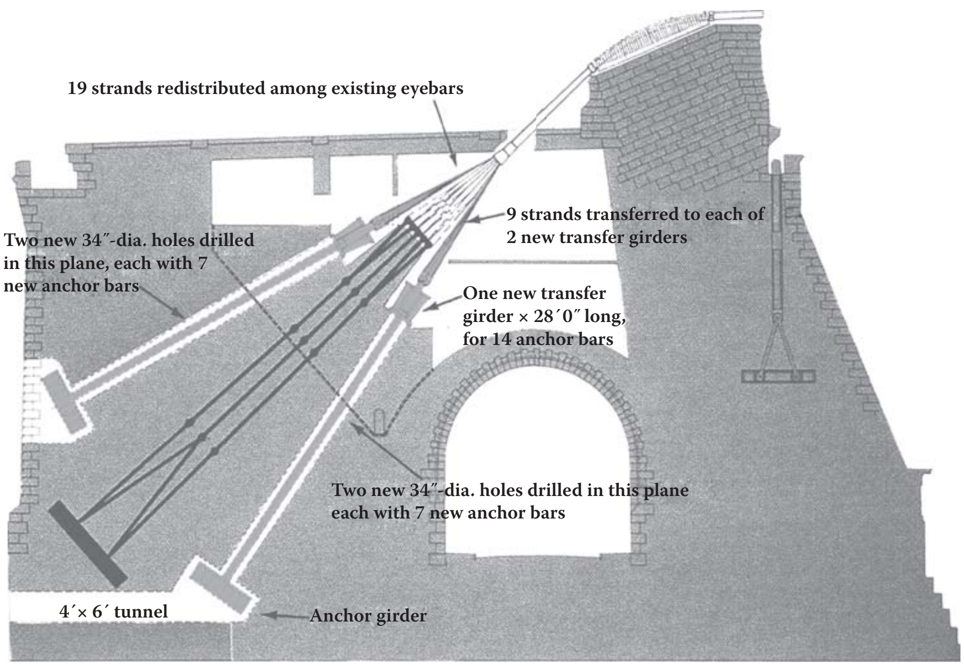


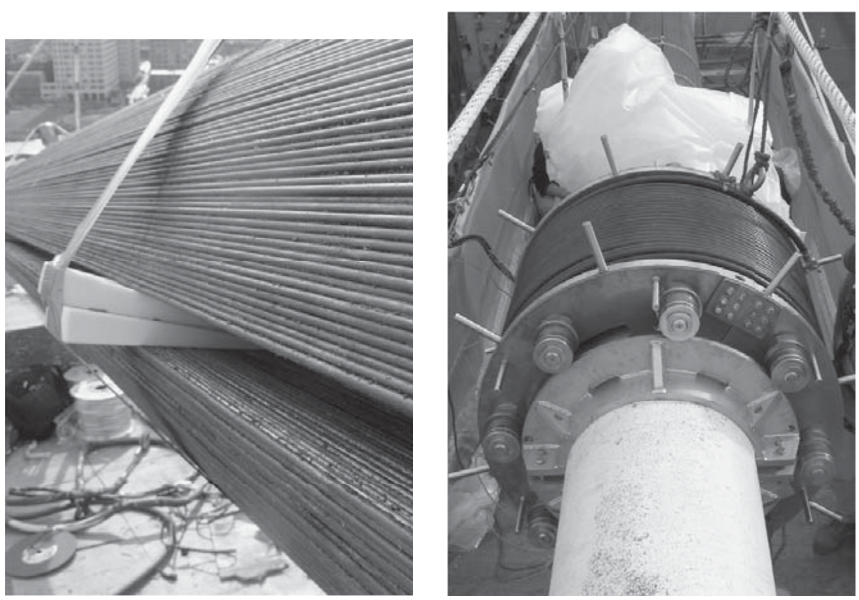
Figure 1.16 Manhattan anchorage, Manhattan Bridge.

