Inspection, Evaluation and Maintenance of Suspension Bridges

Case Studies

Edited by

Sreenivas Alampalli and William J. Moreau

CRC Press
Taylor & Francis Group
A SPON PRESS BOOK

Inspection, Evaluation and Maintenance of Suspension Bridges

Case Studies

Inspection, Evaluation and Maintenance of Suspension Bridges

Case Studies

Edited by

Sreenivas Alampalli

New York State Department of Transportation

William J. Moreau

Formerly Chief Engineer, New York State Bridge Authority

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

A SPON PRESS BOOK

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Version Date: 20150930

International Standard Book Number-13: 978-1-4665-9689-4 (eBook - PDF)

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

To all the bridge engineers around the world
for their dedicated service to public safety.

Sreenivas Alampalli and William J. Moreau

Contents

Preface

Owners and operators of long-span suspension bridges are scattered around the globe, just like the bridges they maintain. Some of the oldest long spans are in the United States; the newest are in and around the Pacific Rim; and Europe is home to many world-class suspension bridges, with many built post World War II. New construction continues throughout Europe in the Netherlands, the United Kingdom, and Turkey. An array of interesting concepts to connect Italy with the island of Sicily is also on the drawing board.

A challenge for long-span suspension bridge operators is that most operators oversee only one or two bridges through small single-purpose public authorities or subdivisions of state-run transportation agencies. This, combined with the fact that most suspension bridges operate over a very long lifetime, makes it difficult for bridge owners to acquire the experience necessary to detect signs of deterioration early, develop effective mitigation plans, and implement the appropriate restoration in a timely and cost-effective manner.

The International Cable Supported Bridge Operators' Association was conceived in 1991 when over 125 international suspension bridge owners and operators assembled in Poughkeepsie, New York, to discuss common concerns, present research papers, and observe the main cables of the Mid-Hudson Bridge, which was undergoing a full-length main cable rehabilitation project at the time. Attendees traveled from Europe, South America, Asia, and across the United States to share problems, solutions, and best practices with the goal of reducing this challenge.

The companion volume, which was published in 2015, assembled decades of knowledge and experience through the authorship of many progressive suspension bridge owners. Based upon their own perspectives, each owner discusses their state-of-the-practice for suspension bridge engineering, including the nuances of each bridge element unique to suspension bridges, together with a historical overview, design, inspection, evaluation, maintenance, and rehabilitation.

This volume illustrates historical to current operations of selective suspension bridges all around the world in detail as told by an outstanding array of international bridge operators. The resurgence of the suspension bridge as a practical bridge type has been brought about through a confluence of changes. These changes consist of new materials, new construction methods, and the desire to cross geography with unsuitable foundation locations or depths. Manufacturing centers and shipping routes have also changed considerably throughout the world, thereby making the cost advantages of suspension bridges economically viable once again.

While the number of suspension bridges opened to traffic in the second half of the 20th century was relatively small, the turn of the century has seen dozens of new spans open, some with remarkable span lengths. This series of case studies covers the generic day-to-day issues of suspension bridge inspection and routine maintenance, as well as periodic inspection, maintenance, and evaluation that may uncover some hidden concerns. Timeliness is crucial in arresting the various degradation processes that begin to attack the vulnerabilities of suspension bridges from the day they are built. Careful documentation of the conditions found during these inspections will be invaluable and will be intently studied by future bridge tenders. Trial and error has taught us that many layers of paint on the cable covering may not be the best solution to cable protection. Misconceptions as well as success stories are shared in the hope of advancing the state of the practice for bridge owners and operators.

The principal objective for all of us in transportation is to protect the public safety while enhancing the mobility of our communities for economic and quality-of-life improvements. However, when working with such demonstrable examples of humanity's engineering abilities, we tend to want to ensure a perpetual service life for the grandest engineering icons. Lessons learned over time will be our best asset in improving our performance in this regard. We thank all who were involved in the authorship and development of this book. Their personal efforts and contributions to the industry will not be forgotten.

