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Inspection Evaluation, and Rehabilitation of Suspension Bridge Cables

Inspection évaluation et remise en état des câbles de ponts suspendus

Inspektion Beurteilung und Instandsetzung der Kabel von Hängebrücken

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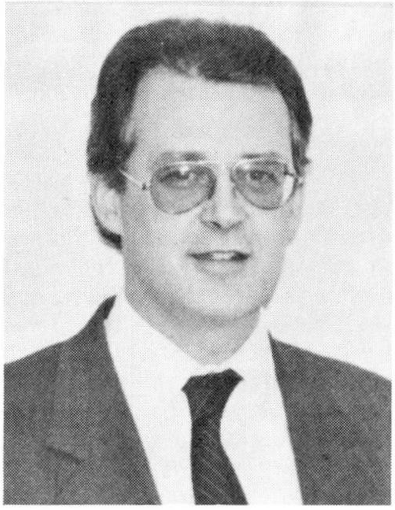

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SUMMARY

Recent inspections of the main suspension cables of the Williamsburg, Brooklyn (New York, NY), and I-74 (Bettendorf, Iowa) Bridges provide a sampling of the longevity and durability of three differing types of cable construction. The cables of each bridge will be rehabilitated in a manner dictated by the details of the original design.

RÉSUMÉ

Les récentes inspections des câbles principaux des ponts de Williamsburg et Brooklyn (New York, NY) et de la I-74 (Bettendorf, Iowa) fournissent un échantillon de longévité et durabilité de trois types de ponts suspendus différents. Les câbles de chaque pont vont être remis en état en respectant les détails des conceptions originales.

ZUSAMMENFASSUNG

Kürzliche Inspektionen der Hauptkabel der Brücken von Williamsburg und Brooklyn (New York, NY) und der I-74 (Bettendorf, Iowa) stellen eine Stichprobe für die Dauerhaftigkeit und das Langzeitverhalten dreier verschiedener Typen von Hängebrücken dar. Die Kabel jeder Brücke werden in einer durch die Einzelheiten des ursprünglichen Entwurfs bestimmten Art und Weise instandgesetzt.

1. THE THREE BRIDGES AND THEIR CABLES

1.1 Brooklyn Bridge

Brooklyn Bridge spans New York's East River, connecting Manhattan with Brooklyn Heights. It is the most famous of John A. Roebling's suspension bridges, completed in 1883 and now a national monument. The main suspended span is 486 m long and is flanked by two suspended side spans, of 283 m each. Each of its four main cables is comprised of 5358 galvanized steel wires, 4.67 mm in diameter. After spinning, the cables were compacted, coated with a thick paste of white or red lead, and then tightly wrapped with 3.8 mm diameter galvanized steel wire. This was then sealed with several coats of paint. The wrapped cables are 400 mm in diameter.

1.2 The I-74 Bridges

The I-74 Bridges are twin, nearly identical suspension bridges crossing the Mississippi River between Bettendorf, Iowa, and Moline, Illinois. The original bridge, now serving Iowa-bound traffic, was completed in 1935, and the newer structure now serving Illinois-bound traffic, was completed in 1959. Both have main suspended spans of 226 m, and suspended side spans of 113 m. Each bridge is supported on two cables, 241 mm in diameter, including wrapping wire. These cables are of a construction that markedly differs from the Brooklyn Bridge. Rather than building up the cross section with thousands of individual wires, these cables consist of 37 shop-fabricated galvanized structural strands, 31 of 38.1 mm diameter, and 6 of 25.4 mm diameter. Each strand contains 19 or 37 wires, twisted in layers. The strands are laid parallel to each other, roughly forming a circular cross section. Extruded aluminum fillers are added around the circumference to round out the surface, and the whole is tightly wrapped with 3.8 mm diameter galvanized wire, and covered with three coats of paint.

2. INSPECTION SAMPLING, AND TESTING

2.1 Brooklyn Bridge

Inspection of the Brooklyn Bridge cables was performed in two distinct parts: Wrapped areas between the anchorages; and the unwrapped individual strands within the anchorage chambers. The four cables were visually inspected end to end and based on conditions observed, an in-depth investigation was programmed.