Figure 1.17 Nine transferred strands, cable C, Manhattan anchorage.

1.4 CABLES

Each of the four Manhattan Bridge cables comprises 9472 parallel high-strength galvanized wires (256 × 37 strands) with an overall diameter of 55.2 cm (21.2 in). Given a wire diameter of 5 mm (0.198 in), the void ratio of the cable is close to the typical, if not optimal, 20%. Figure 1.18a shows a portion of the cable, unwrapped and wedged for inspection. The cable wires are considered in good condition. Their red pigment is a remnant of the original lead paste. None was applied during the current rehabilitation. The original grease coating still covers the zinc surface of the wires. Figure 1.18b shows a test of the magnetic flux method developed by Tokyo Rope for estimating the amount of steel in the cable without unwrapping.

As the age of the parallel wire suspension cables surpasses a century, their life cycles enter unfamiliar territory. In 1988 the need to estimate the remaining strength of the Williamsburg Bridge cables was particularly urgent. That task intensified the research and development of methods for suspension cable inspection, evaluation, and preservation. The four suspension bridge owners in the New York City metropolitan area (New York City Department of Transportation [DOT], New York State Bridge Authority, Port Authority of New York & New Jersey, and Metropolitan Transportation Authority [MTA]) commissioned a joint report on the condition of the cables at their 10 bridges from Columbia University (Bieniek and Betti, 1998). The Transportation Research Board funded National Cooperative Highway Research Program Report 534 by Mayrbaurl and Camo (2004) on the evaluation of cable strength. The Federal Highway



(a) (b)

Figure 1.18 (a) Unwrapped wedged cable and (b) testing of cable D by magnetic flux.

Administration (FHWA) followed with the report on field cable strength evaluation (Chavel and Leshko, 2009). The need to unwrap cables periodically, wedge them at numerous locations along their length and circumference, and examine the conditions of the wires was emphasized. Guidelines for statistical evaluation of the limited findings were recommended.

Concurrently, the noninvasive monitoring of cable wire condition by means of new technologies for data acquisition and transmittal has become a potentially cost-effective alternative to unwrapping and wedging. Through an act of Congress, FHWA funded an investigation of that possibility with particular emphasis on the East River bridges, as well as for general application. Many sensing technologies were tested on a 7 m (21 ft) 10,000-wire model at the Carleton Laboratory, Columbia University. The most promising ones were field-tested on Manhattan Bridge in 2012. The locations of the implanted sensors are shown in Figure 1.19. The cable model

