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A STUDY OF THE BROOKLYN BRIDGE

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Abstract: This paper describes relevant information pertaining to the Brooklyn Bridge in several aspects, such as general description of the engineers and construction process of the Brooklyn Bridge. It also critically analyse the aesthetics, strength, serviceability, durability and susceptibility. Furthermore, the paper describes how the loadings, such as dead, superimposed dead, live, temperature and wind affect the structure of the bridge and analyse how the construction of the Brooklyn Bridge could have been improved on.

Keywords: *Caisson, anchorages, cable spinning, temperature and wind effect, Rules of Fritz Leonhardt, strand*

1 Introduction

The Brooklyn Bridge, one of the most magnificent bridges in the world, spans 1825m across East river connecting the Boroughs of Manhattan and Brooklyn in New York City. It is the first bridge built with the technology of steel wire to carry the deck. This is one of the oldest suspension bridges in the world and at the time it opened, the longest among all. The most conspicuous feature of the bridge is the two great towers. At the time it was completed, the 99-meter high neo-Gothic granite towers dwarf everything in view. By the time only the slim spire of Trinity Church was higher than the Brooklyn Bridge on New York skyline. Today, the towers are the landmark of the New York cities (NYC), and are entitled to be ranked as national monuments. Not only does it represent the greatness New York, the Brooklyn Bridge fully symbolizes American ingenuity. The achievement of building a bridge connecting Manhattan and Brooklyn was spectacular; what impressed people most was the overall stretch of the bridge across the river. Refs. [3,7]

The bridge took a total of thirteen years to complete and was open for public use on 24th May 1883. At the time it started its service, it was 50% longer than any bridges which had been built. Brooklyn Bridge necessitated the construction of additional bridges. Further later, due to the projected growth in the cities of New York and Brooklyn, more bridges such as Williamsburg and Queensboro were built to support the heavy traffic across the river.

3 Background

The first ferry across the East River dated back to 17th century, which was a row boat operated by Cornelius Dircksen. In the following two centuries, there was a rapid growth of traffic across the river due to the development of shipping industry. The congestion problem was not relieved until the 19th, when the residents of Manhattan and Brooklyn petitioned to the government to construct a bridge across the East River. Although there is a boom of population in Brooklyn from 1860 – 1870 (266,000 – 396,000), it is still more rural than urban. The city of New York, which only consisted of Manhattan at that time, had twice as many residents. The bridge was seen as a solution to spur the development in Brooklyn and hence solved the overcrowded Manhattan. It would also enable a faster traffic across the river, regardless of weather conditions. A bill for the construction of the Brooklyn Bridge was finally passed by the New York State Legislature in 1866. Ref [3,7]

Roebling was appointed as the Bridge Design Engineer with salary $8000 per year. He worked out every detail of the bridge, from its foundations to the deck and steel cables. Two years later, in March, 1869, he convened a board of consulting engineers to examine his plans and also to report upon the feasibility of the work. Meanwhile, a commission of three engineers was appointed by the government to report any general problems in the projects and particularly examine whether the bridge would be an obstruction to navigation. Eventually the government commission accepted John

Roebling's plans but requested an increase of 1.8 meters in height at the mid span. Ref. [6]

3 Cost Ref. [6]

In order to adapt the increasing volume of inter-urban commerce and the rapid growth of cities, considerable changes must be made in the original plan. The new design was not only become larger and more capacious, but also strengthens its structure. Such changes caused the entire project out of budget.

At start, John Roebling estimated the project would last 5 years and cost $10,800,000 in which $7,000,000 would be the spent on the bridge and $3,800,000 on the land required. Due to several changes on the bridge required by the United States government, the actual cost, when completed, was about $15,000,000. These additional items are:

The original estimate for building the foundations of the towers was found to be entirely inadequate. For the New York tower it was necessary to excavate 28.1 meters to the reach the bedrock. The cost of labor for such unprecedented depth was founded to be four and half times of the original cost. Although the Brooklyn Tower could have a sallower foundation, the cost was still two times of the origin.

The United States government required an increase of 1.8 meters in height at the central clearance of the bridge, which resulted to be 48.6 meters. It was also decided to widen the bridge from 28.8 meters to 30.6 meters. The total cost, including superstructure, towers, foundations and anchorages, increased 8 percent due to these changes.

In order to strengthen the bridge, John Roebling decided to use steel instead of iron in the construction of both the cables and the suspender superstructure. This replacement cost $2,000,000, which covers the excess in cost on the bridge proper.

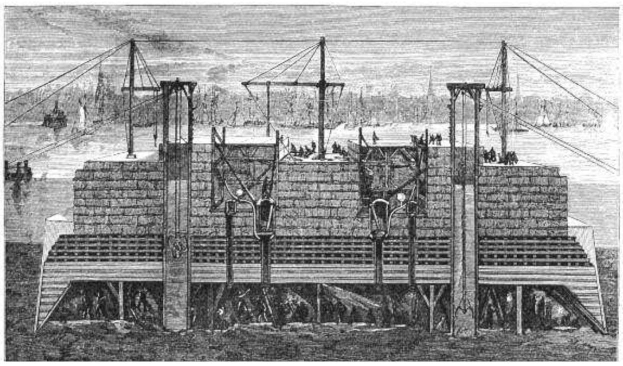
The United States government decided to connect the system of rapid transit of New York and Brooklyn. The new station building and elevated railway structures were to be built on the approaches.

The above changes and additional items were not originally contemplated, and they totally swelled the cost of the bridge by five million.

