Studies on the Longevity of Suspension Bridge Cables

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Man has been building suspension bridges for at least 2,000 years; the earliest recorded example going back to 65 A.D. in China. Throughout the centuries, the main tension elements have evolved from primitive organic rope materials to iron chain, eyebars, and finally, wire. Since the first iron-wire cable suspension bridge (built in 1816 at Fairmount, Pennsylvania), the materials, design, and construction procedures have been refined to today's state of the art. We are still learning how well our design and construction methods for these structures will stand up over time. Recent in-depth inspections of three of New York's major suspension bridges have provided valuable information to compare the effects of variations of materials and construction details on the durability of parallel wire cables. The Brooklyn Bridge, possessor of the world's first steel wire cables, is now undergoing rehabilitation that will allow it to continue in service for its second century. The Williamsburg Bridge, which narrowly escaped demolition after a recent study to determine its fate, will have its cables cleaned, oiled, and rewrapped at an estimated cost of more than 60 million dollars. The Mid-Hudson Bridge, youngest of the three, will undergo a detailed study and testing program after strong evidence of stress corrosion cracking was found during a 1987 inspection and confirmed by observations made by Steinman engineers in 1989.

THE BRIDGES AND THEIR CABLES

The following paragraphs provide a brief description of each bridge. Detailed cable information is provided in table 1.

Brooklyn Bridge

The Brooklyn Bridge, which spans New York's East River, connecting Manhattan with Brooklyn Heights, is the most famous of John A. Roebling's suspension bridges. Completed in 1883, the bridge is now a national monument. The exact number of wires in each of the main cables is not known because Roebling called for the addition of supplemental wires after discovering that an unscrupulous contractor had tricked the engineers into spinning some inferior wire into the cables. After spinning, the cables were compacted, coated with a thick paste of white lead, and then tightly wrapped with galvanized steel wire. This was then sealed with several coats of paint.

Williamsburg Bridge

The Williamsburg Bridge, completed in 1903, is within sight of the Brooklyn Bridge, and spans the East River between Manhattan and the Williamsburg section of Brooklyn. Its designer, Lefferts L. Buck, took it as a personal challenge to construct the bridge with a greater main span length than Brooklyn Bridge and to do it in a shorter time at less expense. The cable wire was drawn and cables were spun by John A. Roebling's sons. Buck decided to depart from usual practice where instead of galvanizing the cable wires and wrapping them with wire, the cables were coated with a mixture of graphite and oil, wrapped in cotton duck impregnated with an asphaltic compound, and then covered with sheet steel. By 1921 the sheet steel covering had corroded so badly that it was removed and replaced with galvanized wrapping wire.

Mid-Hudson Bridge

Mid-Hudson Bridge spans the Hudson River at Poughkeepsie, N.Y. It was constructed in 1929-30 by the American Bridge Company. The wire for the cables was supplied by American Steel and Wire Company, a sister organization. This was one of the earliest contracts of bridge wire manufacture and cable spinning undertaken by these companies, a fact that may prove to be significant in the ultimate fate of the bridge. The cables were compacted, painted with red lead, wrapped with soft galvanized wire, and finally coated with three coats of lead-based paint.

TABLE 1. CABLE INFORMATION

CHARACTERISTIC	BROOKLYN BRIDGE	WILLIAMSBURG BRIDGE	MID-HUDSON BRIDGE
Main Span	1,595.5 ft (486 m)	1,600,ft (488 m)	1,500 ft. (457m)
Side spans (2)	933 ft. (285m)	596.5 ft (182m)	750 ft. (229m)
No. of Main Cables	4	4	2
Wires per cable	~ 5,434	7,696	6,080
Wire Diameter	0.180 in (4.57 mm) 0.184 in (4.67 mm) [after galvanizing]	0.192 in (4.88mm)	0.192 in (4.88 mm) 0.196 in (4.98 mm) [after galvanizing]
Compacted Cable Diameter	15.75 in (400 mm)	18.75 in (476 mm)	16.75 in (425 mm)
Average tensile strength of wire	160,000 psi (1,100 MPa)	218,000 psi (1,500 MPa)	215,000 psi (1,480 MPa)
Average 2% offset yield point	106,000 psi (730 MPa)	191,000 psi (1,310 MPa)*	Not Available
Average recovered elongation in 10 inch gage length	2.88%	2.6%	2.5%**
Average reduction in area at fracture	15.6%	20%	23%**
Maximum Working Stress (Nominal)	46,000 psi (320 MPa)	56,000 psi (390 MPa)	56,000 psi (390 MPa)

* Based on limited tests, 1988
** Based on limited tests, 1989

INSPECTION, SAMPLING AND TESTING

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. Based on conditions observed, an in-depth investigation was programmed.