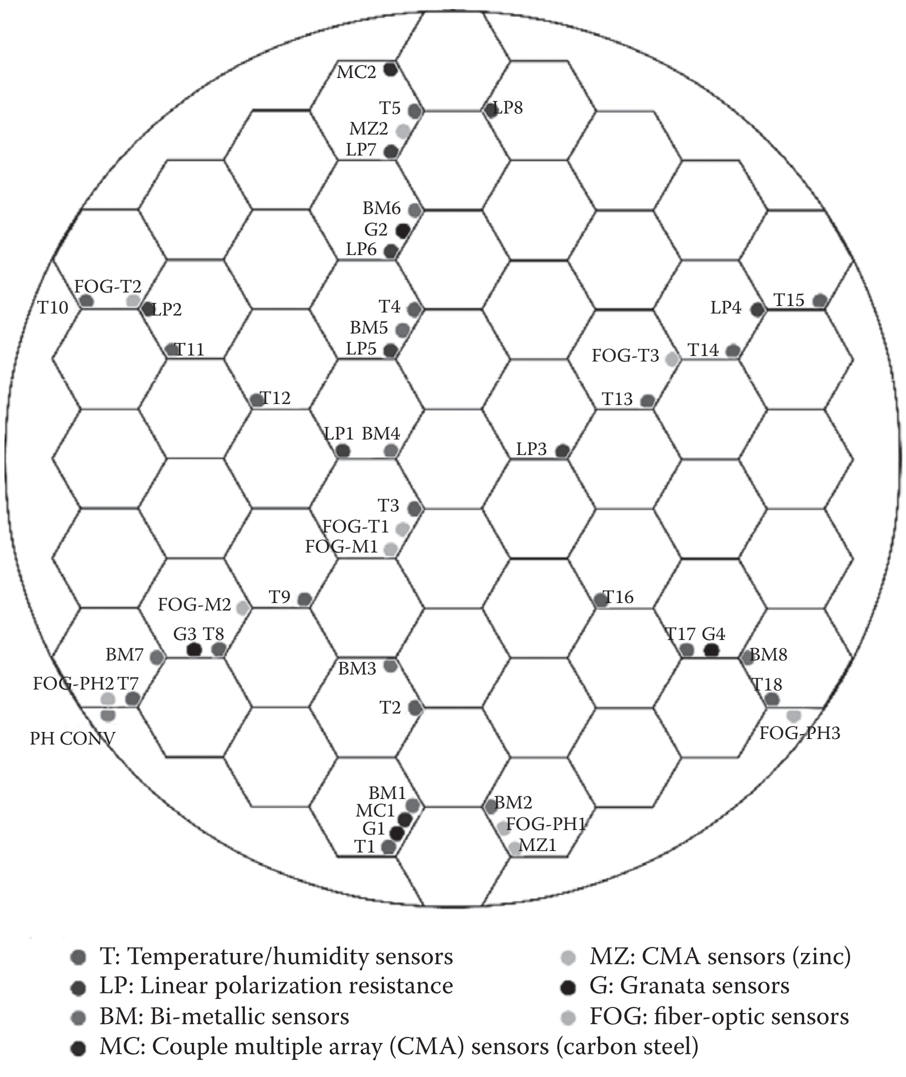


Figure 1.19 Locations of various sensors in the cable model.

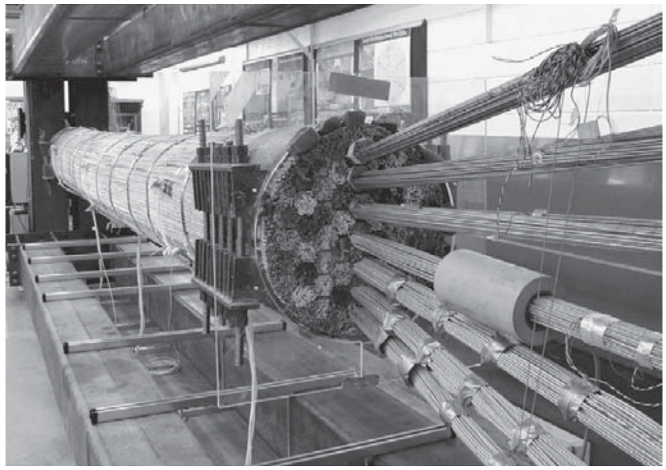


Figure 1.20 Cable model, Carleton Laboratory, Columbia University.

is shown in Figure 1.20. The results are reported in FHWA-HRT-14-024 (Betti et al., 2014).

The sensors installed with the assistance of New York City DOT at Manhattan Bridge monitored temperature, humidity, wind velocity, vibrations, and the rate of corrosion. A clear correlation was demonstrated between ambient temperature and internal humidity. That finding may explain why certain locations on a cable are more corrosion prone than others.

While noninvasive monitoring is explored in this manner, the Honshu–Shikoku Bridge Authority developed cable dehumidification by injection of dry air. The method precludes corrosion by maintaining humidity below 40%. The first applications were at the (then) new Kurushima and Akashi Kaikyo Bridges. The method is now contemplated for older structures, where linseed oil, lead, and zinc paste, as well as other active and passive corrosion inhibitors have been applied since the time of construction. The rate of air penetration under such conditions is investigated on the cable model at Columbia University (Figure 1.20).

