Zeitschrift: IABSE reports of the working commissions = Rapports des commissions de travail AIPC = IVBH Berichte der Arbeitskommissionen

Band: 032 (1979)

Artikel: Service behaviour of suspension bridges

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DOI: https://doi.org/10.5169/seals-25610

Service Behaviour of Suspension Bridges

Comportement en service de ponts suspendus

Bewährung von Hängebrücken

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SUMMARY
This paper reports on portions of the experience record in the maintenance of four American suspension bridges and is restricted to discussion of only the superstructure, cables and suspenders. The contents evolved from personal experience, examination of engineering reports and interviews with some of those responsible for the operation and maintenance of the facility.

RESUME
Le rapport présente une partie des expériences acquises dans la maintenance de quatre ponts suspendus aux Etats-Unis et se limite à la superstructure, aux câbles et aux montants de suspension. Ce rapport est le résultat d'expériences personnelles, de l'examen des rapports d'ingénieurs et d'entretiens avec les responsables de l'exploitation et de l'entretien des ouvrages.

ZUSAMMENFASSUNG
Dieser Bericht zeigt Erfahrungen im Betrieb und Unterhalt von vier Hängebrücken in den USA, wobei er sich auf Brückendecken, Kabel und Hängesäulen beschränkt. Der Inhalt des Berichtes beruht auf persönlicher Erfahrung, Untersuchung von Ingenieurberichten und Gesprächen mit den für den Betrieb und Unterhalt des Bauwerkes Verantwortlichen.

Engineers and Architects are not the only ones to appreciate the concept of a bridge or its beauty; there is no greater expression of man's ability to build. Bridges are among the finest examples of structural art, powerful objects of pure utility and science.

One of the best known bridge types is the long-span suspension bridge which, as a result of its beautiful lines, has frequently captured the public's fancy and sometimes has even become a symbol of a city.

The United States is well known for its suspension bridges and one of New York City's main attractions is its eight suspension bridges, the most well known being the Brooklyn Bridge. Another example of a famous bridge is the Golden Gate Bridge which is immediately identified with San Francisco.

Engineers feel privileged if they are fortunate enough to be associated with the design or construction of such monumental structures. But as soon as the ribbon is cut on opening day of the bridge to traffic these same engineers rush on to another new exciting project. In general they are not interested in what they believe to be the tedious jobs of observing the performance, inspection or maintenance of the newly completed structure.

The public is not interested in day-to-day operations. It is even difficult to interest politicians in providing money for maintenance of an existing facility since they would rather have their names associated with new projects. Sometimes it takes a bridge failure to cause a public outcry which results in a spate of maintenance activity on an emergency basis.

While the task may be unglamorous, there is no more important job than ensuring that an existing facility is properly maintained and is capable of providing the services for which it was designed for the desired life of the project.

During this century and especially during the last 50 years, which coincides with the life span of IABSE to date, an experience record has emerged on the service behavior of long-span suspension bridges. This behavior, some of which was planned and some unexpected encompasses not only design but operations and maintenance as well. The designer, owner and users of a bridge have a view, each from a different perspective, of what satisfactory performance might be.

The unique features of suspension bridges, cables, suspenders, towers and anchorages are what distinguishes them from other type of bridges. In addition they are much more flexible and susceptible to damage from wind. In the early history of suspension bridges during the 19th century many suspension bridges were destroyed as a result of oscillations due to wind. Even to this day, the major performance problems of suspension bridges can be traced to their flexibility and response to wind forces. Another major problem concerns corrosion of suspenders, their anchorages and the deterioration of the protective system of the main cables.

This paper reports on portions of the experience record of four American suspension bridges and is restricted to discussion of only the superstructure, cables and suspenders. The contents evolved from personal experience, examination of engineering reports and interviews with some of those responsible for the operation and maintenance of the facility.

Delaware Memorial Bridge

The first Delaware Memorial Bridge was built at a cost of $43,900,000 by the State of Delaware to form a highway link between Delaware and New Jersey across the Delaware River just south of Wilmington. The bridge with a main span length of 2,150 feet and side spans of 750 feet was the sixth longest span in the world when opened to traffic on August 16, 1951. It was designed by Howard Needles Tammen & Bergendoff, and the American Bridge Company was responsible for the fabrication of the steel superstructure, main cables and suspenders. The 7" concrete roadway slab carries four traffic lanes and in addition there is a 3-ft. steel median and two 3-ft. sidewalks.