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 7.5 feet (2.3 meters), it was first necessary to remove the suspender and cable band (or cable post in areas where the cable passes below the floorbeams) to provide enough free cable to penetrate with the wedges. Unlike modern practice, the cable bands were installed over the wire wrapping. 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 wires immediately below the wrapping and cable bands had corroded sufficiently to consume most of the zinc galvanization, and rusting of the wires had occurred. One wire broke after losing more than 75 percent of its cross section. 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 (a pit is a defect that is at least as deep as its width at the surface). At the areas between the cable bands, the surface wires were still in excellent condition. Dried white 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 6 inches (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 indicated that the typical corroded wires had not lost measurable strength as compared to the 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 to 0.91 percent, whereas modern wire is generally in the range of 0.78 to 0.82 percent. Average tensile strength was 160,000 psi (1,100 MPa), and the 2 percent offset yield point was approximately 106,000 psi (730 MPa). The most significant finding was that the original wire was of low ductility: reduction of area varied from practically 0 to 26.5 percent, averaging 16 percent (reduction of area for modern galvanized bridge wire is typically 35 percent).

The samples and results of these tests were evaluated by various materials experts, including faculty members of Columbia University and bridge wire specialists at Steinman. While the small reduction of area values indicated low ductility, it was concluded that the wire had not suffered any degradation from its original condition. Fracture surfaces indicated failure by microvoid coalescence originating within the wire. The low ductility was attributed to the coarse pearlite grain structure.

It is interesting to note that Roebling had originally specified that each cable be comprised of 6,308 wires of No. 8 Birmingham Gauge, which would have a diameter of 0.165 inch (4.19 mm), but the cables are actually made of 0.184 inch (4.67 mm) wire. It appears that the larger size wire was obtained by drawing the rolled rod through one die, rather than drawing twice, as would be necessary to produce the smaller wire. The "underdrawing" is considered the primary reason for the coarse grain structure. It is believed the wire size was changed due to difficulties encountered in drawing the smaller wire.

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.

Cables at Anchorages

The initial inspection in the anchorages revealed conditions of serious concern. Here, the cables changed their configuration from a single, large, tightly wrapped cylinder to 19 individual, unwrapped strands of 286 (the generally accepted number) wires each. Each strand further separated into two halves before looping around the strand shoes that are pinned to an eyebar chain buried in the masonry. At the point of transition from one cable to 19 strands, the cable was clamped by a forged steel splay band. Serious corrosion and numerous broken wires were found 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 had barely enough room for a man to pass between the strands and the chamber walls. Therefore, it was impossible to determine the full extent of corrosion damage at the shoes or within close proximity to the splay band. 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. It was therefore decided to develop procedures and equipment to splice entire strands concurrently with developing a detailed program to continue 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 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 never done before. New splay bands and strand spreader frames were also designed. Working in the mock-up, methods were tested for zinc-socketing of the strands in the horizontal, rather than the usual vertical, position. This was achieved by inserting the cleaned strand into a cast steel socket, "brooming" the wires within the socket's conical cavity, and then filling the cavity with molten zinc. To provide working room, the existing anchor chambers would need to be enlarged in width and

height by approximately 3 feet (1 m). Tests on the temporary strand, hold-back clamps, and the poured zinc sockets showed that the strand replacement scheme was practical.

The next step was to enlarge the chambers, relocate the cable splay points, and, if needed, to cut and replace 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 12 feet (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. 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. Fortunately, 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 operation proceeded on to 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. Test results on wire samples from the anchorages were essentially identical to the results obtained from the wrapped cable, indicating no insidious degradation, such as hydrogen embrittlement or stress corrosion cracking. This work was completed in early 1987.