1.5 SUSPENDERS

Cables were rewrapped and suspenders were replaced 30 years ago at the Brooklyn Bridge and 20 years ago at the Williamsburg Bridge. The suspenders at Manhattan Bridge had been replaced over 50 years ago. By the mid-1990 the suspenders were exhibiting wire breaks due to corrosion near the sockets at the level of the bottom truss chord (Figure 1.21) and due to friction at the level of the top chord.

Most of the existing suspenders on the Manhattan Bridge were installed under a US$2.2 million contract with Roebling & Sons in 1956 and was one of their last before closing their Bridge Division in 1964 (Zink and

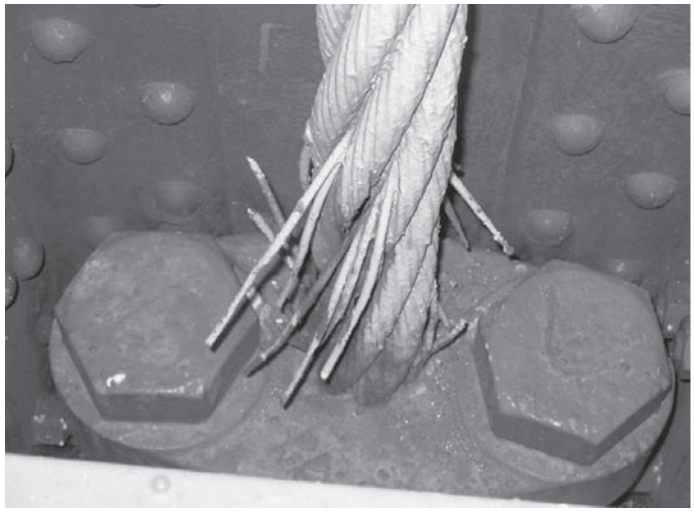


Figure 1.21 Wire breaks in suspender at the bottom socket.

Hartman, 1992). That contract included an attempt to determine the dead-load stresses existing in the structure. Extensometers were used for the purpose with less than satisfactory results.

The latest contract to rehabilitate the main cables; install new wire wrapping, neoprene barrier, and hand ropes; and replace the 1256 individual suspender ropes at the 628 suspender panel points was bidden for US$149.5 million and executed between 2009 and 2013 by Koch Skanska.

As shown in Figure 1.22, the new suspenders represent a significant innovation. With the exception of the portions midspan and near the anchorages, the suspenders are anchored at the top chords of the trusses, rather than (as originally) at the bottom. The suspension reanchoring offered several life-cycle advantages. Due to the unique aspects of this new configuration, much

Figure 1.22 Old and new suspenders.

attention was given to the proper distribution of the loading on the suspenders. Frequency measurements were taken in the longitudinal and transverse directions at the equalizer bars of the new suspender assemblies with triaxial accelerometers and initially calibrated with hydraulic jacks and pressure gauges. Loading of existing suspenders was measured by jacking prior to removal in order to calibrate current as-built loading of the main bridge.

The method considerably accelerated the project. The consultants (Weidlinger Associates and Parsons Transportation Group) also considered checking the new suspender loads using a "laser load" technique.

The geometry layout of the bridge and the requirement for only off-peak upper roadway lane outages dictated the replacements of the suspenders along each of the four cable lines before proceeding to the next.

1.6 LIFE-CYCLE MANAGEMENT

Manhattan and Williamsburg provide the only mutual rerouting alternatives for truck traffic between Brooklyn, Manhattan, and New Jersey. The capacity of the Brooklyn Bridge is limited to passenger and emergency vehicles. Hence, the concurrent rehabilitations had to be coordinated for minimum service interruptions. The very choice of rehabilitating, rather than replacing the Williamsburg Bridge, was influenced by the demand for uninterrupted traffic. Staging the rehabilitations of the East River bridges over the same 30 years elevated their costs to roughly US$1 billion per bridge. These expenditures, and the incalculable user costs, incurred during the inevitable traffic interruptions, underscored the need for cost-effective management of such unique assets over their entire life cycles. It was recognized that while any material structure and all of its modifications over time have finite useful life, the service provided by an essential bridge permanently changes the local geography and must have a perpetual life cycle. Similarly, perpetual is the need for structural maintenance and preservation, since by the conclusion of decade-long projects, new needs are already arising.