Sreenivas Alampalli and William J. Moreau
Editors

Acknowledgments

It has been a great pleasure working with owners of suspension bridges around the world to bring this book to fruition. The discussions for documenting the body of knowledge gained by the current and past suspension bridge owners originated at a meeting of the International Cable Supported Bridge Operators Association workshop held in May 2012 in New York State. It was decided by the editors that documenting these experiences in the form of two books would serve not only the owners but also the entire bridge industry. The companion volume discusses the state of the practice in suspension bridge inspection, evaluation, and rehabilitation methods used worldwide. This volume discusses specific bridges around the world to give a comprehensive picture of how these suspension bridges are operated and maintained by an array of countries and cultures. Knowing that the contributing authors did not have time to undertake such an effort as this but spent valuable time in documenting their experiences and practices for future generation of engineers, we thank them for their time and efforts in making this book, and the companion book that was published earlier, a reality.

We also thank our families (Sharada Alampalli and Sandeep Alampalli and Cheryl Moreau) for their support during the preparation of these books.

Sreenivas Alampalli and William J. Moreau

Editors

Dr. Sreenivas Alampalli, PE, MBA, is director of the Structures Evaluation Services Bureau of the New York State Department of Transportation. Before taking up the current responsibility in 2003, Dr. Alampalli was director of the Transportation Research and Development Bureau, where he worked for about 14 years in various positions. He also taught at Union College and Rensselaer Polytechnic Institute as an adjunct faculty member.

Dr. Alampalli obtained his PhD and MBA degrees from Rensselaer Polytechnic Institute; his MS degree from the Indian Institute of Technology, Kharagpur, India; and his BS degree from Sri Venkateswara University, Tirupati, India. His interests include infrastructure management, innovative materials for infrastructure applications, nondestructive testing, structural health monitoring, and long-term bridge performance. Dr. Alampalli is a fellow of the American Society of Civil Engineers, the American Society for Nondestructive Testing, and the International Society for Health Monitoring of Intelligent Infrastructure. He is the recipient of the Bridge Nondestructive Testing Lifetime Service Award in 2014 from the American Society for Nondestructive Testing for outstanding voluntary service to the bridge and highway nondestructive testing industry. In 2013, he also received the American Society of Civil Engineers' Henry L. Michel Award for Industry Advancement of Research. Other notable awards he received include the American Society of Civil Engineers' Government Civil Engineer of the Year in 2014, and the prestigious Charles Pankow Award for Innovation from the Civil Engineering Research Foundation in 2000. He has authored or coauthored more than 250 technical publications, including two books on infrastructure health in civil engineering.

Dr. Alampalli is an active member of several technical committees in the Transportation Research Board, the American Society of Civil Engineers, and the American Society for Nondestructive Testing. He currently chairs the Technical Committee of Transportation Research Board on field-testing and nondestructive evaluation of transportation structures. He served as the Transportation Research Board representative for the New York State Department of Transportation and as a member of the National Research Advisory Committee. He is a book review editor of the American Society of Civil Engineers' *Journal of Bridge Engineering* and serves on the editorial boards of the journal *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance* and the journal *Bridge Structures: Assessment, Design and Construction.*

William J. Moreau, PE, served as the chief engineer of the New York State Bridge Authority for over 27 years. Two of the six Hudson River crossings previously under his care were suspension bridges, constructed circa 1924 and 1930. Maintenance and preservation of these world-class suspension bridges became a career objective for Moreau, culminating with service on the peer-review panel for the development of National Cooperative Highway Research Program Report 534, *Inspection and Strength Evaluation of Suspension Bridge Parallel-Wire Cables*. Moreau participated for many years as a member of Transportation Research Board committees and served as a chairman of the Construction Committee for Bridges and Structures from 2005 through 2007.

Many early main cable-inspection techniques, evaluation methods, and restoration materials were developed through partnerships Moreau developed with truly outstanding members of the engineering, construction, and material manufacturing communities in pursuit of arresting the effects of age and environment on the main cables of the Hudson Valley suspension bridges. He is currently semiretired and continues consulting in the New York City area.