Williamsburg Bridge

Williamsburg Bridge has had a long, troublesome reputation as one of the few remaining suspension bridges in the U.S. with bright (ungalvanized) wire cables. Historical records indicate that hundreds of broken wires had been repaired over its life and several attempts had been made to pour various oils into the cables to stem corrosion. One study conducted in the early 1980's concluded that by 1992, the cables would be unsafe to carry the heavy live loads of the combined truck, automobile, and rapid transit traffic that use the bridge. Since it was recognized that the earlier study relied heavily on theory and was not supported by sufficient hard data, Steinman was requested to perform immediate and in-depth investigations into the condition and capacity of the main cables. As in the Brooklyn Bridge project, separate approaches were developed for the wrapped portions of the cables and the unwrapped, splayed strands in the anchorages.

Wrapped Portions

A few exotic methods were used to evaluate the condition of the main cables, such as geometric survey of cable sag and photogrammetric deflection measurements under controlled live loads. These seemed to indicate that the cables were actually behaving as they should if no significant loss of strength or elastic properties had occurred. The main thrust of the investigation, however, centered around inspection, sampling, and testing of a statistically significant number of wires from the surfaces and interiors of the cables. Using procedures similar to those on the Brooklyn Bridge, five sections of four cables were unwrapped and wedged open. At each 30 to 40 foot (9 - 12 m) long site, the cable was wedged at eight radial locations, penetrating fully through the center. At each opened groove, four wire samples were cut and removed at predetermined depths. The wires were gauge-marked prior to cutting and their retractions were measured after cutting in order to estimate their actual existing tension. These tests generally confirmed that the wires were equally loaded and were under the anticipated theoretical tension.

More than 160 wires, 20 to 30 feet (6 - 9 m) long, were removed and sent to Carleton for metallurgic examination and testing. Each sample was subdivided into 18-inch (0.5 m) lengths which were inspected and graded according to the apparent degree of corrosion. After testing, the wires were cleaned by non-detrimental methods and reinspected. It was generally found that the extent of actual corrosion was difficult to assess prior to cleaning due to a mixture of oil residues that coated the wires. An apparently corroded wire often appeared in excellent condition after cleaning. A computer program was designed to randomly select samples for testing. More than 1,700 specimens were subjected to tensile tests. Their ultimate strength, recovered elongation, and percent reduction in area were recorded. Several specimens were tested expressly to plot representative stress-strain curves. The average ultimate tensile strength of the wires was 218,000 psi (1,500 MPa). The reduction of area at the fracture averaged about 20 percent. The average recovered elongation was 2.6 percent in 10 inches (254 mm). Chemical tests indicated that the carbon content of the wire varied from 0.6 to 1.1 percent. All tensile test specimens were subjected to fractographic examination and selected specimens of wires were sectioned, polished, and examined under a scanning electron microscope. Approximately 160 specimens were subjected to pulsating fatigue tests.

The conclusions drawn from the visual inspection, testing, and statistical analyses were that the cables had only suffered significant corrosion of a small portion of the wires, primarily in the segment of the bottom third of the cable cross-section, where moisture tended to collect and remain trapped. It was only these heavily corroded wires that exhibited serious loss of strength and possible damage from hydrogen embrittlement due to their proximity to the galvanized wrapping wire. A few broken wires exhibited stress corrosion-type penetration, but these wires were also so grossly corroded that they were not in any way representative of the typical wire population. There was no evidence of stress corrosion cracking or hydrogen embrittlement in the remainder of the cables. While the average recovered elongation of the cable wires was substantially lower than the original specifications, it was concluded that they were essentially unchanged from their original conditions. Historical records indicate that the steel billets, from which the wire was made, was of such variable quality that a major lawsuit ensued in which the Roebling Company sought compensation from the steel supplier for the tonnage of wasted material that was not drawable due to excessive carbon content. It is the high carbon content that is responsible for the low elongation of the wire and not environmental degradation as was once suspected. The existing stress range of the cables is well below the apparent endurance limit of the wire. The overall assessment was that

the existing cables still retain an ultimate safety factor of at least 3.5, a larger strength reserve than a modern cable would be designed for.

Cables at Anchorages

There were documented repairs to broken wires in the anchorages performed at various times during the bridge's history. At the time of Steinman's inspection, the area of greatest concern was at the Manhattan end of cable D (the northernmost cable). Between the splay casting and strand shoes, hundreds of broken wires were visible, jutting out in various directions in clusters and individually. It was clear that most of the breaks had occurred near the bellmouth of the splay casting, which was located at the outside face of the anchorage wall. The broken wire ends were, in general, grossly corroded, with some reduced to a "pencil point" at the break. Heavy leakage was getting to the wires, but since the cable and splay casting were obscured at the masonry wall, it was impossible to determine the cause or full extent of the damage. A detailed inspection revealed that strands 19 and 20 had each lost virtually all 208 of their wires.