4 Construction

4.1 Foundation

After clearing the site for the bridge, the construction of foundation on the Brooklyn side was started. Washington Roebling used a technology known as 'caisson' to excavate the foundation.



Firgure 1: The caisson

The caisson, 36.7 meters by 61.9 meters, was built to a thickness of 7.9 meters of dense Southern pitch-pine in timbers to provide sufficient strength and rigidity in the structure for its tremendous load. The sides were 2.9 meters thick at their junction at the top, but tapered on the inside and became 0.2 meters thick at the base. Iron bolts and angle-irons were strong and numerous that nothing can loosen timber from timer. In fact, the bolts and angles of the caisson aggregated 250 tons. The platform that was to support the great tower was supported by six cross partitions of solid timber four feet thick. These partitions ultimately rested on the bedrock and bear the everlasting load. Finally, the caisson was lined with boiler iron, seamed air tight for protection against the danger of fire. Ref. [6]

Air lock chambers were used for the ingress and egress for workers and materials. They were lined with iron, continuous and air-tight with the lining of the interior. Two successive doors with an air-tight chamber between them were provided for a gang of workers to enter. However, for the removal of the excavated earth, water locks were used. Ref. [6]

At first, a dock was built to fix it in exact position of the intended tower. A row of plies, with a length of 61.9 meters, was driven along the landward line. At the right angle of these piles, another row of piles was driven out 36.7 meters into the river at each end, making three sides of an oblong enclosure. The caisson was then towed into this enclosure. The next business was to begin with the foundations of the pier on the massive platform. The vast squared blocks of granite were laid at leisure in hydraulic cement in uniform courses. Their weight overcomes the buoyancy of the caisson and eventually settled to the bottom. Initially the caisson only touched the bottom by its weight and did not rest heavily. The workmen went down into the wet cellar to complete the leveling of the earth under the supporting edges of the structures. The engineers adjusted the mass in exact position by easing away the bottom under it. The caisson would become immovable after few more blocks of granite were laid on it. The workers were then to lift out the mud and stones by tools such as shovel, pick and wheelbarrow. The final operation was to fill up the caisson with a solid hydraulic concrete, which would harden into rock and unite itself immovably with the rock on which it rested. Further in time, the increasing weight on the wooden support would eventually bear the caisson firmly. Refs. [6,9]

Experience shown that, wood is perfectly incorruptible when buried beyond reach of air and changes of temperature. Thus wood could be trusted to support the bridge between New York and Brooklyn as long as it does not reach any oxygen and chemical. Refs. [3,6]

On May 1870, ten of the fifteen thickness of timber in its roof were built on after the caisson for the Brooklyn Tower was placed into its berth. On 15th of June the first granite blocks were laid on the timber. This masonry, each four to seven tons weight, is partly built of less expensive blue limestone from Kingston, New York. Compressed air was pumped in, water was driven out and workers started excavation on 10th July. On this side, The foundation on the Brooklyn side was only needed to be 16.0 meters below the mean high tidal level because the bed consisted of tenacious conglomerate of clay, sand, extending to a great depth. Meanwhile, work had been interrupted for two months due to a fire accident in the caisson. The fire was extinguished by flooding the interior with water. This accident cost $15,000. The final stage was to fill up the caisson with concrete to fix its position. The entire operation finished on 11th of March, 1971. Refs. [3,7]

Washington Roebling encountered a much greater magnitude and difficulty of work in the New York foundation. It was necessary to sink the pier to the bed-rock, 28.1 meters below high water-mark because the material down the river was mainly consisted of sand. This process, although no difference in method, required a larger launching size of caisson and much more workmen to excavate a deeper depth in a greater air pressure. The caisson was towed into its berth in October, 1871 and rested on the rock in May, 1872, and eventually sank into bed in less then one year. Ref. [7]

The construction of the Brooklyn Bridge took 30 deaths and caused thousands of injuries. One of the most common injuries during excavation is called Caisson Disease. It is a decompression sickness commonly known as 'the bends'. The maximum air pressure inside the caissons was 158 kPa. As workers left the caissons from underground they experienced a great reduce of air pressure from 1.58 bar to 1.01 bar and therefore had rapid decompression. This is same as the process of decompression sickness in divers. Ref. [3]

Due to working in compressed air in caissons, Washington Roebling was also stricken from Caisson Disease. He became an invalid in Early Summer 1872. This disease also caused him to halt the management of construction of the tower for several months. Thereafter, his wife, Emily Roebling, assisted her husband to direct the construction of the bridge by passing every message from Washington to the on-site engineers and workers. She studied higher mathematics and bridge engineering, and soon made daily visit to monitor the process of construction. Ref. [7]

4.2 The towers of the Brooklyn Bridge

Washington Roebling started the construction of towers in late 1872 after the completion of foundations. The two massive towers were made by stone masonry which was provided by Quarries of J.R. Bodwell, Hallowell, Maine. This stone was also used in Tombs prison and the reservoir in Central Park. The height of the towers above the mean high tide was 99m. By the time there was only The Spire of Trinity Church (101m) could reached this height. The two towers were designed to be high and bulk enough to serve fundamental purposes. They supported the enormous weight of the roadway and cables. The deck and the towers were high enough so that the traffic on the river would not be interfered. The mass of the anchorages, where they were secured on the two sides of land, had to be sufficient to hold the great tension of the cables. As a result, the towers, whatever their height, had to be able to sustain the colossal downward pressure of the cables as they passed over the tops of the towers. After three years of construction, the Brooklyn and Manhattan towers were completed in June 1875 and July 1876 respectively. Refs. [8,9,14]

