CRITICAL ANALYSIS OF THE MANHATTAN BRIDGE

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Abstract: This paper provides detailed information about the different aspects of the design of the Manhattan Suspension Bridge. Analytical reasoning is given to why each design feature was designed in the manor it was in order to fulfil the engineers’ design criteria. An attempt is also made to illustrate any shortcoming in the design of the structure and any ways in which the engineers could have potentially improved the design of the bridge. Attention will also be paid to the ways in which the bridge would be designed and constructed if it were to be built in the 21st century. The reasons why design principals and construction methods have changed will also be outlined.

Keywords: truss, stiffness, tension, deck, torsion

1 Overview of The Manhattan Bridge

The Manhattan Bridge, although unfinished, was opened in 1909 and was the third bridge to span the East River running between Brooklyn and Manhattan. It was built to provide another transport link between the two boroughs. Before construction began there was a great deal of controversy over the proposed designs for the bridge. Eventually a fairly typical looking suspension bridge design was approved that was designed by engineer Leon Moisieff.

The bridge was to span 448 metres between piers, which was a somewhat shorter distance than the main spans of either the Brooklyn or Williamsburg bridges that neighbored it. Even though the Manhattan Bridge made no advancement in the spanned length achievable by a suspension bridge, it did represent a significant step forward in the progression of bridge building. The bridge was the first to be designed using deflection theory, which quickly replaced all previous methods of bridge design. The design also incorporated steel towers that were only braced in two dimensions rather than three. This was another aspect of bridge design that had not been seen prior to the building of the Manhattan Bridge.

The entire structure of the Manhattan suspension bridge was to be designed in steel. The deck structure is comprised of four steel stiffening trusses that were each supported by regularly spaced suspenders that hang from one of the four main cables. The four cables are supported by the two towers and are held down by anchorages 224 metres from each side of the main span.

2 Aesthetic characteristics

In order to try to convey whether or not the Manhattan Bridge is successful from a visual viewpoint,
rather than an engineering perspective, I will subdivide its aesthetic characteristics into different architectural objectives.

At the time at which the Manhattan Bridge was designed, there were conflicting opinions over the importance that architecture should play in bridge design. Bridge engineering had evolved to a point where fairly long spans were achievable by suspension bridges and this was coming more and more commonly done. Pressure to not only construct a bridge that fulfilled its purpose, but to also look aesthetically pleasing mounted. Several early designs for the Manhattan Bridge were thrown out for this very reason.

In the subsequent text I will give my own opinions as to where the Manhattan succeeds and where it has shortcomings architecturally. Ultimately however, as with any bridge, the beauty of the Manhattan Bridge lies in the eyes of its beholder.

2.1 Fulfilment of function

The structure of the Manhattan Bridge is very clearly on show. Generally speaking, suspension bridges are naturally very beautiful feats of engineering due to their elegant structures being completely on show for all to behold. The Manhattan Suspension Bridge is no exception. It is clear that the suspending cables from the four main cables are supporting the deck. Relatively deep trusses, providing stiffness to the deck, can be seen. It is therefore clear to the beholder how this bridge works in order to span the water. Overall this bridge is very successful in showing how every different element fulfils its function, as very little is concealed.

2.2 Proportions

The bridge is designed to allow trains and vehicles to travel at an upper and lower level. This naturally means that the deck must be deeper than that of a conventional one-storey deck. It is of my opinion that the deck therefore looks deeper than it ideally would for the span of the bridge. The depth of the deck, to length of the main span is about 1:60. To put this into some kind of perspective, the aspect ratio of the golden gate bridge (widely regarded as a bridge with ideal proportions) is 1:168, meaning its deck if far more slender. It does however seem that the depth of the stiffening trusses used on the deck of the Manhattan Bridge is helped by the fact that from a distance light can be seen through the deck from one side to another. This makes the deck look a lot lighter and less dense than it otherwise would. On the other hand, the piers and towers look very slender in comparison, especially when viewed from the sides of the bridge.

It is of no coincidence that the side spans of the Manhattan Bridge each measure exactly half that of the main span. In doing this, the main cables meet each side of the towers at exactly the same angle making the whole structure look perfectly balanced.

2.3 Order

The Manhattan Bridge seems to be a fairly “busy” Bridge to look at. This particularly applies when crossing it, or looking at it from beneath. All the minor bracing elements and truss elements can be seen, making the deck construction almost look cluttered. However, and perhaps more importantly, from afar only the major truss elements can be seen with a relatively thin deck above and below it. The repetitive and symmetrical order of this truss can be seen, and this helps to make the elevation of the deck pleasant to look at.