An important goal of Steinman's cable investigation was to determine the remaining load capacity and safety factor of the existing cable system. Based on conditions observed, Cable D in the Manhattan anchorage was the obvious critical location. Because the deterioration had concentrated at some strands more than at others, it was desirable to determine the actual distribution of load in each of the 37 strands. This would permit the analysis of ultimate cable strength by modelling a sequence of progressive failure of the critically loaded strands. It was also necessary to determine the extent of damage to the cable at the splay point. A procedure to accomplish both of these goals was developed by Steinman.

The 49 eyebars, to which the strands were anchored, were equipped with strain gauges wired to a PC based scanner and data recorder. These gauges would register changes in axial force and bending in the eyebars. The dead load in each eyebar was then determined by attaching an electronic accelerometer that measured the bar's natural frequency of vibration (the bars constantly vibrate on their own), and computing the corresponding tension. Because each group of four strands was anchored to three eyebars, it was not possible to compute individual strand loads directly from the known eyebar loads. Relative loads in each strand were therefore determined by measuring the force required to deflect each strand, horizontally, a set amount. While this would not have been accurate enough to deduce the strand loads directly, it was sufficiently accurate to yield the relative loads. Using the data obtained the actual dead load was determined in each strand with a high degree of confidence.

To determine the condition of the cable at the splay required drastic steps. The anchorage wall masonry was partially removed, enlarging the cable opening to approximately 9 by 12 feet (3 by 4 m). Then at 10 PM on Friday, January 8, 1988, the bridge was closed to all transit and vehicular traffic. With temporary splay castings in place, the original splay casting was removed. By leap frogging the temporary castings in the method developed on Brooklyn Bridge, the cable was gradually spread out, enabling a detailed inspection of the wires previously hidden by the masonry and the splay casting. The eyebar-mounted strain gauges were used to continuously monitor the stresses in the eyebars and strands as the strands were spread apart and the strand shoes rotated. As more wires became visible, Steinman engineers updated the count of corroded and broken wires, and the data was fed into a PC in the anchorage that was programmed to compute the cable's factor of safety. The bridge was reopened to all traffic by noon Saturday. A total of less than 500 wires was found to be significantly corroded. Most of the damage had been confined to a local area at the downhill edge of the old splay casting where water and debris tended to collect. The safety factor of this cable was computed as 3.5.

Mid-Hudson Bridge

The cables of the Mid-Hudson Bridge were inspected in 1969 by means of unwrapping short lengths of both cables near the bridge's mid-point and the south cable near the west anchorage. This unwrapping consisted of the removal of two of the three plies of wrapping wire in order to inspect the main longitudinal wires immediately underneath. Some deterioration of the galvanized coating of the longitudinal cable wires was recorded, together with some areas of steel surface corrosion and light "pitting," primarily on the underside of the cables. The overall condition of the cables was recorded as "generally good."

In 1981 and 1982, various short lengths of wrapping wire were removed to inspect the cable wires at 10 locations. Increased deterioration of the cable wires was recorded near the midpoint of the center span, with lesser amounts of surface corrosion and "pitting" at the other locations. In 1982, approximately 6.5 feet (2 m) of cable was unwrapped between panel points 75 and 76. The cable was probed to a depth of approximately 2.5 inches (63.5 mm) by spreading with wooden wedges to view inner wires. Significant corrosion and "pitting" were recorded on the outer four layers of wire.

In 1987, at eight locations, one or two plies of the wrapping wires was removed for short lengths. At the midpoint of the center span on the south side, the cable was completely unwrapped for approximately 6.5 feet (2 m). One broken wire was discovered at this latter point, and five wires, each approximately 5.5 feet (1.7 m), were removed from the cable for observation and testing. Laboratory tests undertaken on the five wire specimens included fatigue testing at varying stress ranges, static load testing to failure, fractographic examination of the failed cable wire, and chemical analysis of corrosion product samples taken from the cable wires. Some specimens from the fatigue tests broke at obvious pre-existing crack sites, where penetration of a black corrosion product was readily visible. Microscopic examinations revealed many secondary cracks common to classic stress corrosion cracking.