4.3 Anchorages

At the end of the suspension cables, they are secured by anchorages, which are solid cubical structures of stone masonry. They are 42.8 by 47.5 meters at the base and rising 32.4 meters above high-water mark. To resist the great tension from the suspension cables, their weight has to be at least 60,000 tons each. These massive stone masonry structures are situated 334.8 meters back from the towers on each side. Refs. [6,8]

4.4 The cables, suspenders and stays

In the 1840's, John Roebling opened the first wire rope manufacturing company in America. He involved in several engineering projects which consisted of the use of steel wire and was eventually appointed as The Chief Engineer to design the Brooklyn Bridge. He introduced the use of steel, which is named as 'the metal of the future', for the cables. This decision to use steel instead of standard iron wire was a revolutionary proposal. At the time, steel was regarded as a suspect material, not yet proven over time as was iron. It was only being used for the construction of the railroads, but it had not yet been used for the major structures such as bridges. In fact, at the time of the construction of the Brooklyn Bridge, the use of steel in any structure in the Great Britain was illegal. Before the Brooklyn Bridge was constructed, no engineers tried the use of steel wire in bridge construction. As the public doubted his revolutionary proposal, he defended in an article pointing out the weakness of earlier iron-wire and chain suspension bridges and their vulnerability to destructive oscillation caused by high wind. Moreover, his son, Washington Roebling, ran a test indicated that the strength of steel wire (160 ksi) is twice of iron. Refs. [3,7]

4.5 Connection between the towers and anchorages

Before spinning the cables, Washington Roebling used a 19 mm wire rope to make the first connection between the anchorages. This wire rope was coiled on board a scow by the Brooklyn shore. First, it was hosted up and passed over the top of the Brooklyn Tower, and then carried back to the top of the Brooklyn anchorage and fastened. This wire rope was ready to connect to the New York shore provided that the river was clear of vessels. Again, the scow was towed across the New York tower, paying out the wire rope and hoisted it up, passed over and lowered again on the landside. The rope was eventually fastened to a drum connected with a steamengine and the first connection between the shores was made. A second span of wire was carried in the same manner. The two wires were joined at the anchorages around grooved driving-wheels or pulleys. Refs. [4,6]

4.6 Spinning wire ropes

Thirty-two drums, 2.9 meters in diameter, were installed in the position of carriage-wheels just clear of the floor. Thousands of coils of wire were delivered on site, dipped in linseed-oil and dried.

Meanwhile all was ready for the spinning of wires. The skein of wire to form a strand of the cable would be winded up, turned at each extremity and secured on the anchorage. A wire was fastened to the anchorage, and passed around a grooved pulley which held by traveler rope by iron arms. This traveler rope carried the skein of wire taking across the two spans, or a complete circuit at once. This spinning took eight minutes to reach the New York side. The bight of wire was passed around shoe and one circuit was finished. Ref. [6]

The next operation was to regulate the wires together. They must be adjusted to the exact length and height required. On the top of the Brooklyn Tower, a clamp, which directly reaching from the end secured at the anchorage, is fastened on the first span of wire. A small tackle-block is hooked on, two men pulled the slack of wire between the towers and anchorage until the positions were accurately adjusted at their respective points. A similar method was repeated on the New York tower and anchorage to regulate the curve of the wire on mid span and between tower and anchorage respectively. Same adjustment of wire was carried out on the return span in reverse order, started from the New York Tower. Immediately after the skein of wire passed around the shoe, held fast, and the bight is again placed on a sheave, the second circuit could be carried on. The continuous skein was uniform in tension and unbreakable, and the wires were parallel in alignment. Once 139 circuits were finished, the 278 wires were ready to be bound together in a round and solid cord three inches thick and finally formed a strand. Strands for the four cables were made and fixed simultaneously. One circuit took about thirty minutes to finish. Speed up of the operation was not necessary because the adjustment of the wires was a grand difficulty of work and took long time to finish. It was recommended to lay forty wires on an average each working day. Refs. [3,6,7,9]

4.7 Temperature and wind effects

The regulation and adjustment of the strands were delayed due to two causes – sun and wind. Since each strand varied in height, and had to be located in its exact and peculiar place, they must vary in length. As they were too slack or too taut for their fellows, it would be difficult to bind them solidly in one mass and make them pull together. This problem was caused by the change of temperature, which fluctuated so irregularly and unceasingly through out the day. The calculations showed that the deflection of cables from the tops of towers was 45.95 meters at 10 ℃, and 46.31 while at 32 ℃. There was a 9 mm variation in every degree of temperature. Moreover, different spans were unequally acted on by the sun. One curve was in shadow while another was exposed to the sun. On the other hand, the regulation of strands would be disrupted by the wind. Hence the engineers could only do the work when the condition was not influenced by wind and direct sunshine. Alternatively, this construction could have been improved by shielding the wires during spinning. Over the top or on the two sides of the wires, they are surrounded by reflective shielding compose of materials which are resistant to heat and light. This shielding can maintain a constant temperature throughout the spinning. Refs [6,13]