The Delaware Memorial Bridge was the first major suspension bridge to be designed following the Tacoma disaster other than the Tacoma Bridge itself. As such, the designers were conservative and called for a double lateral system as well as sponsoring a model at Princeton University of a portion of the suspended structure to study performance under torsional loads. The stiffening trusses are 20 feet deep with 26 feet panels and are 61 feet apart. Each cable consists of 19 strands of 436 No. 6-U.S. gage galvanized cold-drawn steel wires for a total of 8,284 wires. After application of substantially all of its load, the cable was coated with red lead paste and wrapped with No. 9-U.S. gage soft annealed galvanized steel wire and then painted. Four hanging suspenders at each panel point are 2-inch diameter galvanized wire ropes.

Traffic on the bridge grew so rapidly that the bridge became functionally inadequate. Consequently the Delaware River and Bay Authority, established in 1962, as the operator of the bridge, proceeded with the construction of a twin bridge, also four lanes wide. Each structure now operates as a one-way facility. The Consulting Engineers for the second bridge were Howard Needles Tammen & Bergendoff and E. Lionel Pavlo, and the bridge superstructure, as well as the cables and suspenders were constructed by the Bethlehem Steel Co. To the eye, there is not much difference between the twin spans.

For the new bridge, recognizing the trend to heavier wheel loads, a substantially stronger roadway was designed to provide for reduced maintenance costs and to keep future traffic disruptions resulting from required deck repairs to a minimum. In addition, the concrete slab was overlain with a 1-1/2-thick-inch bituminous concrete wearing course. The first bridge was designed for a 12,000-lb. wheel load and the second bridge for a 20,000-lb. wheel load which resulted in a concrete slab depth of 8 inches with an increase of 50 per cent in the required reinforcing steel. Furthermore, welded bar trusses were fabricated and used as the reinforcing steel in the new slab.

The concrete deck slab on the original bridge, which was only 7" thick, had developed hairline cracks, and spalling and potholes at many locations on the top surface of the slabs. In addition the 3-foot wide steel median and barrier had to be removed to provide for the free movement of four lanes of traffic in one direction. Also, each of the existing 24-foot wide concrete slabs were crowned at their respective center lines to provide drainage runoff in two directions and would have to be rebuilt to provide a normal four-lane roadway transverse profile with a single crown at the center line of the bridge, the area formerly occupied by the steel median. In view of the above three reasons, a decision was made to replace the concrete deck slabs in their entirety. The same design criteria for the design of concrete slabs as used for the new bridge was adopted and resulted in an 8" slab thickness. However it was not possible to add a separate bituminous concrete wearing surface on the new concrete deck slabs as on the second structure because calculations indicated that the additional weight imposed on the cables could not be tolerated.

In establishing the design criteria for the second structure, the Authority asked that a more extensive network of catwalks throughout the suspended span be provided in order to facilitate access to the various parts of the structure below the bridge deck for inspection and maintenance purposes. This was done and in addition a waterline system, extending across the entire bridge, with valves and outlets located at convenient intermediate points was also provided. This waterline enables maintenance personnel to wash and clean the structural steel members below the deck at regular time intervals. It was also decided to install these systems on the first structure to facilitate maintenance operations.

An important step in the continuing maintenance program of the original structure was the replacement of worn suspender ropes. The bridge deck is suspended from the two main cables by means of 276 suspender ropes, each 2 inches in diameter. At alternate panel points of the stiffening truss, two suspender ropes are looped over the cable bands which are placed around the main cables and at their lower ends are socketed by four forged steel sockets which are slid into slots of the bearing angles connected to the verticals of the stiffening truss. The suspenders pass through a steel collar casting which is riveted to the top chord of the stiffening truss. Reversed conical shaped holes were provided to permit the ropes to move slightly in horizontal directions under the movement of the suspended deck. In addition the suspenders were protected from abrasion at the collar by galvanized steel sizing wound around each wire rope. Nevertheless there was wear at the collar casting level when seizing wires became loose and broken and the suspender ropes came into direct contact with the surface of the steel collar castings. This situation was particularly serious at the panel points in the middle sections of the center span where the suspender ropes were the shortest and the deck movements greatest. The Authority decided to replace 44 of these damaged suspender ropes and to remove and replace the existing damaged sizing wires. In addition a research program was initiated with the purpose of developing a collar liner of suitable material that would minimize the damage to suspender ropes.