The developments at the East River bridges during the 1980s and 1990s contributed to the interest in life-cycle bridge management on all levels from the federal to the local. The following innovations in bridge management have resulted, among others, in the following:

- The FHWA recognized expenditures for major maintenance, such as repainting as eligible for federal funding.
- The New York City DOT commissioned a preventive maintenance report on the bridges in its purview (Bieniek et al., 1989, 1999). As a follow-up, detailed maintenance manuals were compiled for all East River bridges. Tasks such as oiling of wires in the anchorages, repairs of wrapping, painting, spot painting, maintenance of travelers, and cleaning of joints were scoped, scheduled, and budgeted.

- On the East River bridges and their approaches, deicing with salt by the city's Department of Sanitation was replaced by anti-icing with potassium acetate by New York City DOT. In a significant change of policy, the FHWA treats this costlier activity as eligible for federal funding.
- All designs for rehabilitation and replacement of structural elements must specify the expected useful life and supply maintenance instructions.
- Estimated life-cycle direct and user costs are gaining in importance over first direct costs as criteria in design proposal selection. For example, the reanchoring of the suspenders at Manhattan Bridge to the upper truss chords was motivated primarily by maintenance considerations.

1.6.1 Ownership and landmark status

Although the Manhattan Bridge is currently considered a city street, both New York City and State are currently looking for ways to collect revenue from the Manhattan Bridge, which is busiest trucking routes for the 7.7 million people living in Long Island (third most populous island in the Western Hemisphere). In the past, the city has suggested tolling through the PlaNYC congestion pricing. There was no vote on the proposal by the state legislators. New York State has suggested tolling through MTA's Blue Ribbon Panel. The MTA offered the city US$1.00 for the right to toll the bridge. A more equitable alternative proposes a fare-pricing plan that would toll all city and MTA bridges and tunnels to/from Long Island equally.

The Manhattan Bridge is an American Society of Civil Engineers National Engineering Landmark. The city's Landmarks Commission considers the portion of the bridge crossing four blocks of the recently designated Down under the Manhattan Bridge Overpass (DUMBO) Historic District part of their jurisdiction for any proposed work on the sub- or superstructure (New York City Landmarks Preservation Commission, 2009). Paradoxically, the Brooklyn anchorage may not be viewed by the Design Commission in the same way as the Manhattan anchorage was viewed by the Landmarks Commission. Consideration is being given to submit the entire bridge for City Landmark status to avoid the need to seek approval for two commissions for similar work on one contract.

REFERENCES

Betti, R., D. Khazem, M. Carlos, R. Gostautas, and P. Virmani, 2014. Corrosion Monitoring Research for City of New York Bridges, Report FHWA-HRT-14-023, Columbia University, New York.

Bieniek, M. et al., 1989. Preventive Maintenance Management System for the New York City Bridges, Report of a Consortium of Civil Engineering Departments of New York City Colleges and Universities, the Center of Infrastructure Studies, Columbia University, New York.

Bieniek, M. et al., 1999. Preventive Maintenance Management System for the New York City Bridges, Report of a Consortium of Civil Engineering Departments of New York City Colleges and Universities, the Center of Infrastructure Studies, Columbia University, New York.

Bieniek, M., and R. Betti, 1998. The Condition of Suspension Bridge Cables, Technical Report, Columbia University, New York.

Birdsall, B., 1971. Manhattan Bridge—Structure and Model: A Study in Motion and How to Arrest It, *Municipal Engineers Journal*, Paper 385, the City of New York.

Burr, W. H., 1913. *Suspension Bridges Arch Ribs and Cantilevers*, John Wiley & Sons, New York.

Chavel, B., and B. Leshko, 2009. Primer for the Inspection and Strength Evaluation of Suspension Bridge Cables, Federal Highway Administration, Washington, DC.