4.8 Unite and Wrap the strands

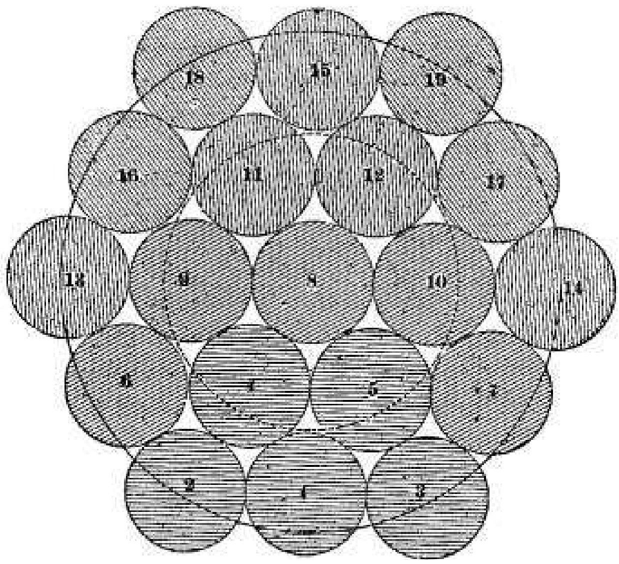


Figure 2: Nineteen strands in a cable

The running and regulating of wires started on 11th June, 1867, and finished on 15th, October, 1878. After the nineteen strands for each of the four cables were made and located, the final operation was to use a little machine to unite and wrap them to form cables as shown in Fig 3. Temporary fastenings of wire around each strand were removed once the work started. An iron clamp, which is of the size and cylindrical shape of the cable before wrapping, screwed tightly and compressed the nineteen strands together as shown in Fig 2. They were arranged in the cylinder in a symmetrical order, with one in the centre and the other eighteen strands surrounded it. After the clamp was screwed the wrapping machines bound the cable with a close spiral wrapping of wire. This machine comprised of an iron cylinder cast in halves. Its function was to bolt the cable together and compress it firmly. Finally, the skin of the cables was galvanized to resist corrosion by the salt air. These four cables were the backbone of the bridge. Each of them hanged over the river in the shape of catenary curve, the perfect natural form taken by any rope or cable suspended from two points, which in this case were the summits of the two stone towers. Thus the bottom of the curve would hit the middle of the span. Refs. [3,6,9,10]

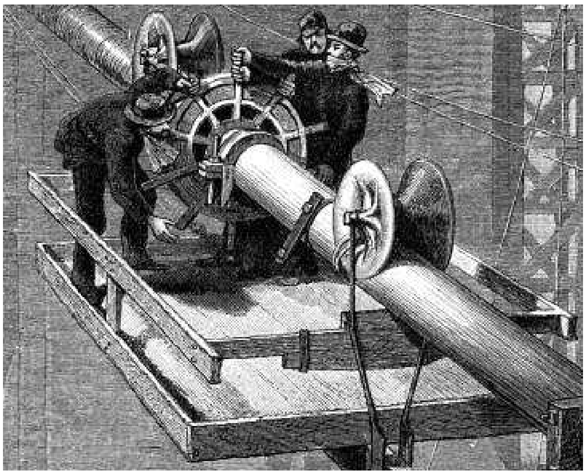


Figure 3: Wrapping the cable

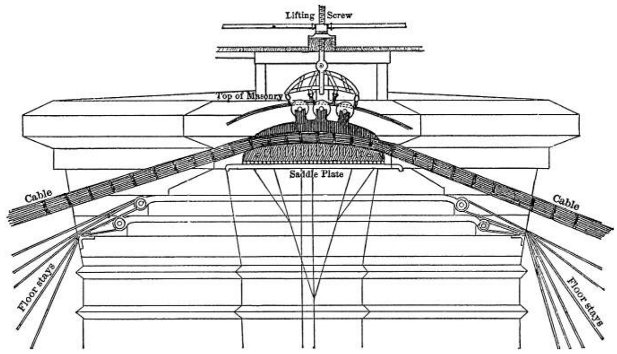
4.9 Suspenders and stays

The cables were ready to load the bridge floor through suspenders. The cables and suspenders were connected by suspender bands, which were made of wrought iron 127 mm wide and 16mm thick. The bands were cut at one point, two ends turned outward, so that the ends can be placed over the cables. There were holes on the end of the bands for the screw-bolt 44mm in diameter. They were served as the support of the suspenders and for tightening the bands and the cables. More than 14,000 miles of wire were used for the 1520 suspenders ropes. They were made in the same way as the ordinary hemp wire rope, with hundreds of fine wires twisted to form a rope. To relieve the enormous burden of the cables, and effectually prevent any vertical oscillations in the bridge floor, 400 diagonal stays were installed. These steel wire ropes diverge from the tops of the towers to points about fifteen feet apart along the bridge floor, in the direction of land and toward the center of the river span. Refs. [3,6,7]

There was a scandal over the supply of faulty wire. Most of the wire that was actually used was not to specifications. The wire contractor substituted weaker and cheaper Bessemer steel for the cables. Fortunately, Washington Roebling had initially designed the cable to be six times stringer than necessary. He calculated that these weaker cables were still four times larger than the maximum load than they had to take, and thus it was not necessary to remove the strands already in place. Refs. [3,7]

The dead weight of deck, including suspenders and stays was 14,680 tons. Since the load was evenly distributed to the four cables, each cable would support 3670 tons. Each cable has an ultimate strength of 24,600 tons, but the total maximum load including live load such as vehicles and pedestrians rarely exceed 6,000 tons. Thus the factor of safety is 4. Refs. [8,10,11]

4.10 Iron bed plates



Firgure 4: Section of tower

The cables approached the top of the towers and rested on iron bed-plates. These plates were in the form of segment of a circle. The iron casting plates had grooves which receive the cable on the upper and convex side. The iron rollers on the top of the cables held in place by flanges on the surface of the bed-plate. This could prevent the slipping and chafing of cables on the saddles by several effects such as force of storms or variation load. Lengthening and contracting of cables under changes of temperature might also cause slipping. According to the following calculations:

$$\delta=\alpha\ \Delta T \ell_1 \qquad (1)$$

Table 1: Temperature effect in cables

Data	
α (temperature coefficient)	$12x10^{-6}$/℃
ΔT	20℃
ℓ_1 (Length of cable)	612m