2.1.1 Wrapped Portions

Two sections of the cable in the main span and one section in the Manhattan side span were unwrapped and split open with oak wedges. Because cable bands are located every 2.3 meters, it was first necessary to remove the suspender and cable band (or cable post) to provide enough free cable (about 7 meters) to penetrate with the wedges. It was found that the wrapping wire beneath the cable bands had begun to corrode significantly due to the tendency for moisture to lay between the ribbed surface of the wrapping and the smooth inner surface of the cable bands. The outer layer of main cable wire immediately below the wrapping and cable bands had corroded sufficiently to consume most of the zinc galvanizing and rusting of the wires had occurred. One wire had lost over 75 percent of its cross section and had broken. The remainder exhibited localized loss of material that is commonly referred to as "pitting" although in the strict technical definition no real pits were present (the technical definition of a pit is a defect that is at least as deep as its width at the surface). At the areas between cable bands, the surface wires were still in excellent condition. Dried red lead paste covered most of the surface, but in occasional spots powdery zinc oxide from the galvanizing coated the exposed wires.

Oak wedges were driven between the wires at four radial points (one point at a time) and the cable was penetrated approximately 15 cm, or almost to its center. It was found, even under the cable bands, that all corrosion had been limited to the outside layer of wires. From the second layer in, the original galvanizing was still in near-perfect condition.

Fifty seven wire samples were cut from the cables at various locations and sent to Columbia University's Carleton laboratory for testing. The cut wires were replaced with lengths of new wire spliced in using a combination of pressed-on and threaded ferrules.

The results from the laboratory indicated that the typical corroded wires had not lost measurable strength as compared to uncorroded wires, but it was apparent that the original material was not uniform and was of considerably lesser quality than modern bridge wire. Carbon content varied from 0.55 percent to 0.91 percent, whereas modern wire is generally in the range of 0.78 to 0.82 percent. Average tensile strength was 1,100 MPa, and the proportional limit was approximately 690 MPa. The most significant finding was that the original wire was of low ductility: reduction of area varied from practically zero to 26.5 percent; reduction of area for modern galvanized bridge wire will typically be on the order of 35%.

Fatigue testing results and microscopic examination of longitudinally sectioned wires provided the assurance that there was no evidence of stress corrosion cracking in the wires.

2.1.2 Cable at Anchorages

The initial inspection on the anchorages revealed serious corrosion and numerous broken wires were found both between the splay band and strand shoes, as well as at the back of the shoes, where concrete had been placed in contact with the wires. The confined space of the anchor chambers provided barely enough room for a man to pass between the strands and the chamber walls. It was impossible to determine the full extent of corrosion damage at the shoes or within close proximity to the splay band. It was apparent that extraordinary measures would be necessary in order to fully examine and evaluate the conditions at the anchorages. The possibility existed that entire strands were damaged beyond repair, and it was therefore decided to develop procedures and equipment to splice entire strands concurrently with developing a detailed program to continue the investigation.

First, the anchor chambers would need to be enlarged to provide working space; second, the existing splay bands would need to be removed to allow spreading of the strands for inspection at the splay points, and third; repair details for various possible conditions needed to be developed. With the assistance of the faculty and staff at Columbia University's Carleton Laboratory, a mock-up of a typical anchor chamber and splayed cable was constructed. Clamps, sockets, and jacking equipment were designed for the worst case scenario, in which entire strands would need to be cut, socketed, and reanchored in the field, something that had never been done before. New splay bands and strand spreader frames were designed.

Working in the mock-up, methods were tested for zinc-socketing of the strands in the horizontal, rather than the usual vertical position.

A contractor was awarded the contract to assist Steinman in enlarging the chambers, relocating the cable splay points, and if need be, cutting and replacing the deteriorated strands. It was decided to start at Cable B in the Brooklyn Anchorage. After the chamber had been modified, two temporary splay bands were installed spanward of the existing band, and the old band was removed. In a series of "leap frog" moves, the two temporary bands were moved up along the cable until they reached the location of a new permanent splay band about 4 meters from the original splay. Horizontal and vertical spreader frames were placed between the strands and the strands were gradually spread apart using specially designed hydraulic equipment. The placement of the new splay was such that the total length of each strand would be unchanged after the splay relocation was completed. Electronic strain gauges were used to monitor stresses in the anchor eyebars as the strands were spread.