Contributors

Sreenivas Alampalli
New York State Department of Transportation
Albany, New York

Finn Bormlund
A/S Storebælt
Copenhagen, Denmark

Anna Chatzifoti
Halifax Harbour Bridges
Dartmouth, Nova Scotia, Canada

Ahsan Chowdhury
Halifax Harbour Bridges
Dartmouth, Nova Scotia, Canada

Barry Colford
AECOM
Philadelphia, Pennsylvania

Jon Eppell
Halifax Harbour Bridges
Dartmouth, Nova Scotia, Canada

James D. Gibson
TIML MOM Ltd
Hong Kong, China

Brian Gill
New York City Department of Transportation
New York, New York

Mary Hedge
MTA Bridges and Tunnels
Metropolitan Transportation Authority
New York, New York

Justine Lorentzson
MTA Bridges and Tunnels
Metropolitan Transportation Authority
New York, New York

William J. Moreau
HAKS, Engineering
New York, New York

Kim Agersø Nielsen
A/S Storebælt
Copenhagen, Denmark

Katsuya Ogihara
Honshu-Shikoku Bridge Expressway Co., Ltd.
Sakaide, Japan

Dora Paskova
MTA Bridges and Tunnels
Metropolitan Transportation Authority
New York, New York

Mohammad Qasim
MTA Bridges and Tunnels
Metropolitan Transportation Authority
New York, New York

Stewart Sloan
Port Authority of New York/ New Jersey
New York, New York

Leif Vincentsen
A/S Storebælt
Copenhagen, Denmark

Judson Wible
Parsons Brinckerhoff, Inc.
New York, New York

Gongyi Xu
China Railway Major Bridge Reconnaissance and Design Institute (BRDI)
Wuhan, China

Bojidar Yanev
New York City Department of Transportation
New York, New York

Jeremy (Zhichao) Zhang
MTA Bridges and Tunnels
Metropolitan Transportation Authority
New York, New York

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.

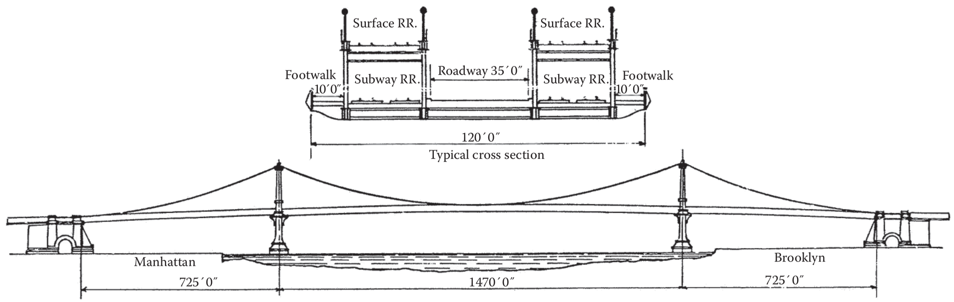
The Manhattan Bridge is 1761.4 m (5779 ft) long between abutments at the lower level and 1855 m (6086 ft) between portals on the upper levels. Both approaches are supported by three- and four-span continuous Warren trusses. Several stringer and floor beam spans support the upper roadways between portals 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 woodblock 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