Calculation showed that the thermo expansion (δ) was 147mm under a 20℃ increase of temperature. The saddles, as well as the towers experienced a compressive stress due to the thermo expansion during the day and a tensile stress due to the thermo contraction during the night. Refs. [6,12]

4.11 The deck

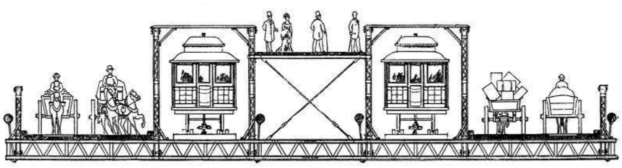


Figure 5: Cross-section of the deck

The entire bridge floor rises from the towers at an elevation of 42.5 meters above the high water level in gentle curve to the centre of the span, where it meets the cables at an elevation of 48.6 meters. The framework comprises of two systems of girders at right angles to each other. To support the load, and to protect the span from high winds and vibrations, light trusses, 0.84 meters deep, were added. They are attached by the four steel suspenders from the cables. Six parallel trusses extending along the entire length of the bridge were installed to unite the cross-beam together and give stiffness and strength to the floor. The floor is further united by eighty-six feet wide longitudinal trusses together with a system of diagonal braces or stays. The whole combination increases its strength, weight and stiffness. Refs [3,10]

Unlike the typical suspended construction, where the deck segments lifted into position off a barge and the construction starts in the center of the span, the crossbeams placing were started with those nearest each anchorage and each face of towers. As Brooklyn Bridge has the characteristics of cable-stayed bridge – diagonal stays, a method similar to suspended cantilever construction was used. Workmen attached the first iron beam on the nearest suspender of the anchorage or face of tower by clamps or stirrups and start launching. After that the beam was swung out in position, which served as support flanks for workmen to stand on and launch the second beam, and so on. Once the vertical, horizontal trusses and diagonal bracing were attached, the deck was at last ready for planking. This method is an old style of construction. As the deck launched from each side and met at the center, barges were not needed throughout the construction and thus it could maintain the navigation in East River. Refs [3,6]

As the stays near the centre of the span do not act efficiently against any tendency to distortion, the two outside cables were drawn inward toward each other at the bottom of their curves. Each of them acts as an arch and against the oblique pressure from below and the opposite side. Meanwhile the two inner cables were drawn apart at the bottom of their curves, thus each of them is approaching their corresponding outside cables. This approach is to combine their opposing arches against lateral forces from either direction. Ref. [6]

Expansion and contraction of the deck, by change of temperature, was again one of the considerations of the bridge. To solve this problem regarding the change of length of the deck, the two spans were connected by an ‘expansion joint’ at the center. Most suspenders were separated at an equal distance from each other. Except the two suspenders from each of the four cables hang at the centre, they hung close together, up to few inches apart or sometimes separated more than a foot. Each half piece was attached to one of the two suspenders and the two halves were connected by plates. The upper surface of the deck experienced much greater heat and cold than the bottom. Thus the expansion and contraction was more on the upper surface. The deck might feel squashed and bended due to its thermal expansion. Since the centriod located above the middle axis, calculations showed that more tension produced at the bottom and the deck in turn became sagging. Ref. [6]

The bridge consists of five parallel avenues of an average breadth of 5.8 meters. They are separated by six vertical lines of trussing, which projected upward like so many steel fences. The central avenue is a footway elevated 4.3 meters above all the others, thus giving to the pedestrians an unobstructed view of the river. The outside avenues are 6.8 meters wide and devoted for vehicles. The intermediate avenues, one on each direction, were occupied by cars, constantly and rapidly moving back and forth from terminus to terminus. Ref. [3]

5 Changes and improvements

At first, John Roebling planned to run two elevated tracks to connect the elevated railroad systems in New York and Brooklyn. These tracks were situated down the center of the bridge. Over the tracks, an elevated promenade is provided for pedestrians and bicyclists. On the either side of the tracks, each with two lanes, he designed for the use of carriages and horseback riders. Fifthteen years later in 1898, trolleys and automobiles were allowed to travel in the outer lanes.

In 1944, the elevated trains that ran along the interior of the bridge stopped service. Over the next decade, bridge engineer David Steinman took a reconstruction project which included the strengthening of inner and outer trusses and installation of new horizontal stays between the four main cables. As the railroad and tracks were removed, he widened from two lanes to three lanes in each direction, and constructed new approach ramps.

During 1981, two of the bridge’s 216-meter support cables snapped, but the bridge did not collapse. Since then, all the broken and damaged cables have been repaired and all the suspenders and diagonal stays have been replaced.

In 1999, inspectors discovered concrete chipping away from the steel girding and causing the bridge deck to weaken. This emergency re-decking project took six months to finish.

Instead of structurally improving the bridge, several changes and construction can be made on the approaches of the bridge. Brooklyn Bridge Park will be built in early 2008. It will stretch 2.1km along the East River. This park can draw residents and tourists to spend their leisure time next to the river and appreciate the Brooklyn Bridge. Also, the pedestrian walkway on the Brooklyn side is needed to overhaul. This walkway encountered poor lighting, uninviting entrances and inadequate signage which greatly reduced its attraction. People often missed this hidden treasure. The overhaul of the Brooklyn side pedestrian walkway and the Park will take full advantage of the growth of Brooklyn. Refs [1,2,3]

Figure 6: The Brooklyn Bridge Park

6 Susceptibility to intentional damage and future improvements

The four cables, which support the enormous weight of the entire deck, are the backbone of the bridge. These main suspension cables, as on many suspension bridges, are made of many individual wires wrapped together and anchored on each side of the river. The Brooklyn Bridge is vulnerable compare to other bridges in NYC because the main suspension cables all come together at each end of the bridge. They meet in two rooms, 5.4 meters to 7.2 meters below the walkway as shown in Fig 7.