Upon completion of the strand spreading and removal of concrete behind the strand shoes, a detailed inspection was made strand by strand. It was considered very fortunate by all involved that the serious corrosion and breaks were primarily confined to surface wires. Most of the wires were slightly corroded, or uncorroded, although much of the galvanizing zinc had been consumed by oxidation. The operations proceeded in the remaining seven anchorages and similar conditions were found. All in all, several hundred broken or seriously corroded wires were found, but these were repairable by splicing in new sections of wire, and no full strands needed to be replaced.

This work was completed in early 1987.

2.2 I-74 Bridges

Our assignment on the I-74 Bridges was to perform a close condition inspection of all cables and the superstructures of both bridges. The cables to be inspected included all handropes, main cables and all suspenders of both bridges.

2.2.1 Suspenders

All of the suspender ropes were inspected and as anticipated in bridges of this design with no center tie, one-way traffic, and increasingly heavy truck traffic, many of the shorter suspenders near mid span of both bridges contained cracked or broken wires. The mechanism which causes these breaks are fatigue related and caused by the differential longitudinal motion under live load of the main cable with respect to the top chord of the stiffening truss. The measured motion of 19 mm though relatively small, is sufficient to alternatively stress the suspender wires near the extremity of the suspender. The cyclical loading causes the wires to break over a period of time and the number of breaks occurring increases rapidly once the critical number of live load cycles has been reached. It has been recommended and accepted that center ties be installed on both bridges and that all suspenders with cracked wires be replaced.

2.2.2 Main Cables

The main cables of both bridges were inspected from anchorage to anchorage and included all associated cable bands, saddles and appurtenances.

The anchorages were inspected first and found to be in very good condition. No deterioration, rust blooms, moisture or staining were found on the splay saddles, splay strands, strand shoes or eyebar assemblies and no cracks or water were found in the chambers themselves.

The next step was to inspect the main cables between anchorages to determine if water had entered the cables and if so what damage had occurred as a result. Here we found that the paint on the cable wrapping was in poor condition with many cracks in the paint layers, some loss of galvanization and some rust on the wrapping wire. In addition, we found pop-outs of the bottom caulking and staining had occurred at many cable bands which is a sure sign that water under pressure or water under freezing conditions had been present in the cable. At random we removed some cable band bolts and found that no bolts from the top of any band was rusted, however, all bolts removed from the bottom of the bands were deteriorated with some section loss and the bolt chambers were filled with rust. Some of the rust and some of the bolts were wet. Next we removed some of the sealed covers from the tower saddles and the cable bent saddles to see if any leakage was occurring at these points. We observed that the sealed covers were watertight and that the cables across the saddles were in like new condition. The covers were replaced and resealed. Based upon our findings that water was entering the cable thru the many small openings in the paint protection at the wrapping wire it was decided to unwrap the main cables at various points between cable bands for closer inspection. The areas to be unwrapped were designated by us and were chosen to reveal varying types of cable exposure to water. Total length of unwrapping was 83 meters (horizontal projection) on the 4 main cables.

The unwrapping procedure began by first having the contractor install the work platform on both sides of the cable for the full length of the panel to be worked on.

To start the unwrapping, the wrapping wire was cut with a small electric grinder at a designated point where damage to the main bridge strands would not occur. Once the initial cut was made, the wrapping was unwound by hand, cut into pieces using a wire cutter and removed. Tie wire was placed around the cable to hold the aluminum fillers in place. With the wrapping wire removed, the strands and fillers were exposed.

Each of the 18 aluminum fillers was marked with an identification number as it was removed from the cable and placed in a special box made to hold the fillers. These fillers were then taken to the plaza area on the bridge where they were wire brushed clean and painted with neoprene paint.

With the aluminum fillers removed, the strands were inspected. Hard wood wedges driven between the strands along with a hydraulic wedge were used to spread the strands apart. A putty knife, steel awl, magnifying glass, flashlight, and a fiber optic device were used to inspect the strands. All of the strands, except where noted, were covered with a maroon colored paint. The paint had been applied before the strands were placed on the bridge.

In some locations, the strands were found to have white oxide formation along with, or sometimes without, deposits of ferrous rust. In cases where the ferrous rust was at a more advanced stage, "pitting" typical local corrosion was found. In order to determine if the individual wires had any defects such as cracks, the wires were carefully cleaned using a stiff bristle brush and a cleaner solvent to remove as much white oxide and ferrous rust deposit as possible. Once the wire was sufficiently clean, the wires were carefully examined by an engineer using a magnifying glass. No cases of visible wire cracking were found. Since the cables are composed of twisted wire strand, it was undesirable to remove wire samples for labratory testing, and the conditions found did not warrant further investigation.