2.4 Refinements

The piers supporting the main span are designed to taper inwards from their base towards mid height, and then to widen as they meet the deck. This is visually pleasing, as the connection between the piers and the deck looks less abrupt. This is also the case where the steel piers connect to the masonry just above water level. It may be worth noting that the widening of the piers as they meet the deck is achieved from additional steel fixed to the piers. This steel does not form part of the primary structure. The structure of the Manhattan Bridge has been designed to include many architectural embellishments, such as spheres on the tops of the towers where the main cables rest. Architectural details like this make the bridge visually quite interesting, rather than it purely being a functional object.

2.5 Integration into the Environment

Spanning a large stretch of water, the chosen suspension bridge design looks fitting for it’s purpose. This is convenient, as this would have been the only means of spanning such a distance when the Manhattan Bridge was designed. Such a large bridge construction would have possibly seemed out of place in many cities just after the turn of the century. However the Manhattan skyline was by this point already full of high-rise structures, so the height of the Manhattan Bridge would have not seemed out of place. The one thing that might have made this bridge clash somewhat with its surroundings could be the choice of construction material. The bridge is almost completely built from steel, and this is very much on show. Whereas the high-rise buildings in Manhattan were practically all clad in masonry, so this huge steel structure might have looked somewhat alien. This however is no-longer the case, and I feel that the bridge is probably much better suited to its surroundings today more than ever before.

2.6 Colour

All the diagonal truss elements along the deck and all the supporting cables have been painted white, whereas the decks and the supporting piers have been painted a dark blue. This would probably have been done in order to put emphasis on the deck spanning the large distance. The white also helps conceal the vast amount of suspender cables against the sky, which helps give the illusion that the deck alone is able to span between piers. The strip of white elements between the top and bottom lines of blue also helps to break it up. The white paint was probably chosen to take emphasis away from the heavy looking deep trussed deck and make it look lighter.
2.7 Character

It is difficult to look at the Manhattan Bridge and say whether or not it has character. On one hand, it leaves nothing to the imagination, as it is clear which bit of it is working in a certain way. However at the time when it was completed I would imagine that it would have looked spectacular. It is easy to look at it now, and think it is nothing special, but at the time it opened there would have not been a great deal of bridges of its proportions.

2.8 Complexity

The bridge is of a relatively standard looking suspension bridge design. However, the massive number of bracing elements on all parts of the structure makes the design look more complex than it actually is. This is particularly obvious when looking at the towers. They are formed by a series of steel sections all connected together which a huge amount of diagonal members to create four vertical columns, which are then braced to each other. When this design is compared to the towers of the adjacent Brooklyn Bridge, they seem very complex in comparison.

Figure 2: The complexity of the design of part of one of the towers

3 Serviceability

The Manhattan Bridge was designed and built in order to cross the East River that runs between Manhattan and Brooklyn within New York. At the turn of the century the only means of spanning the river (448m) would have been by building a suspension bridge. A couple of hundred metres down the river this had already been achieved with the completion of the Brooklyn Bridge. However the foremost difference between the requirements of the two bridges was that the Brooklyn Bridge was to allow crossing by vehicles and pedestrians, whereas the Manhattan Bridge was to also allow crossing by trains. This would have a significant impact on the design of the bridge, as any deflections of the deck that would have been acceptable for vehicle for pedestrian use could potentially cause damage to a train track. The large concentrated load that the trains would put on the deck would also further increase this problem.

Suspension bridges are not ideally suited to rail applications, as it is in their nature to deflect easily, compared with stiffer forms of bridge with a more direct load path. This comes from the deck being supported by hanging cables, which on their own have no resistance to deflecting asymmetrically under a concentrated load. Being flexible in response to concentrated loads, suspension bridges are generally not used for heavy rail crossings, which concentrate the maximum "live" loading at the location of the locomotives. However at the time that the Manhattan Bridge was designed and built, a suspension bridge was the only possible solution.

The engineers would have known that the deck of a suspension bridge that carried trains would need to be very stiff. This is because it is the deck that provides resistance to local deflection. By making the deck very stiff, the engineers were able to limit the amount of deflection caused by a concentrated load. An infinitely stiff deck would behave like a beam and the whole deck would deflect downwards as one. If the deck were to be designed without a high stiffness, the bridge would flex under the concentrated load of a locomotive.