Figure 7: Cable storage

As this is most vulnerable point along the bridge, terrorists may break into the room and destroy the cables, thus it is essential to tighten the security for future improvements. Sensors, security cameras and alarms may be installed so that police officers are able to respond to a tripped alarm in seconds and shut down traffic on the bridge. There may be 24-hour foot patrols and a police boat kept nearby. Ref. [5]

Although the small room was the most critical point for terrorist attacks, it would still take a while to break the cable. As describe above, each of the suspension cables is 400mm in diameter, containing 19 strands. Each strand consists of 278 wires all laid up straight, parallel to one another. A substantial amount of time and a lot of hard work would be needed in order to do serious damage on these cables. The Brooklyn Bridge was built in a time when bridge collapses were common, thus John and Washington Roebling built theirs to be more than sturdy. So the suspensions cables have a factor of safety of 4, which means each cable can support four times of the normal dead and live load. If anyone of the cables is broken, the bridge may not collapse immediately regard there is no other damages in other elements of the bridge. Refs. [5, 11]

7 Durability and creep

In fact, in its 124 years life, several changes and improvements have been made. Nowadays, the bridge accommodates six lanes of automobile traffic and approximately carries 145,000 vehicles per day. There is a huge increase in loading compare to the first estimation, where the bridge was carrying horseback riders and elevated trains. Ref. [3]

Most bridges built at that time collapsed due to several reasons, such as load capacity, aerodynamically unsustainable or material failure etc, but the Brooklyn Bridge is still surviving. It is because it was designed to have a factor of safety of 6. Although there is a scandal over the supply of faulty wire, the cables are still able to carry 4 times its estimated loading. Thus the bridge is able to sustain the loading nowadays and regarded as durable.

Moreover, the use of steel in decking provide durability and corrosion resistance of the bridge. It can provide safe service under an extremely heavy traffic load for over 100 years. Ref. [15]

Creep is a “time-dependent’ deformation of material. It occurs due to a long term exposure to levels of stress that are below the yield or ultimate strength of material or subjected to heat which near melting point. Creep is more severe in materials such as concrete. The rate of deformation under same conditions is higher when comparing to steel. As steel is the structural material which supports the deck and concrete is just the topping for road surface, the effect of creep is less in the Brooklyn Bridge. In fact, no steel beams or girders have been replaced since its completion due to creep.

8 Aesthetics

According to John Roebling, ‘the Brooklyn Bridge will not only be the greatest bridge in existence, but it will be the great engineering work. The great towers will serve as landmarks to the adjoining cities, and be entitled to be ranked as national monuments.’ It was designated as a National Historic Landmark by the federal government and a National Historic Civil Engineering Landmark by the American Society of Civil Engineers. Over the years, the Brooklyn Bridge has been proved as one of the most aesthetic bridges in the world.

The aesthetic of the Brooklyn Bridge can be analyzed in several areas according to the perspective of Fritz Leonhardt.

8.1 Function

The bridge reveals its structure in a pure, static form. The four enormous cables and hundreds of vertical suspenders clearly show how the deck is held. Although trusses are not necessary in every suspension bridge, they were added on the bridge floor to strengthen the bridge. The whole structure, after strengthened by the trusses, exposes a feeling of stability. Diagonal stays are the main component in cable-stayed bridge, but they were introduced into the Brooklyn Bridge. From the elevation view, since they are the same color, the diagonal stays were mixed with the vertical suspenders. People may be confused whether the Brooklyn Bridge is a suspension or cable-stayed bridge, because diagonal stays can not truly reveal its bridge type. Refs. [13,16]

8.2 Proportions

The double arches on each tower express a good impression balance between masses and voids. They provide sufficient light intensity to the deck and do not create any opaque barrier. The height to span ratio in the Brooklyn Bridge is small compare to other magnificent suspension bridges in the world. This makes the whole structure, especially the catenary shape cables, looks flatter and longer. The lengths of main span and side span are 574 meters and 335 meters respectively. Thus the span ratio is approximately 1:1.7:1 and it is reasonable. To allow ships and ferries passing through, the clearance at center above mean high water is 48.6 meters. This figure has become the standard height clearance for the later bridges. The depth of the bridge, including the bottom trusses and the top steel fences, is 5.8 meters. The depth/span ratio is 1:99. This proportion is also sensible. The two towers were made up of stone masonry and designed to be stout, thus match the total thickness of the bridge floor including trusses.

8.3 Order

The vertical suspenders are evenly distributed. They represented a good impression of order in lines. The design of sharp edges, both within buildings or bridges, was popular in 19^{th} century, but some excessive edges of the towers may arouse mental disquiet. The diagonal stays mixed with vertical suspenders when viewed from oblique angles may result in confusing.

8.4 Refinements

Similar to the bridges design by the Greeks, tapering towers were used to prevent optical illusion. The top of the towers may look more slender. Since the main span is long (574 meters), the oblique angles of view will not create an opaque barrier. Ref. [10]

8.5 Integration into Environment

Suspension bridge is the most suitable bridge type for spanning rivers. It provides clearance underneath the middle span of bridge. The towers and anchorages look stout and heavy because they were made of masonry. Although the design of Brooklyn Bridge may not integrate with the modern style of NYC, the big contrast of antique bridge and contemporary may bring a positive feeling to visitors.