In 1989, Steinman was asked to assist in a further investigation of the cables, and to provide a report on the observed conditions. The north cable between panel points 75 and 76 was the first section to be unwrapped. Two broken wires were evident in this 15-foot (4.6 m) section. Both wires were in the upper half of the cable and in the outer two layers of wires. The lower half of the cable exhibited fairly heavy corrosion, tending towards the north side lower quadrant. This corrosion was generally limited to the outer two or three layers of wire. There was also evidence of local concentrated corrosion of the main wires at all locations in the cable. This was observed in stages, from small local black corrosion products to larger areas of localized section loss, all on otherwise apparently

clean wire. The south cable at panel point 72 was the first position on the bridge to have a suspender and cable band removed. It was centered approximately 40 feet (12.2 m) west of the main span midpoint. Eight broken wires were evident in this 20-foot (6.1 m) length. The majority of these breaks were in the lower half of the cable, and in the outer two or three layers of wires; but one broken wire was recorded at approximately 3 inches (76.2 mm) into the cable (12 o'clock opening). The lower half of the cable exhibited heavy corrosion on the outer layers of wires, which penetrated the cable up to three wires deep. There was also local concentrated corrosion of the wires, from surface black marks to deep local depressions, with black corrosion products showing up in the depressions. This corrosion was present, in varying degrees, at all positions in the cable.

When the cable band was removed from the cable, a section of seizing wire (5 or 6 turns) was discovered under the center line of the cable band. The cable bands were fabricated with a groove passing all around the cable presumably to accommodate this seizing wire. However, the wires of this short section were heavily corroded, and each of the main cable wires in contact with this seizing wire had a spot of corrosion at or adjacent to the contact point. The caulking of the circumferential edges of the cable bands was originally done using lead wool. The samples of lead wool that were observed after the cable band had been removed, appeared to be porous and not fully compacted. This is conducive to the absorption of moisture by capillary action.

The north cable at panel point 125 was the third site chosen. This location is approximately at the two-thirds point of the east side span measured from the east anchorage towards the east tower. It was the last position to be inspected. The suspender and cable band were removed, the cable was unwrapped for approximately 10 feet (3 m) on either side of the suspender center line, and the cable was wedged at selected positions around the perimeter. Three broken wires were recorded. The locations of the breaks corresponded with the positions of the upper location lugs of the cable band at the downhill position. It is possible that these wires were crimped during the assembly and the tightening of the cable band. A section of seizing wire was located at the center line of the cable band, with corrosion similar to that described for the south cable, panel point 72. The main cable wires on the uphill (west) side of the cable band location were in fair condition with some moderate corrosion on the lower half of the outer layer of wires. The cable surface under the band location, and downhill from the band location, was heavily corroded over a large section of the outside surface. Corrosion was also observed in the grooves introduced by the wedges. The worst visible corrosion was on the top surface of the cable for some 8 to 10 feet downhill from the cable band location. There were no wrapping wire indentation marks in the heavy brown corrosion products that were found downhill from the cable band, which would indicate that the wrapping wire was not tight. The local concentrated corrosion, previously described for panel points at the north and south cables, was also evident at this panel point. Again, it was observed generally at all positions within the cable, but the majority of cases were adjacent to the heavy corrosion areas. Lengths of the broken wires have been removed for physical and chemical testing and fractographic analysis.

CABLE REHABILITATION PROGRAMS

Brooklyn Bridge

There were several factors that influenced the scope of rehabilitation for the Brooklyn Bridge cables. Contrary 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 downhill on the cable because their design precluded a secure clamping effect. The original white lead paste was dried out and did not provide the necessary sealing between the wrapping wires. It was also found 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 near or below the roadway and are subject to splash by runoff water and deicing salts, the cables will be wrapped with 1/8 inch (3 mm) thick neoprene wrapping material. All eight anchorage chambers have been enlarged. They 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 shows that the cutting of threads on existing wires is difficult and uncertain, a length of damaged wire is first cut out and to its two ends new wires are spliced using specially designed ferrules. These ferrules consist of a mild steel cylinder, approximately 3/8 inch (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 wire to be stressed to a predetermined tension. After repair of the damaged wires, the cables are virtually as strong as when they were originally built.

The entire cable rehabilitation contract, including the replacement of stays and suspenders, will cost approximately $50 million, and is scheduled for completion in late 1990. It is fully expected that the rehabilitated Brooklyn Bridge will serve New York City for at least another 100 years.