The engineers achieved this stiffness in the deck by using four parallel trusses, each supported by one of the main cables. The trusses needed to be deep enough to have a high bending stiffness so that any concentrated loads could be adequately spread and hence reduce local deflection. The chosen truss depth was 7.4 metres. The type of truss used was a Warren truss, which was the first use of this type of truss in a suspension bridge.

Figure 3: Deep Warren trusses run the length of the deck.

4 Designing The Structure

The Manhattan Bridge was the first suspension bridge to be designed using deflection theory in calculating how the horizontal deck and curved cables worked together to carry loads. Until this point, suspension bridges could only be designed using elastic theory which meant assuming small deflections. However, whilst this was an incorrect approximation, as suspended structures were sometimes observed to undergo significant deflections, this was the only mathematical modelling that had been applied up to that time. At the time the Manhattan Bridge was designed, this was the first occasion there had been an appropriate opportunity to use Melan’s deflection theory. This new method of analysis allowed the engineers to design the bridge with a more accurate understanding of how it would actually perform, allowing a greater economy of material usage.

Deflection theory meant that all suspension bridges were proved to be stronger than previously considered
due to the curve in the main cables being more efficient at carrying loads than stiffer forms of bridge. The new theory allowed the Manhattan Bridge to be designed to be lighter, with smaller stiffening trusses, than it otherwise would have been using elastic theory. These smaller lighter trusses would have been acceptable in normal circumstances for example if the bridge was to carry only vehicular traffic, but in the case of the Manhattan Bridge, it was to also carry subway trains. Despite the application of the new theory, after the initial use of the bridge, it became clear that there was a significant flaw in its design.

4.1 Inadequacy of Design

Each time a heavy subway train passed over the bridge, it caused local deflection of the stiffening trusses on the side of the deck of the train’s passage. The deflection on one side induced torsion in the deck. This problem was further accentuated when trains began to pass over each side of the bridge in opposing directions at the same time. It was reported that at this point, each side of the deck deflected by up to 1.2 meters, meaning a total relative deflection of over 2 meters. [1]. This put significant stresses into the bridge deck and subsequently lead to extensive repairs and stiffening work needing to be carried out in order to allow the bridge to remain serviceable.

In my mind, the most obvious failing in the design of the Manhattan Bridge is the location of the subway tracks. They have been located at each edge, rather than placing them in the central section of the deck, with road lanes separating them. Keeping the tracks close together would have reduced the length of the effective lever arm that the trains’ live loading would have had, reducing the torsional moment induced.

Although I am uncertain as to the design engineer’s reasoning behind locating the subway tracks in these positions, a possible reason becomes apparent when looking at a cross section of the deck.

![Figure 4: Cross section showing location of lanes across deck](image)

The figures illustrate that the main cables and corresponding stiffening trusses are “paired” on each side to enclose a region of deck resulting in a larger span of deck between them.

As shown in figures 4 and 5 these enclosed regions are where the design engineers located the subway tracks and is where the distance between the stiffening trusses is smaller. The engineers would have realised that the heavy live loading from the subway trains would have caused a significantly greater degree of bending across the deck between stiffening trusses in comparison to the bending due to vehicular loading over the same span. Therefore it would have made sense to locate the lighter vehicular live loading over the larger span of deck in the region between the two pairs of trusses. By then locating the subway tracks in the smaller spanning regions of deck, the resulting bending moment from their load is far smaller than if they were located in the central section. This would have meant that the design bending moment across the whole deck could have been of a similar magnitude, allowing the supporting deck structure to be designed more economically than otherwise using a section with a constant moment capacity across the whole deck. I.e. exactly the same the beam section could be used over the decks full width, resulting in simpler construction and less wasted material. These paired cables consequently could have been designed in this way intentionally for the purpose of accommodating the subway tracks. It is possible therefore that the distribution of the load types across the deck in this configuration was a fundamental part of the design of the whole superstructure.

As a great deal of planning was most likely given to the most efficient location of the subway tracks as discussed above, it is unfortunate that the chosen configuration would go on to cause torsion in the deck.

An alternative solution to changing the location of the subway tracks would have been to use deeper stiffening trusses. These would have helped prevent the deflection of the outer main cables and hence reduced torsion in the deck. However this would have resulted in a significant detrimental effect on the bridges aesthetic qualities.

Overall the bridge was designed adequately in a two dimensional sense, but proper analysis appears not to been carried out in three dimensions, otherwise the torsional deflections could have been prevented.

The whole process would be easily avoided in the design of a modern suspension bridge. Three dimensional finite element analysis software would be used in order to check the structural capacity of the deck in longitudinal and transverse directions.