Results of the investigations indicated that adiprene (a urethane elastomer) or neoprene liners molded to conform to the shape of the suspender ropes would be the most effective in protecting the suspender ropes. Accordingly, all existing collar castings were replaced with new lined steel collar castings, half of which were lined with adiprene and the other half with neoprene. This procedure would allow a comparative study of the long term performance of the two types.

The two 24-foot concrete roadway slabs of the original bridge were separated by a three-foot steel median and supported on steel stringers that were continuous over four spans and 104 feet in length between expansion joints. The performance of these stringers was satisfactory. However shortly after the roadway deck modification as described earlier, cracks were discovered at the ends of the stringers in the web at or near the bottom flange. At these points a diaphragm between stringers, which supported the end of the concrete deck, was connected by an angle to the stringer web. This angle was not full depth and a gap was left between the bottom of the angle and the bottom flange of the stringer. It was concluded that lateral secondary bending of the web in this gap resulted in a fatigue failure. The secondary bending resulted from the resistance of the roadway deck system to the torsional motions of the suspended span. These same type cracks also appeared in the second structure and in at least one other suspension bridge.

The purpose of maintenance operations is to preserve the physical facilities constructed in as nearly perfect condition as possible. A continuous and thorough maintenance program assists in minimizing total maintenance costs for the life of the project.

The work of maintaining a system, as large and having so many different elements as the Delaware Memorial Bridge, includes many diversified types of activity. The useful life of a structure and its value is directly influenced by the care and thoroughness with which maintenance is conducted. Poor maintenance of a costly project will result in accelerated deterioration and eventually result in expensive emergency repairs or rehabilitation.

Maintenance operations are centered in a maintenance building constructed adjacent to the bridge. The equipment is housed and repaired at this location.

A highway facility for which a toll is charged must be kept in satisfactory operation as nearly 100 per cent of the time as possible for if the project is closed for any great length of time, then a distinct dollar loss accrues because of the inability to collect tolls. Locating the maintenance headquarters and equipment yards immediately adjacent to the project insures that emergency operations associated with snow and ice, the most frequent causes of temporary interruptions in service, will be initiated promptly.

Periodic inspections of the bridge are made by the Consulting Engineers who prepare and publish an annual report on the condition and operation of the bridge. The inspection includes all parts of the project including the substructure, anchorages, superstructure, concrete decks, towers, cables and suspenders, fenders, lighting, signing, signal and television surveillance systems, drainage, toll facilities and buildings. The report includes a recommended schedule of major repairs for the next year. Also included is a maintenance and operation budget.

To supplement this annual inspection a 5-year repetitive program was adopted by the Authority in 1971, which provided for a comprehensive detailed in-depth inspection covering every accessible portion of the bridge. The general limits of each year's in-depth inspection are as follows:

- 1st year : Underwater Inspection (both bridges)
- 2nd year : Approach Spans of Second Structure
- 3rd year : Main Spans of Second Structure
- 4th year : Main Spans of First Structure
- 5th year : Approach Spans of First Structure

It is expected that this program will be repeated after a one-or-two-year interval since it has proved to be very effective.

Golden Gate Bridge

The Golden Gate Bridge has a main span of 4,200 feet with side spans of 1,125 feet and was constructed at a cost of 27 million dollars. The bridge connects San Francisco with Sausalito and at the time of its opening to traffic on May 28, 1937 until 1964 it had the longest span in the world. The Chief Engineer for the project was Joseph B. Strauss, the superstructure steel was furnished and erected by the Bethlehem Steel Co. and the steel cables, suspenders and accessories were furnished by John A. Roebling's Sons Co.

The bridge has a 60-ft. roadway with two - 10-ft. shoulders. The roadway deck is a 7-inch thick concrete slab. The stiffening trusses are 90 feet apart and 25 feet deep. The panels of the stiffening truss are 25 feet on centers with suspender support points at alternate panel points. There is a top lateral system and at the time of opening there was no bottom lateral system.

Each 36-3/8-inch diameter cable consists of 61 strands with 452 wires for a total of 27572 wires. These wires are No. 6-U.S. gage galvanized cold-drawn steel wire which have a diameter of 0.196 inches. The wrapping wires, No. 9-U.S. gage soft annealed galvanized steel wire,were laid in a heavy red lead paste. A galvanized metal primer was applied to the wrapping and followed by a red lead paint and then the final coat of International Orange Paint.