Williamsburg Bridge

The Williamsburg Bridge obviously has not fared as well as Brooklyn Bridge. Unfortunate decisions made during the original design and later modifications resulted in a much less durable cable construction. The original decision to use bright

wire rather than galvanized now appears to have been "penny wise and pound foolish." Because hot dip galvanizing of bridge wire tends to lower its tensile strength by a few percentage points, Buck reasoned that he could design his cables with fewer wires and thus save money. The bright wire is also less expensive, pound for pound, than galvanized wire. While Buck's original sheet steel wrapping was a dismal failure, the error was not fully corrected when the cables were rewrapped in the 1930's. At that time, the cables were oiled, wrapped with galvanized wire, and painted. An important fact was overlooked - to be fully effective, wrapping wire must be bedded in a sealing compound such as red lead paste in order to fill the interstices between wires and to seal out moisture. Additionally, modern cable bands have grooves at their ends for the installation of caulking material and they include drainage openings to allow the escape of condensed open moisture. The cable bands of Williamsburg had no caulking grooves and no drainage openings, which let water enter, but not exit. Compounding the problem, the galvanized wrapping wire in contact with bright cable wire sets up a galvanic cell. While the zinc protects the steel from corroding, the electrochemical reaction produces hydrogen atoms at the surface of the steel, capable of penetrating into and embrittling the material.

Conditions in the anchorages varied. In the worst case (Cable D on the Manhattan side), localized corrosion had destroyed nearly all 208 wires in strand 20 and over half the wires of strand 19. Relocation of the original splay casting at this cable revealed that the damage had mainly been limited to the anchor-side strands. The wires under the wrapping, spanward of the splay casting, were found in generally excellent condition. Other anchorages contained some broken and corroded wires, but to a much lesser extent. Rehabilitation of Williamsburg's cables will require removal of all wrapping wire, cable bands, and suspenders. New properly designed bands and suspenders will be installed, after which the cables will be cleaned, oiled, and compacted. Bright steel wire wrapping, bedded in red lead paste, will be applied. The wrapping wire will be overwrapped with neoprene. This dual system will ensure that the cables remain tightly compacted and protected from water entry. Strands 19 and 20 of Cable D at the Manhattan anchorage will be cut and replaced with new strands using the procedures developed during Steinman's work on Brooklyn Bridge. The remaining deteriorated wires in all the anchorages will be repaired individually by splicing. Providing that the rehabilitation program is promptly carried out and the cables are properly maintained in the future, there is no reason that the Williamsburg will not serve for another 100 years. On the basis of our findings, the New York City and New York State Departments of Transportation have discarded two contingency plans: 1) to demolish and replace the entire bridge; and 2) to replace the main cables and rehabilitate the superstructure. The present plan to rehabilitate the cables is estimated to cost approximately $50 million, but will save more than $200 million, the amount needed to recable the bridge.

Mid-Hudson Bridge

Visual inspections of the cables indicate that the wrapping wire system on the main cables was inadequately installed, as red lead paint, instead of red lead paste, was used to coat the main cables. This has resulted in the formation of linear voids between the wrapping wire and the main cable wires which act as capillaries to absorb moisture in the event of any water getting past the wrapping wires. Existing documentation indicates that wrapping wire was installed to a tension of only 95 pounds (423 N). It is very likely that this tension relaxed significantly over time, as witnessed by the observed looseness. The caulking at the ends of the cable bands also seems to have been inadequately installed. This resulted in a spongy lead wool matrix which, contrary to the design intent, absorbs moisture through the porous lead wool instead of acting as a moisture barrier. This has been compounded by the lack of red lead paste between the cable band and cable, resulting in voids which allow the passage of moisture into the cable.

An important characteristic of the wire samples was the presence of many short transverse cracks on the inside curvature of wire No. 4 (6 o'clock position), taken from the north cable at panel point 125. This sample was stripped of its zinc coating to expose the as-drawn wire surfaces. The cracks could have been formed during wire drawing due to excessive cold working conditions, poor lubrication, or some mechanical defect on the hot-rolled rod surface. With regard to the manufacturing process of the wire, the reported practice of drawing down from a 0.625 inch diameter rod to a 0.192 inch diameter wire, a reduction of some 90 percent in area, is markedly different from accepted practice for bridge wire, which would normally be drawn from a 0.360 inch diameter rod, giving a reduction of some 72 percent. The 90 percent reduction would result in a far higher degree of cold working, giving a resultant loss in ductility. However, no figures are presently available for the wire ductility in the form of percentage elongation and cross-sectional area reduction on static load test specimens.