Griggis, Jr., F. E., 2008. The Manhattan Bridge: A Clash of the Titans, *Journal of Professional Issues in Engineering Education and Practice*, *134*(3), 263–278.

Hool, G. A., and W. S. Kinne, 1943. *Movable and Long-Span Steel Bridges*, McGraw Hill, New York.

Johnson, A., March 23, 1910. Presentation to the Municipal Engineers, Paper 55, the City of New York.

Mayer, L., B. Yanev, L. D. Olson, and A. W. Smyth, 2010. Monitoring of the Manhattan Bridge for Vertical and Torsional Performance with GPS and Interferometric Radar Systems, Annual Conference, Transportation Research Board, Washington, DC.

Mayrbaurl, R. M., and S. Camo, 2004. Guidelines for Inspection and Strength Evaluation of Suspension Bridge Parallel-Wire Cables, National Cooperative Highway Research Program Report 534, Transportation Research Board, Washington, DC.

Mayrbaurl, R. M., and J. Good, 1988. Reanchoring a Main Cable on the Manhattan Bridge, The First Oleg Kerensky Conference, London.

Modjeski, R., 1909. Report on the Design and Construction of the Manhattan Bridge, For the Department of Transportation, New York City.

New York City Department of Bridges, 1901. Annual Report, Commissioner Gustav Lindenthal to the Mayor of the City of New York, Martin Brown Co., New York.

New York City Department of Bridges, 1904. Annual Report, Commissioner George McClellan to the Mayor of the City of New York, Martin Brown Co., New York.

New York City Department of Bridges, 1912. Annual Report, Commissioner Arthur O'Keeffe to the Chief Engineer Alexander Johnson, New York.

New York City Landmarks Preservation Commission, 2009. *Guide to New York City Landmarks*, Fourth Edition. Edited by Postal, M., John Wiley & Sons, Hoboken.

New York Times, December 11, 1908. Mayor Completes Last Bridge Strand, New York.

New York Times, December 5, 1909. One Hundred Cross the Manhattan Bridge, New York.

New York Times, January 1, 1910. Manhattan Bridge Opened to Traffic, New York.

Nichols, O. F., 1906. Manhattan Bridge, Its Terminals and Connections, Paper Number 23 presented March 27, 1906 to the Municipal Engineer of the City of New York.

Perry, A. I., January 14, 1909. The Manhattan Bridge Cables, Presentation to the Brooklyn Engineers' Club—Paper 86, New York.

Reier, S., 1977. *The Bridges of New York*, Dover Publications, New York.

Scientific American, February 1, 1908. Erection of the Manhattan Bridge Across the East River.

Shea, J., 1901. Report of the Commissioner of the New York City Department of Bridges to Honorable Mayor Robert A. Van Wyck.

Steinman, D. B., 1913. *Theory of Arches and Suspension Bridges.* Translation Authorized by Melan, J., Myron Clark Publishing, Chicago.

Steinman, D. B., 1922. *A Practical Treatise on Suspension Bridges: Their Design Construction and Erection*, John Wiley & Sons, New York.

Steinman, D. B., April 1955. An Investigation of the Structural Condition of the Manhattan Bridge, Report to the New York Department of Public Works.

Steinman, D. B., and S. R. Watson, 1941. *Bridges and Their Builders*, Putnam's Sons, New York.

Steinman, Boynton, Gronquist & London, April 1971. Study and Recommendations for Reduction of Torsional Deflections in the Suspended Spans, Manhattan Bridge, Report to the Transportation Administration, Department of Highways, City of New York.

Winpenny, T. R., 2004. *Manhattan Bridge: The Troubled Story of a New York Monument*, Canal History and Technology Press, Easton, in association with the Smithsonian Institution, Washington, DC.

Zink, C. W., and D. Hartman, 1992. *Spanning the Industrial Age: The John A. Roebling's Sons Company*, Trenton Roebling Community Development Corporation, Trenton.