Since the extent of damage was generally limited to localized areas, the condition was discovered in time to save the cables by applying a new protective wrapping of neoprene to preclude the entrance of water.

3. CABLE REHABILITATION PROGRAMS

3.1 Brooklyn Bridge

There were several factors that influenced the scope of rehabilitation required for the cables of the Brooklyn Bridge. In contrast to present practice, the cables had been wire wrapped continuously prior to installation of the cable bands and suspenders. While the original wrapping had admirably protected the cables throughout most of their length, the cable bands were trapping moisture and corrosion was taking place beneath them.

The bands were also prone to slipping down hill on the cable because their design precluded a secure clamping effect. The original red lead paste was dried out and did not afford the necessary sealing between the wrapping wires. It was also found during our general inspection that virtually all of the wire rope suspenders were seriously corroded near their lower sockets, and would need to be replaced, as would the diagonal wire rope stays.

The cable rehabilitation contract, designed and inspected by Steinman, includes the removal of all existing wire wrapping, cable bands, suspenders and stays. New bands of modern design and new suspenders will be installed, followed by the rewrapping and painting of the cables. The greater part of the cables will be rewrapped with galvanized wire bedded in a thick paste of red lead. At the sag points, where the cables pass below the roadway and are subject to splash by runoff water and deicing salts, the cables will be wrapped with 3mm thick neoprene wrapping material.

All eight anchorage chambers have been enlarged and now provide ample space for inspection and maintenance of the strands, which will remain in their newly spread configuration. All broken and badly corroded wires have been replaced with sections of new wire, using a technique developed by Steinman. Since past experience has shown that the cutting of threads on the existing wires is difficult and uncertain, a length of damaged wire is first cut out and to its two ends are spliced new wires using specially designed ferrules. These ferrules consist of a mild steel cylinder, approximately 10mm in outside diameter, bored to accept a hardened helical steel wire insert of slightly larger inside diameter than the original bridge wires. After inserting the end of one old and one new wire into the ferrule, a hydraulic press crimps the ferrule onto the wire, developing a splice that is 95 percent as strong as the original wire. The two mating ends of the new wires which have shop-cut threads, are then spliced using a ferrule with internal left and right hand threads. The threaded ferrules act like turnbuckles and permit the spliced wires to be stressed to a predetermined tension. After repair of the damaged wires, the cables are now more than adequate to carry the dead and live load of the bridge.

It is fully expected that the rehabilitated Brooklyn Bridge will serve New York City for at least another one hundred years.

3.2 I-74 Bridges

Our recommendations for protection of the cables was as follows:

Clean the loose paint from the cable exterior by wire brushing and wrap neoprene flashing completely around the cable along its entire length over the existing wrapping wire. The exposed neoprene wrapping surface should be painted for protection. The lead wool packing between the wrapping wire and the cable band will need to be removed and replaced with caulking in order to ensure a watertight seal.

It is not considered necessary to recommend complete removal of the wrapping wire because both the main cable and the wrapping wires are in relatively good condition. The major problem is that the lead-based paint on the exterior of the wrapping wire has failed, permitting water to enter the cables between the wrapping wires, and similar to other cables of this design, no red lead paste had been applied under the wrapping wire. Neoprene wrapping has been used on suspension bridges for the past 16 years with very good results. Neoprene wrapping placed over the original protection represents the best means of positively waterproofing the cables.

The cable bands should be reconditioned by removing the caulking from the bottom slot separating the cable band halves in order to permit any water which may leak into the cable to drain rather than being retained. It is also recommended that the lower cable band bolts be replaced with new ones and that the loose rust inside the cable band bolt housings be removed. This loose rust tends to retain moisture which is detrimental to the cable strands. A program of cable band bolt retensioning should also be performed at the same time.

4. CONCLUSION

These bridges can give the Engineering profession valuable insight into the longevity of different suspension bridge cable designs. Most notably, it can be seen that the Brooklyn Bridge, with its galvanized wires, red lead paste coating, and galvanized wrapping wire, performed almost perfectly for 100 years. The I-74 bridges, with galvanized strands, galvanized wrapping wire, but no paste sealer under the wrapping wire, will need relatively minor cable rehabilitation work after 50 years in service.