4.2 Tower Design

The Manhattan Bridge was the first suspension bridge to be designed with towers braced only in a plane transverse to the deck.

![Figure 5: The four main cables are not evenly separated.](image)
Figure 6: The towers are braced for stiffness in two dimensions, rather than three.

Making the towers flexible in the same plane as the main cables allows for any movement at the top of the towers to be taken as bending in the towers. The flexing of the towers prevents large bending moments being transferred straight to the foundations. Therefore smaller foundations under the piers are needed compared to under a more typical tower design for the time the bridge was designed and built. This is possible because the foundations would mostly be there to take the vertical load, rather than a combination of a vertical load and a large bending moment.

The four main steel sections that comprise each tower have however been braced with cross members in the transverse plane to the deck. Elasticity in this plane would be undesirable and of absolutely no benefit. The engineers would have been fully aware that without the bracing in this plane, the structure would be much more unstable, and that the columns could potentially buckle under the load of the main cables supporting the deck.

The design of the towers of the Manhattan Bridge was the first example of the application of many of the principals adopted in the design of modern suspension bridge towers.

Towards the base of each pier, the steel section increases in size until it meets the masonry footing. These would have been designed in this manner for two reasons. Firstly, the larger area where the steel meets the masonry would be advantageous in creating a greater area for the steel to bear onto, spreading the load spread evenly over the masonry. Secondly, the larger area of steel meeting the masonry would have made it more possible to form a fixed connection that didn’t allow any rotation.

It appears that the steel piers broaden as they approach the underside of the deck, implying a moment resisting connection. Although this is not the case as the vast majority of this steel is for non-structural purposes, as explained previously. However, one practical use it does serve is to act as a cantilever supporting the pedestrian walkway to take it around the towers. Considering there is no fixed connection between the support piers and the deck trusses, it would be presumed that there would be bearings at this point. These would allow the bridge to respond to any movements due to wind, temperature and live loading, without putting huge stresses into the decks structure.

The four main cables are not fixed to the top of the towers. Instead they are free to slide over their supports. This is to prevent any deflection of the main span causing a huge bending moment in the foundation. The connection between the cables and the tower is made directly above each of the four columns, so that the load supported by the cables is directed only into an axial load on each column. This allows for the four columns comprising each tower to be relatively slender.

4.3 Construction

As with any suspension bridge, the Manhattan Bridge would have required very large foundations. These foundations would have most likely had to have gone down to bedrock, to ensure that there would be no settlement of the piers. The bridge piers are located within the East River. Each foundation would have been built by floating a caisson to the desired location and then sinking it using very heavy weights. The caissons would have probably been made from timber braced with steel. After workers had removed all the soil and debris, the caissons would have been filled with concrete to form the foundations.

After the foundations would have been completed, the towers would then have been erected. These would be able to stand with no propping due to the fixed connection at their base.

Figure 7: The erected towers

Each tower measured 102.4 meters in height. Construction would have comprised of bolting together relatively small sections of steel, using the masonry pier as a platform to work up from. Bracing would have been bolted onto the main structure as the structure increased in height, ensuring stability.

After the completion of the towers, the main cables would then be spun. Each of the four main cables are comprised of 9472 individual wires, making the total cable thickness come to 0.54 meters in diameter. These main cables each run through a corresponding saddle on the top of the towers. The ends of the cables would have
been fixed into the anchorages, probably by wrapping the strands around massive steel I bars. These would then have been embedded within the huge masonry anchorages, which would prevent any slip of the main cables. These anchorages would work by gravity, having a massive dead weight.

Figure 8: The towers and main cables are in position but there are no suspending cables or deck at this stage.

Figure 9: Section through the anchorage showing restraint of the cable.

Figure 10: Large masonry anchorages tie down the main cables. The anchorage shown is on the Manhattan side.

From the main cables, steel cable suspenders would have then been hung at regular intervals across the length of the suspended section of the bridge. This then allowed the deck to begin to be fixed to the suspenders. This was done starting at each tower and working in both directions towards the opposing tower and the anchorages.

Currently, common practice is to begin this process from the centre of the span. However at the time the Manhattan Bridge was built, this would have been very impractical, as there would have been no simple means of lifting materials or plants to this location. The building of the deck was however carried out symmetrically in each direction. This is an important aspect in suspension bridge construction as it avoids any asymmetrical deflection of the deck, which would add an unnecessary complexity to its construction.