The preliminary conclusions concerning the cable manufacture are that the wires comprising the main cable have been subjected to excessive cold working which caused the formation of small transverse cracks on the surface of the wires. It appears that the zinc coating penetrated into the cracks during galvanizing. This would tend to embrittle the material at the crack tip. These cracks and the excessive cold working combine to make the wire distinctly susceptible to stress corrosion cracking. The present condition of the cable is a mix of galvanized wire and wire made bare by the loss of zinc due to oxidation. This mix of zinc and steel creates the potential for the formation of corrosion cells throughout the cable, which may generate hydrogen penetration into the wires. The hydrogen embrittled areas may in turn promote the stress corrosion cracks that have been found. It is suspected that each of the black spots observed throughout the cables may be a potential crack site.

This information isn't sufficient to draw definite conclusions regarding the status of the main cables, but the available evidence strongly indicates that stress corrosion is occurring. A detailed, rigorous, and methodical cable wire investigation will therefore be undertaken in order to determine the present capacity of the cables and their predicted life. The detailed investigation will include statistical wire sampling, at selected points along the cables, and a full program of laboratory testing of wires in order to establish a firm data base. The New York State Bridge Authority, along with its general consultant, began this investigation in early 1990. Steinman will continue to provide technical consultation as the work progresses.

CONCLUSION

The Brooklyn Bridge provides indisputable proof that Roebling's original cable protection system is effective when executed properly. However, the legendary degree of care and a number of other factors that went into the construction of this bridge make these cables unique. Each wire was coated with an oil/white lead mixture first in the shop, and again in the field before being loaded in the spinning apparatus. The strands were again coated prior to compacting and wrapping the cables. This formed an impervious mass that would resist moisture penetration even if the wrapping was not fully effective. Great care was then taken in compacting and wire-wrapping the cables. What little moisture did enter the cables over the past century was effectively handled by the galvanizing on the main wires. The net result is that the wrapped portions of the cables are still practically as good as new. In the anchorages, the unprotected strands had corroded. Much of the original zinc coating had oxidized and there is presently a mix of bare and galvanized wire near the strand shoes. However, the investigation has shown that the wires have not suffered any degradation of their physical properties. Although there has been the potential for hydrogen embrittlement and stress corrosion, no evidence was found. While hydrogen may well have been generated during the corrosion process, it may have dissipated over time. Since the Brooklyn Bridge wires are of relatively low strength and carry relatively low stress for bridge wire, they may not be susceptible to stress corrosion cracking nor sensitive to hydrogen penetration.

While the cables of the Williamsburg Bridge were not protected nearly as well as those of the Brooklyn Bridge, they have also survived in remarkably good condition after almost 90 years. These wires were also coated with various oils and binders during the manufacture and spinning, including lin seed oil and slushing oil mixed with graphite. The wrapping system did not effectively exclude the intrusion of water, and many wires did corrode. However, the significantly damaged wires were confined to those areas where water collected, and the oil apparently was effective in the other parts of the cables. In general, the damaged wires suffered from metal loss due to corrosion, with no embrittlement or cracking or change in physical properties. Samples of the bright wire that were in close proximity to the galvanized wrapping did appear to have lower ductility then the general population, and this is attributed to possible hydrogen embrittlement. Although this wire is nearly as strong as modern wire, its working stress is only 25 to 30 percent of its ultimate strength, a factor that would usually preclude stress corrosion cracking.

The Mid-Hudson Bridge is the most modern of the three, and the original specifications for its cable wire is very similar to present day specifications. However, the practices used in its manufacture are suspect and may have been misguided. The wire wrapping system is also similar to the system used on Brooklyn and subsequent bridges, but its execution appears to have been lacking in the application of a thick bedding compound, tightness of the wire, and caulking at the cable bands. The bridge wire received no oil or other coating over the galvanizing. Water freely penetrates these cables and the galvanizing has not been able to protect the interior bridge wires from corrosion. The surface defects created in the wire drawing compound the situation. All these factors together set the stage for stress corrosion cracking throughout the bridge's cables. Only further study will reveal the ultimate prognosis for the Mid-Hudson Bridge.