Through the years the Golden Gate Bridge has been exposed to severe wind storms. In 1941, one of these storms lasted for three hours with wind gusts up to 60 mph. It was reported that lateral deflections of the bridge reached 5 feet and the vertical movements at the quarter point of the main span were 2 feet with a frequency of 0.13 hertz. The most severe storm occurred in December 1951 and lasted for over six hours. At its peak a wind gust velocity of 69 mph was recorded with an average wind velocity of 55 mph for 20 minutes. A double amplitude of 11 feet was measured at the quarter point with a frequency of .28 hertz. Traffic on the bridge was stopped at the peak of the storm. There was considerable damage to the lateral system connections of the center span to the tower which had to be repaired.

As a direct result of the storm a Board of Engineers was appointed to investitate the viability of installing a bottom lateral system and report on the benefits that would result. Section models to a scale of 1:75 were tested in a wind tunnel. In addition tests made at Princeton University in connection with the Delaware Memorial Bridge were cited in that they indicated that the bottom lateral system on that bridge increased the torsional rigidity by about 20 times. The Board recommended that a bottom lateral system be added to the Golden Gate Bridge and it was installed in 1954. It has evidently solved the wind stability problem of the bridge.

At the same time that the bottom lateral system was being installed, travelling maintenance platforms were added to the main and side spans to facilitate the inspection and maintenance of the bridge.

During the period 1967-1969, the firm of Ammann & Whitney conducted an in-depth inspection of the bridge. The wrapping on a section of the main cable 10 feet long near the center of the main span was removed and the condition of the wires observed. The surface of wires were all found to be in excellent condition. Wooden wedges were driven into the cable to examine some of the interior wires which were also found to be in excellent condition.

The cable band bolts on the bridge were retightened in 1954. Measurements in 1968 indicated average per cent relaxation from 31 per cent to 71 per cent with an average of 48 per cent for 14 panel points.

The suspenders consisting of 2-11/16-inch diameter galvanized wire ropes were found to require replacement due to severe corrosion especially in the bottom four feet of the ropes which were inaccesible. On the other remaining part of the ropes it was found that the galvanizing had worn quite thin. The severest corrosion occurred in the lower three inches of the rope and at the point where the suspender passes through the guide casting on the top chord. As on the Delaware Memorial Bridge, the suspender had been wrapped with wire at this point to prevent abrasion. The suspenders structural bearing connection to the stiffening truss vertical has undergone severe metal loss. These connections will be removed at the same time that the suspender ropes are replaced and replaced with a new bearing connection detail that provides ample space for inspection and maintenance.

Mr. Henry D. Reilich, Chief Engineer, Golden Gate Bridge, Highway and Transportation District, has reported that the bridge has been undergoing a complete new painting cycle which should soon be ended. He expects that the paint system will have a 20-year life. The following operations describe the process:

- First sandblast all metal.
- Apply 3 mils of a dry inorganic zinc primer.
- Apply 1/4 mil vinyl wash primer.
- Apply two coats of 1 mil each of a vinyl top coat keeping the the landmark color of the bridge namely International Orange.

Ambassador Bridge

The Ambassador Bridge spans the Detroit River between Detroit, Michigan, and Windsor, Ontario. The bridge was opened to traffic on November 15, 1929 and has a main span of 1,850 feet which at the time was a record span, which was exceeded in 1931 by the George Washington Bridge with a span of 3,500 feet. The bridge carries four lanes of traffic on a 47-foot wide concrete slab roadway deck and has an 8-foot sidewalk on one side only.

The bridge is 67 feet wide between cables but only 59.5 feet center-to-center of stiffening trusses which are 22 feet deep. The load from the deck is transferred via a cantilever bracket from the center-line of stiffening truss to the suspenders at the center-line of cables. An unusual arrangement but one that allows the suspenders to be accessible for maintenance and inspection at the bottom.

An in-depth inspection of the bridge was performed in 1974. Few alterations have been made to the bridge over the years. The bridge was found to be in remarkably good condition despite its age.

The condition of the suspender ropes is particularly noteworthy as little corrosion was observed. The bottom connections of suspender ropes are often a problem area. In this case, good initial design and continuing maintenance has paid off.

The main cables were found to be in good condition and the cable wrapping had just a few places where the paint had chipped. Cable anchorages, including strand shoes, eyebars and pins, are in good condition except for some corrosion on some strand shoes.

Three cable bands were reported as having moved slightly. In view of this observation it was decided to embark on a program of determining the remaining tension in the cable band bolts. The American Bridge Division of U. S. Steel performed the required testing for 11 cable bands. The average bolt tension at the cable bands tested was found to be 13,400 lbs. Assuming the initial tensioning to be 60,000 lbs., as was specified at the time the bridge was constructed, the average loss of tension is about 78 per cent in fourty-seven years.