Figure 11: The deck was built from each tower at the same rate towards the middle of the span.

5 Potential Changes to the Bridge’s Use

When first opened to the public on December 31st 1909, the bridge was only able to accommodate traffic, as it was not fully finished. Upon completion in 1912, the Manhattan Bridge had two pedestrian walkways, four traffic lanes, four tram lanes and four subway tracks.

The bridge had been designed with a far greater load carrying capacity than either the Brooklyn or Williamsburg bridges that had already been completed.

The Manhattan Bridge was to provide an alternative crossing between Brooklyn and Manhattan, and to share the traffic load. It was also to provide a rail link between the two cities so that the subway could also cross between the two boroughs. During the planning stages of the Manhattan Bridge, the designers would have seen how congested the Brooklyn Bridge had become in a relatively short space of time. For its time the Brooklyn Bridge was somewhat experimental by spanning such a large distance, but at the time the Manhattan Bridge was designed, the engineers had a far better understanding of the technology. This allowed them to design a bridge that could be much more practical by ensuring there was an adequate amount of lanes for instance, without being restricted by the idea that the bridge may not be strong enough.

The engineers had designed the Manhattan Bridge to carry the different types of transport that were relevant to its time of completion. However, over the subsequent decades cars and other road vehicles became the dominant mode of transport. This was also balanced by a decline in the use of trams (streetcars) in the city, until eventually the tram system in Manhattan and Brooklyn was removed. The Manhattan Bridge had been designed with so many lanes over the two levels that it was possible to convert the four tram lanes into more road lanes to meet the changing transport demands. The large numbers of lanes for each mode of transport also allowed for alterations like these to be carried out with minimal disturbance to the flow capacity over the bridge.

Currently, the Manhattan Bridge has seven road lanes and four subway tracks. The additional road lanes being created on the upper levels of each side of the deck. In its current lane layout, the central lanes can be reversed in direction. The approach lanes come from one road that do not split at any point to go in differing directions, making it very simple to change the direction of flow of
traffic across the bridge if desired. This gives the Manhattan Bridge a bit more versatility than otherwise, as changing the direction of flow on the central lanes allows the bridge to adapt to suit the current demands of the traffic. It also means that the bridge could better cope with traffic that arises from a planned event rather than the lanes being grid-locked in one direction and empty in the other.

An issue that regularly arises with bridge design is that adequate thought is not given to how demand for its use might increase in years to come. At the time the Manhattan Bridge was designed it would have been impossible to predict how popular cars would have become, or how many people would end up needing to cross the East River on a daily basis. However the designers were very successful in creating a bridge that had a huge potential for transporting vehicles of different natures, and created a bridge with a very large amount of useful deck space, especially for its time. This has meant that today, almost one hundred years later, on a normal day the bridge carries about 78,000 vehicles and about 266,000 subway riders.

It is likely that in the future there will be even greater demand on the bridge, and thought may be given to adapting the existing structure in order to increase its capacity. If possible, this would be a vastly cheaper alternative to building a new bridge next to or near the existing structure.

In many cases it is impossible to adapt an original bridge design, however in the particular case of the Manhattan Bridge it may be possible due to the design of the deck.

As shown previously in Figure 4, the deck is comprised of two levels. This was probably done originally to make use of the depth of the 7.4m deep trusses, rather than making the deck wider. The design does however seem to leave a large void in the centre of the deck where it may be possible to create an upper level road of three lanes above the existing ones. If there had been no demand for that many lanes at the time the bridge was designed it would have been pointless to construct these additional lanes. However the designers may have considered that demand may warrant them in the future and therefore allowed the space for them. Whether or not this was the intention of the designer I am unsure, but the addition of extra lanes in this place does look as if it would be possible.

The main implication of constructing a new set of lanes above the existing central ones would be the additional dead load that would be added to the deck of the bridge. A thorough analysis would need to be carried out to ensure that the existing components would be able to safely support the additional load. In particular the strength and condition of the hangers and main cables would need to be confirmed. A side benefit to having a road deck spanning between the two central trusses would be that the box shape that would then be formed would perhaps provide a greater degree of stiffness to the effects of torsion in the deck.

6 Strength of the Structure

Using basic calculations, it is possible to determine the approximate strength of some of the main components of the Manhattan Bridge. This could then allow a comparison between how strong a bridge of its type would be built today, compared with the way in which it was designed over one hundred years ago. It would also be possible to judge whether it was necessary for there to be four main cables, rather than two, as most modern suspension bridges are built with.