8.6 Color

There is not much decoration regarding the color of the bridges. The entire bridge is in dark and boring color. Nevertheless, seventy blue-white, electric arc lamps were installed along promenade at intervals of 30 meters. The lightings on the cables bring the bridge into life interacting with the prosperous Manhattan.

8.7 Character and complexity

The Brooklyn Bridge has character and lots of special features which in turn ranked as landmarks of New York Cities. This character comes from its integration of traditional construction material into modern form of bridge.

Every element in the bridge can clearly show its function respectively. Compare to other types of bridges, the Brooklyn Bridge has a certain degree of complexity. The public may wonder how the bridge works. The deck is held by vertical suspenders which in turn supported by the four enormous cables. The two towers counteract the reaction forces from the vertical suspenders through the cables. Two anchorages at the side serve to pull the cables in tension. Refs. [13,16]

8.8 Conclusion

Although the Brooklyn Bridge can not satisfy all the above criteria, it can still result in a magnificent structure. Although the installation of diagonal stays in a suspension bridge may result in structural confusion, the other elements of the bridge portray their functions and structure in a simple and obvious way.

9 Loadings Refs [6,7,8,9,10,11,12]

In the calculation of loadings and bending moments, several assumptions have been made. Suspension bridge is fundamentally supported by hangers rather than towers or anchorages, so when calculating the bending moments, I assume the bridge is divided into thousands of pieces, in other words, each end of the pieces are supported by the suspenders. Thus the calculation is based on uniformly distributed load (UDL) on simply supported beam by equation $wl^2/8$. As a result most calculation is based on the length of each piece. 1520 suspenders were used in the main span and the two side spans. By calculation, since the total length of the three spans was 1243 meters, each of the ‘small span’ was 0.82m long.

9.1 Dead and super-imposed dead load

Figure 8:

Assume the dead loading simply consisted of three major elements: transverse trusses at the bottom Fig 5, steel fences 5 meters apart as shown in Fig 8 and 4 pairs of longitudinal trusses along the deck. Calculations below are based on every 5 meters:

Table 2: weight of elements

weight	
Transverse trusses at the bottom	40kg
Steel fences (5m x 12m)	10kg
Longitudinal trusses along the deck	30kg
Total weight	784kN
UDL	157kN/m

Super-imposed load, including parapet, lamps, guard rail, road surface, drainage system, is assumed to be 20kN/m.

9.2 Live loading

9.21 HA loading

The total length of the span (574 meters) is taken in the calculation of HA and wind loading. Thus the nominal HA is 9kN/m. The KEL per notional lane is taken as 120kN.

9.22 HB loading

This loading represents an abnormal truck load on the bridge. Assume the full HB loading in each axle is 450kN, as there are 4 wheels on each axle; each wheel will carry 112.5kN nominally.

9.3 Wind Load

According to the New York Wind Speed Map, the mean high wind speed is 60 km/hr, which is equivalent to 16.7 m/s. According to the following equations and data in **Table 2** and **Table 3**:

$$V_c=vK_1S_1\,S_2 \tag{2}$$

Table 3: Data for Eq. (2)

Data	
V (Mean hourly wind speed)	16.7 m/s
K_1(Wind coefficient)	1.53
S_1 (Funneling factor)	1.00
S_2(Gust factor)	1.30

The Mean hourly wind speed V_c is 33.2 m/s

$$P_t=qA_1C_D \tag{3}$$

Table 4: Data for Eq. (3)

Data	
q (Dynamic pressure dead)	$0.613v_c^2$
d	4m
Length of solid horizontal area	574m
A_1 (Solid horizontal projected area)	$2296m^2$
b (Width of span)	31m
b/d	7.75
C_D (Drag coefficient)	1.2

The horizontal wind load P_t acting at the centroid is 1,856kN and hence the uniform distributed wind load is 3.2kN/m. Uplift caused by wind may also be considered in Eq. (3) and data in **Table 4**.

$$P_v=qA_3C_L \tag{4}$$

Table 5: Data for Eq. (4)

Data	
Q	$0.613v_c^2$
Width of span	31m
Length of span	574m
A_3	$17{,}794m^2$
C_L	0.38

Hence, the nominal force P_v is 4,555kN and the uniform distributed uplift is 7.9 kN/m.

9.4 Temperature effect

Steel, a material which expands or contracts easily during temperature fluctuate, is the major material in the Brooklyn Bridge. Thus a small change of temperature may seriously change the strain of the bridge. Moreover, the Expansion and contraction of the deck, by temperature fluctuations, caused bending of the bridge floor. Thus temperature is an important consideration in bridge design. According to the maximum and minimum temperature of NYC from Ref. []:

Table 6:Temperature effect on span

Data	
Maximum Temperature	39℃
Minimum Temperature	-26℃
ΔT	65℃
α (temperature coefficient)	$12x10^{-6}$/℃
l_2 (Length of span)	574m

$$\delta=\alpha\,\Delta T l_2 \tag{5}$$

The maximum variation due to heat and cold is 447mm, which means the expansion joint at the middle of the span has to sustain this amount of displacement.

$$\sigma=\varepsilon E \tag{6}$$

Assume the whole bridge was made by steel (E= 200,000 kN/m^2), the axial compressive stress is 156 kN/m^2.

9.5 Safety factors

Both Ultimate Limit State (ULS) and Serviceability will be considered.