Wheeling Bridge

The suspension bridge at Wheeling, West Virginia, spanning the Ohio River is one of the oldest bridges of this type in the world and was the first bridge with a span length greater than 1,000 feet. It was designed by Charles Ellet, constructed by the Wheeling & Belmont Bridge Company, and opened to traffic on August 1, 1850.

In 1969, the American Society of Civil Engineers dedicated the bridge as a National Historic Civil Engineering Landmark and in 1975, the National Park Service designated the bridge as a National Historic Landmark.

In 1854, a wind storm caused excessive vertical oscillations of the bridge which resulted in the hangers breaking loose and the deck dropping into the river. Mr. Ellet, making use of much of the original material, restored the structure to use and it was reopened to traffic in January 1856.

In 1872, a system of radiating stay cables from the tower tops to the deck was also installed in accordance with a scheme designed by the Roeblings.

During the late 1940's, more than a hundred badly corroded wires at the East Tower were discovered. The damaged lengths were removed and new lengths of wire spliced in.

In 1966, the 1-inch Ø hanger rods on all four cables for 49 panel points over the central 400 feet of the bridge were replaced.

Over the years, there have been numerous changes in the cross-section of the bridge. The original wood floor was replaced in 1930 by creosoted yellow pine laminated flooring. In 1956, the entire floor system was replaced with open steel grating, both for the roadway and sidewalks. In addition new floorbeams were installed at the same time.

The bridge has served well with several cycles of rehabilitation. However age has taken its toll in recent years and the bridge has deteriorated to such a degree that major repairs are required to allow the bridge to continue providing services. Because of the Bridge's great historical significance, the owner, the West Virginia Department of Highways, will make these repairs and also provide for on-going maintenance and inspection.

In the past 37 years, Howard Needles Tammen & Bergendoff (HNTB) has conducted six inspections of the bridge, the latest being in the summer of 1978.

The present-day bridge has a main span of 1008.5 feet, carries two lanes of automobile traffic on a 20-foot roadway and has two 4-foot sidewalks. The stiffening truss with approximately 8-foot panel lengths is 6.17 to 6.75 feet deep and is constructed of timber. This is a very shallow structure for so long a span.

There are four main cables supporting the bridge, each about 7.5 inches in diameter and consisting of 2200 - No.10-gage galvanized wires with a diameter of 0.135 inches. To protect the cable from the weather each is tightly wrapped with No.14-gage galvanized wire with a diameter of 0.080 inches. The cables are painted to produce a seal to exclude moisture. Of note, that while some of these wires have broken and rusted away, the original cables are for the most part still intact and carrying load after 130 years of service. Perhaps there is something to learn here for our modern day cable-stayed bridges, some of which are being constructed with ungalvanized wires. Some engineers are even talking about replacing cables on such bridges every 30 years which has to be expensive, inconvenient and not in the client's or public's interest.

During the latest inspection, the main cables were unwrapped at 13 locations, wedged apart to permit a close visual observation, and then rewrapped using the elasto-wrap system which utilizes an elastomeric material rather than wrapping wire. At 12 locations, the main cable wire strands appeared to be in good condition. At the 13th location, however, 15 broken strands were found. On the top half of the cable, the corrosion appeared to extend 4 layers deep and on the bottom half, only the outside layer showed indications of deterioration.

At many locations, the wire wrapping was found to be badly corroded, loose and broken away, all of which allows deterioration of the underlying main cable strands. At several of these locations serious corrosion of the main cable wires was found.

In view of the broken wires of the main cable found at location 13 and the indication of loose cable wrapping, a subsequent inspection was authorized to examine the entire length of main cables for additional signs of distress. The inspection was carried out and revealed that the paint coat was worn off and the wire wrapping loose or corroded over 50 per cent of the length of the main cables. More locations were pinpointed that had a number of broken main cable wires. At one point, 50 cable strands were found to be broken and about 85 additional strands had up to a 50 per cent loss of section. The cable was wedged open at four positions at this location and no corrosion was observed beyond the second outermost layer of wires.

To ensure that this historical bridge remains in service, the entire wire wrapping will be removed. New wire strands will be spliced in wherever a strand is found to be broken or seriously corroded and a protective coating will be applied consisting of liquid neoprene followed by a neoprene hypalon cable wrapping.

The timbers that comprise the stiffening trusses are weathered and deteriorated. The entire bottom chord will be replaced as well as the decayed sections of the diagonals and top chord.

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