6.1 Load carrying capacity of the main cables

The diameter of each of the main cables is 0.54 metres. If an approximate value of the yield strength of the steel used to spin the cables is used, then it is possible to calculate the maximum allowable tensile force in each main cable before the steel in the cables yields.

\[ A = \pi \left( \frac{0.54}{2} \right)^2 = 0.23 \text{m}^2 \]

Let \( \sigma_y = 450 \times 10^6 \text{N/m}^2 \)

\[ T_y = \sigma_y \times A \]

\[ \therefore T_y = 103 \times 10^6 \text{kN} \]

The above value is the force that each cable would be able to carry before it yields, based upon the approximations as explained previously. Using this tensile force as a limit, it is then possible to calculate the maximum allowable load on and including the deck that would result in this force in the cable.

The point of maximum tension and hence the greatest tensile force in the cable occurs at the support points where:

\[ T_y = \sqrt{H^2 + V^2} \]

Where \( H = \frac{\omega l^2}{8f} \)

And \( V = \frac{\omega l}{2} \)

Therefore substituting values for \( l \) and \( f \) gives:

\[ H = 411 \omega \]

\[ V = 224 \omega \]

Using value previously calculated for maximum tensile force:
\(103 \times 10^3 = \sqrt{(441 \omega)^2 + (224 \omega)^2} \)
\[\therefore \omega = 220 \text{kN/m}\]

This means that if a load of 220kN was to be suspended from each of the main cables along every metre of deck, the yield strength of the main cables would be reached.

As there are four main cables and the deck is 36m in width, each of the central main cables support 9m\(^2\) of deck per metre length. Therefore the maximum load per m\(^2\) of area of deck that the cables can support is:

\[\frac{220}{9} = 24.4 \text{kN/m}^2\]

This is all based upon the estimate that the tensile strength of the steel used to form the main cables is 450N/mm\(^2\).

For the purposes of a rough comparison, the Triborough Suspension Bridge, of a very similar span and width, has 100\(\times 10^3\)kN of steel in its suspended structure. Using this as a value for the dead weight of the Manhattan Suspension Bridge, the adequacy of the main cables of the Manhattan Bridge can be approximated.

In order to calculate the dead load per metre length of the deck, that each of the four main cables carries:

\[\frac{100 \times 10^3}{448 \times 4} = 55.8 \text{kN}\]

This dead load figure can then be compared to the load that results in the maximum permissible tensile force within each cable:

Max permissible load = 220kN/m

Approximate dead load = 55.8kN/m

This means that based on these estimated figures, each main cable would be able to carry four times the dead load of the area of deck it supports.

To then simply include a live load with these figures, a load of half that of the dead load has been assumed. The total loading would therefore be 84kN/m, meaning a safety factor of 2.6 in the main cables.

Without knowing the dead weight of the deck in the main span, it is impossible to know how accurate the above calculations are. However, for the purposes of showing the loading carrying capacity of the cables, and to approximate a safety factor, the calculations are very useful.

The calculations show that just two of the main cables would be able to carry the total dead and live loads. This would however have meant a totally unacceptable factor of safety. If this bridge were to be built today, two cables would be used rather than four, but they would have a far greater axial strength than the ones used for the Manhattan Bridge.

**6.2 Extension of Main Cables When Loaded**

Due to the large diameter of the main cables, they are not likely to extend a significant amount when loaded. It may however be worth calculating how much the cables extend when the full live load is added to the weight of the dead:

To calculate an approximate value for the tension in the cable consider the free body and take moments:

![Figure 14: Free body diagram.](image)

\[T = \frac{\omega l^2}{2}\]

As done previously, assume the maximum live loading to be 28kN/m length of deck for each main cable.

Therefore:

\[T = 11.5 \times 10^3 \text{kN}\]

Using this value as the average tension through the length of each cable over the main span, it is then possible to find how much the cables will extend under this load:

\[\Delta L = \frac{TL}{EA}\]

\[\Delta L = \frac{11.5 \times 10^3 \times 488}{200 \times 10^6 \times 0.23}\]

\[\Delta L = 0.12m\]

This extension over the whole length of the cable is going to be insignificant in terms of a deflection of the deck. It may however be worth bearing in mind that assuming that the dead weight of the deck is twice that of the maximum live load (as discussed previously), the each main cable will extend 0.24m from the dead weight alone. The hanger cables will also extend when live load increases. These cables will have a far smaller axial stiffness than the main cables, so a large live load may cause significant extension of the hangers. How much each hanger extends will depend on both where the live load is, and the bending stiffness of the deck. The main concern however with the deflection of the deck of a suspension bridge is not how much the deck uniformly displaces downwards, but rather asymmetric deformation that may result from one side or half of the deck being loaded only.