Table 7: Ultimate limit state

	Safety factor	Unfactored load (kN/m)	Factored load (kN/m)
Dead	1.05	157	165
Super-imposed dead	1.75	20	35
HA	1.3	9	11.7
KEL	1.3	120	156
HB	1.3	112.5	146
P_t	1.1	3.2	3.52
P_v	1.1	7.9	8.69

Table 8: Serviceability limit state

	Safety factor	Unfactored load (kN/m)	Factored load (kN/m)
Dead	1.00	157	157
Super-imposed dead	1.20	20	24
HA	1.1	9	9.9
KEL	1.1	120	132
HB	1.1	112.5	124
P_t	1.0	3.2	3.2
P_v	1.0	7.9	7.9

HA, KEL and HB loading are distributed in the following pattern:

Figure 9:

Full HA + KEL + HB
Full HA
1/3HA
Central reserve No loading for global analysis
1/3 HA

1/3HA
1/3HA

Case 1) ULS: Dead load + live load

Assume KEL and HB are added at the middle of the span. The total point load is 302kN. The sum of HA is 39 kN/m and the total UDL for ULS is 239 kN/m.

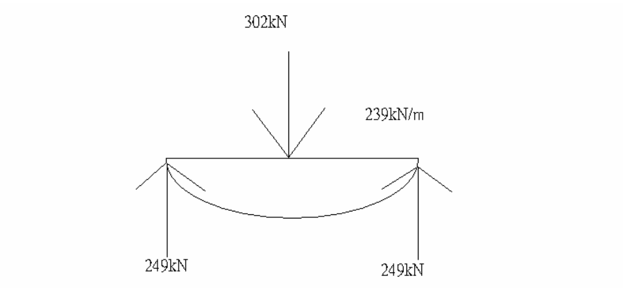


Figure 10: Bending Moment Diagram

Moment at middle point:

$=249 \times 0.82/2 - 239 \times 0.82 \times 0.82/2$

$=21.7$kNm

Case 2) SLS: Dead load + live load + wind load

Sum of HA is 33 kN/m

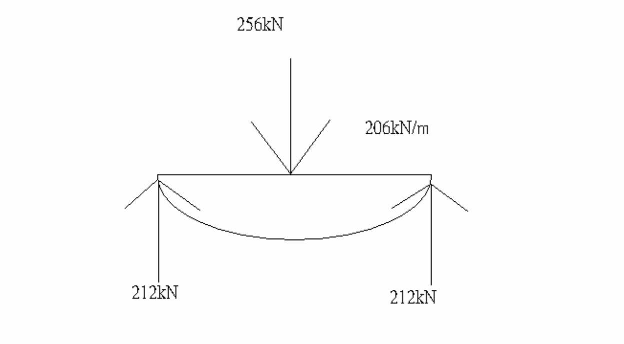


Figure 11: Bending moment diagram

Moment at middle point

$=212 \times 0.82/2 - 206 \times 0.82 \times 0.82/2$

$=17.7$kNm

To find out whether the bridge can sustain this moment, the following equation and data are used.

$$m = \sigma I / y \qquad (7)$$

The depth of the bridge is assumed to be 2 meters, instead of 4 meters. It is unreasonable to include the open trusses into the second moment area calculation. Assuming the centroid is 1.5 meters above the bottom because the solid area is concentrated on the above side.

Table 9: data referring to Eq.7

Data	
σ	275×10^3 kN/m^2
b	31m
d	2m
I	20.7 m^4
y	1.5m

The calculation shows that the moment capacity is 3.78×10^6 kNm. This value is much greater than the required moment. This can be explained by several reasons:

Moment induced by the loadings is very small because it is dependant on second order of length of span ($wl^2/8$).Unlike other bridges, where the separation of suspenders may be 15 to 20 meters, the Brooklyn bridge is held by a series of suspenders which close together and so the moment is restricted.

The calculation is highly inaccurate. In reality, the span are not divided into thousands pieces, they are linked together tightly. Calculation can not only base on one short span.

References

[1] Improvement of the pedestrian walkway http://xroads.virginia.edu/~MA03/pricola/bridge/conclusion.html

[2] Changes and repairs in 1944-1954 http://xroads.virginia.edu/~MA03/pricola/bridge/conclusion.html

[3] Background and construction process http://www.nycroads.com/crossings/brooklyn/

[4] Strength of the cables and wires and construction process http://xroads.virginia.edu/~MA03/pricola/bridge/conclusion.html

[5] Intentional damage http://cryptome.org/brook-bridge.htm

[6] Background, cost and construction process http://www.catskillarchive.com/rrextra/bbstory.Html

[7] Background and data http://www.endex.com/gf/buildings/bbridge/bbridge.html

[8] Weight of the bridge http://www.brooklynexpedition.org/structures/buildings/bridge/bl_bridge_main.html

[9] Changes, repairs and construction process http://www.endex.com/gf/buildings/bbridge/bbridgenews/bb50/bb50.htm

[10] Span length http://www.pbs.org/wgbh/buildingbig/wonder/structure/brooklyn.html

[11] Data of cables, towers and anchorages http://www.pbs.org/wgbh/buildingbig/wonder/structure/brooklyn.html

[12] The climate of New York http://nysc.eas.cornell.edu/climate_of_ny.html

[13] Principle of suspension bridges http://www.brantacan.co.uk/suspension.htm

[14] Materials http://en.structurae.de/structures/data/index.cfm?ID=s0000011

[15] Durability http://www.newmaterials.com/news/1740.asp

[16] Characteristics of Cable-stayed bridge http://www.brantacan.co.uk/cable_stayed.htm