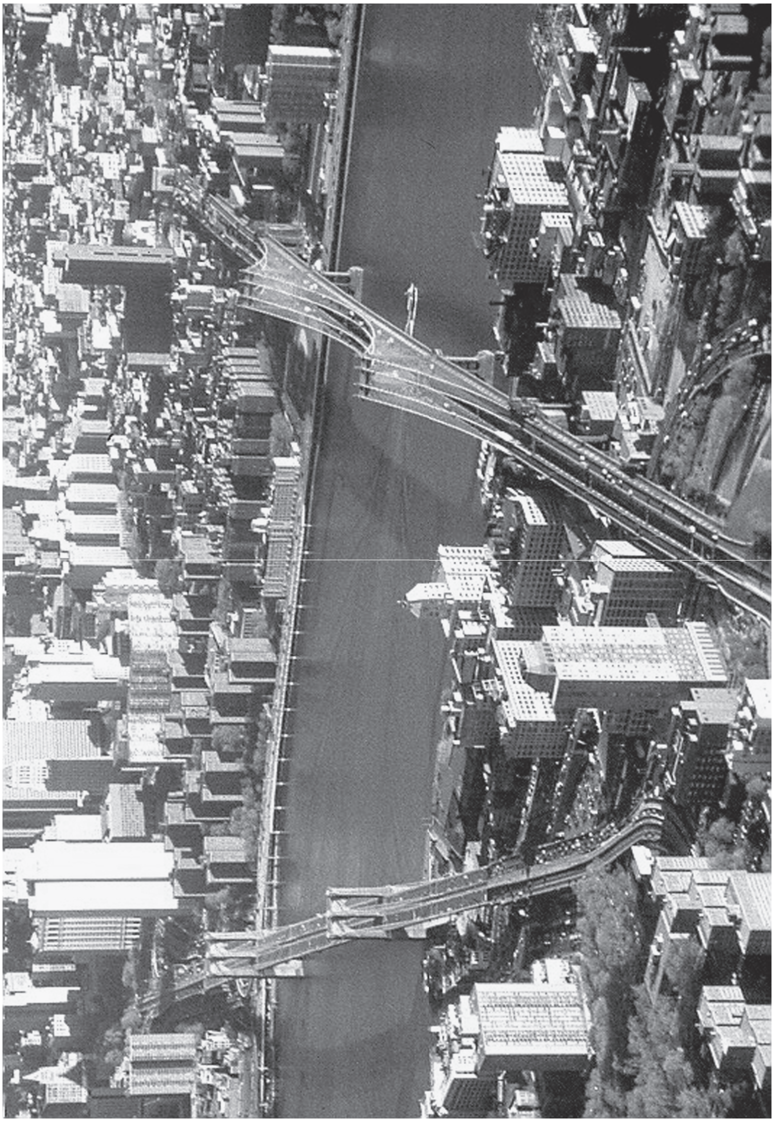
Subway trains	837,651 cars	43,248,000 passengers
Surface railroads	447,454 ”	12,605,000 ”
Vehicles	4,030,867	7,664,000 ”
Pedestrians		412,000

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.

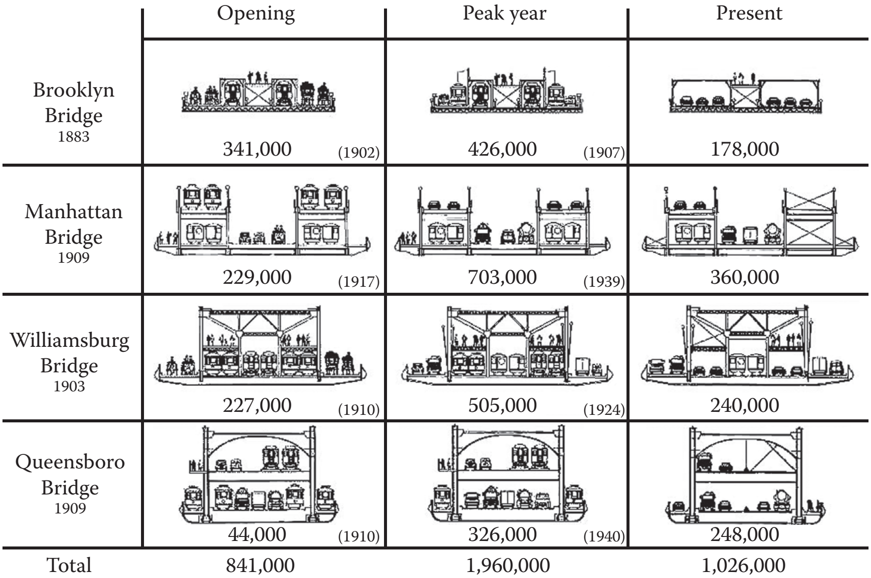


Figure 1.2 Use of the East River crossings from their opening to 1988.

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 23.8×43.9 m^2 (78×144 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