**6.3 Thermal Effects**

The structure of the Manhattan Bridge is made from steel, which will expand or contract as its temperature changes. If the temperature of the steel deck increases, the trusses comprising the deck will want to increase in length. Typically steel has a coefficient of thermal expansion of 12 \(\times 10^{-6}/\text{C}\). It is then straightforward to use this to find an approximate value for how much the deck may extend if there was a temperature change of 60°C.
$$\Delta L = \alpha \Delta T L$$

$$= 12 \times 10^{-6} \times 60 \times 448$$

$$= 0.32 m$$

This means that on a hot summers day, the deck of the bridge could be 0.32m longer than during the winter. This extension is a small fraction of the length of the deck. However, if the deck was to be completely restrained at each end so that this extension wasn’t possible the induced stress in the deck would be significant.

$$\sigma = \alpha \Delta T E$$

$$= 12 \times 10^{-6} \times 60 \times 200 \times 10^3$$

$$= 144 N/mm^2$$

If on a hot day this stress was present in the truss members, their capacity to carry any additional loads would be very significantly reduced. This however was common knowledge at the time the Manhattan Bridge was designed and expansion joints would have been located along the main trusses. These joints had to maintain the bending capacity of the truss, but allow for some movement in the horizontal plane. From previous cases the engineers would have also been aware that these joints could not be relied on to remain unblocked. Expansion joints becoming blocked would have not been uncommon at the time the bridge was designed, due to poor levels of maintenance carried out. Therefore the structural elements in the deck would have probably been designed to be able take the additional stresses that would be within the deck if there were no expansion joints.

As well as the truss members increasing in length, the main cables and hangers will also increase in length due to thermal expansion. There is no restriction to the elongation of the main cables on the Manhattan Bridge. The main cables are able to sag freely when their length increases, rather than going into axial compression in the way the trusses would if it were not for expansion joints. This results in a vertical displacement of the deck each time the cables expand or contract. This is one of the reasons why the deck of the Manhattan Bridge was built with a slight camber. When the deck deflects downward it will never look as if it sagging due to the pre-camber that is already there. The pre-camber serves the same purpose when there is a live load on the bridge deck. Preventing the bridge deck from looking like its sagging, the pre-camber is an effective means of installing confidence in the people who are to use the bridge; any amount of sagging gives the impression structure could be unsafe.

### 6.4 Wind Loading

Arguably the most crucial aspect of designing a successful suspension bridge is to ensure that it can safely withstand the design wind loads. At the time the Manhattan Bridge was designed, not a great deal was known about designing a suspension bridge that would perform well under wind loads, most knowledge was gained from previous examples. Therefore the designers were fortunate in that deep steel trusses were the only solution to stiffening suspension bridge decks at that time. Even though the Manhattan Bridge has a fairly deep deck of 7.4m, wind forces have a much smaller effect than if the deck was constructed from deep girders instead. This is because the large trusses, that constitute the depth of the deck, allow for wind to blow through the large area of gaps. Compared with if the deck was solid in elevation, there is a relatively small area along the horizontal plane of the deck that offers resistance to wind. This is fortunate, as otherwise there could potentially be huge levels of wind loading on the side of the deck. The bridge deck has also been designed to be very stiff, which means that any uplift from wind should have little effect in deforming the deck. The deck itself is also very heavy so wind would not cause enough uplift for the hangers to go slack. This avoids any risk that the deck could suffer from galloping. The engineers have also included a large amount of cross bracing tying the stiffening trusses together across the width of the deck. This is in order to provide stiffness to the deck in the same plane as the horizontal wind load, ensuring a high enough bending capacity in the deck.

In order to reiterate the point that engineers weren’t fully aware of how bridges should be designed to respond to wind loading, it may be worth noting that it was the very same Leon Moisieff that designed the infamous Tacoma Narrows less almost forty years later.

The modern day solution to the designing bridge decks to perform well under wind loading is to make the deck aerodynamic. This reduces the wind load on a deck and allows for it to remain slender and less stiff than otherwise. Suspension bridges are usually constructed with inclined suspenders to help dampen vibrations caused by wind loads. This had not been realised at the time the Manhattan Bridge had been built.

### 7 Maintenance and inspection

As with all bridges, suspension bridges must be regularly inspected and maintained to ensure that the structure is safe. Corrosion of components, or bolts loosening due to vibrations from traffic are examples of the many areas of the Manhattan Bridge that must be regularly inspected and maintained. Railings that run along the main cables are there in order for bridge inspectors to be able to check the connections between the hangers and the main cables. They also allow access to the tops of the towers. Inspectors must check the huge number of rivets over the whole structure. If too many become loose in a region, it could lead to a serious reduction in load carrying capacity of certain members. This can become potentially dangerous. The bridge has been designed to allow inspection to be possible in all regions, which includes underneath the deck. For this purpose, an open topped steel cage that runs on tracks is located under each of the suspended spans. This cage allows the bridge inspectors to stand and have an unimpeded view of the underside of the deck to check for any potential problems. By including this kind of feature in the design of the bridge, it shows that even one hundred years ago, bridge engineers appreciated the need for inspection and maintenance of bridges.

### 8 Durability
The entire superstructure of the Manhattan Bridge is made from steel, which means it is susceptible to rusting. Most structural elements would have presumably been galvanised to prevent this. Other subtle precautions had also been taken in the design, for example the masonry section of the piers meets the steel at a level above the water at high tide. This would have clearly been designed this way to prevent the steel piers coming into unnecessary contact with the water, even though it has all been galvanised.

9 Susceptibility to Intentional Damage

When the Manhattan Bridge was designed, there was probably very little thought given to the idea that somebody might purposely try to destroy it. In some rare cases, potential acts of vandalism would need to be considered when designing a structure. However, a very large structure like the Manhattan Bridge would have no areas regarding the bridges structural integrity that would be susceptible to vandals. When designing such structures today, careful consideration needs to be given to what may happen to the structure if part of it was intentionally destroyed, i.e. as an act of terrorism. Designers would need to consider whether or not the structure could remain standing, even if certain key elements were completely removed. This aspect of design is no common in structures, and the design of a suspension bridge would be no exception.

Without detailed calculation it is very hard to look at the existing bridge structure and judge whether it would collapse completely if certain parts were taken away. In order to try to go about this analysis, the key structural elements that form the core structure of the suspension bridge must be first identified. These are: the main cables, the towers, the suspenders and the anchorages. The deck is not included in this list, as it is not actually supporting anything. This implies that if a section of it were to be removed, the bridge would still stand. The bridge would obviously be rendered useless, but at least there would not be a catastrophic collapse of the structure.

Holding the deck up is the suspenders. These are regularly spaced hanging from the main cables, and fixed to the Warren trusses. At 7.4 metres in depth, these trusses would be able to span a far, far greater distance than that of the spacing between the suspenders supporting them, even with the dead load on the deck acting over the spanned length. The reason for their massive depth is so there is very little deflection due to live loading, meaning the only implication of them spanning further would be a significant amount of deflection. Therefore I can confidently assume that if several hangers next to each other along were removed, the deck, as well as the rest of the structure, would remain intact. Perhaps the most significant point is whether or not the structure could remain standing if one of the main cables was to fail completely through an act of terrorism. This is harder to judge, as the strength of many of the bridges other elements contribute to this. However, a rough guide could be taken from the results of some of the calculations carried about previously. In section 6.1 I calculate that the main cables are designed with a safety factor of 2.6. Assuming this figure to be correct for the purposes of this exercise, we can then say that each of the main cables could support more than twice the area of deck it currently supports before its yield strength is reached. Therefore it could be argued that if one of the cables were to be removed, the adjacent cables would be strong enough to carry the load that the original cable no longer supports. Much of whether or not this would actually happen is very much dependant on the strength of the deck perpendicular to the line of the cables. There would be a good chance that the deck would be unable to span twice the distance, as the bending moment on the deck would significantly increase. Although this may be helped by the fact that there is a great deal of cross bracing beneath the deck across its width. Whether the portion of deck in question could stay up or not, the majority of the deck along with the rest of the structure should still stand.

The most catastrophic collapse could probably only take place if the towers, piers or anchorages of the Manhattan bridge were destroyed. This is because these are the elements that keep the whole of the suspended structure up. The engineers building the bridge would have realised the structural significance of these elements and would have presumably used a factor of safety that reflects this.

Overall, no amount of planning in the design of the bridge could ever make it immune to intentional damage, however if enough thought it given, then a significant loss of life could be avoided if the situation were to ever arise.

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Figures [3,4,] Thomas R Winpenny. Manhattan Bridge, the troubled storey of a New York monumen. Pgs. 16,46.


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