EVOLUTION OF PARALLEL WIRE CABLE CONDITION ASSESSMENT – A CASE STUDY

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ABSTRACT

Approximately 29 bridges with aerially spun parallel wire cables were erected by the end of the twentieth century. Today most of these bridges are over 65 years old and some are over 100 years old. Because some inspections have led to concern regarding the condition of the cables, an interest in methods of evaluating the condition of the main cables has arisen. The purpose of this paper is to illustrate how assessing the condition of a parallel wire main cable has evolved over the past 40 years using the results of an ongoing cable investigation of a 78 year old suspension bridge located in the Hudson River Valley of New York State. A description of the approaches used, as well as the results of a multi-phased investigation and cable rehabilitation project is presented.

INTRODUCTION

Approximately 29 bridges with aerially spun parallel wire cables were erected by the end of the twentieth century. Now that most of these bridges are over 65 years old and some are over 100 years old, the need to evaluate the condition of the main cables is receiving more and more attention. As will be presented in this paper, the New York State Bridge Authority, headquartered in Highland, New York has taken a long-term, proactive approach to cable condition evaluation.

The first limited inspections of the interior of the cables began in 1969 as part of a general condition inspection of the bridge. This is believed to be one of the first condition inspections of the main cable of a suspension bridge. Similar inspections were also conducted in 1981 and 1982. These inspections were limited to the exterior wires of the cable and were accomplished by removing the wrapping wires over very short distances. However, in 1986 the Authority was considering a proposal to add a second deck to the bridge. This led to two preliminary and one detailed cable-condition investigations; Phase I, performed in 1986; Phase II conducted during the period of 1987-89 and Phase III, a detailed investigation of 20% of the length of the main cables begun in early 1990. Finally in 1991-1992, a cable rehabilitation contract, designated as Phase IV, was performed for the remaining length of the cable. Subsequent to Phase IV there have been two, five-year follow up inspection of selected panels of the cable; one performed in 1998-99 and the other in 2003-04.

This paper will present a general summary of the information gathered about the main cables, methods of cable inspection and the general results of the laboratory-testing program that have been performed to date. Prior to discussing these items, a brief description of the bridge and information about the actual construction of the main cables will be presented. To aid the reader, a drawing showing location of the key components of a suspension bridge is shown in Figure 10 at the end of this paper.

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DESCRIPTION OF THE BRIDGE

The total bridge length of the Mid-Hudson Bridge between anchorages is 914.4 meters (3,000 ft.), with a main span of 455.7 m (1,495 ft.) and side spans of 228.6 m (750 ft.). The bridge was the sixth longest suspension span in the world when completed in 1930.

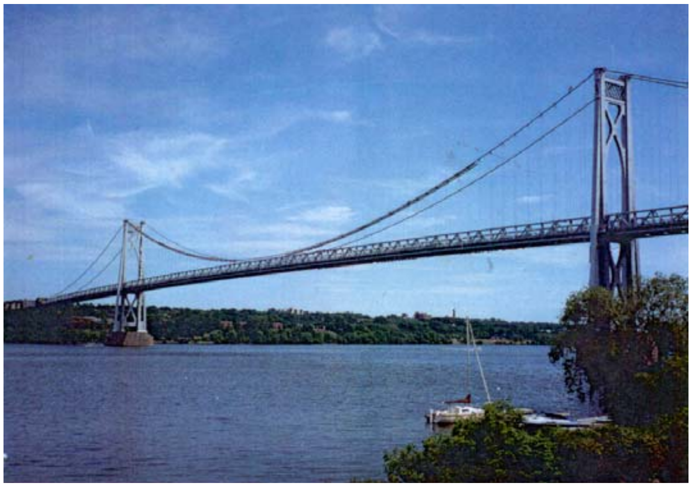

FIGURE 1 – GENERAL VIEW OF MID-HUDSON BRIDGE

Each main cable is composed of 6,080 parallel, No. 6 galvanized cold drawn wires manufactured at the Trenton Plant of the American Steel and Wire Company. The individual cable wires were constructed into 19 strands; each containing 320 continuous, endless wires looped around strand shoes at each anchorage. After the wires in each strand were spun and adjusted, the 320 parts were compacted by special hand tongs and seized with tin bands at 1.5 meter (5 ft.) intervals. The compacted cables, excluding the protective wire wrapping, are 425 mm (16-3/4 in) in diameter and about 1,000 meters (3,286.5 ft.) long between anchorages.

The wire was specified to have a modulus of elasticity of 186,000 MPa (27,000,000 psi) and a minimum ultimate strength of 1,480 MPa (215,000 psi). The diameter of the bright wire, prior to galvanizing, was specified to be 4.9 mm (0.192 in.), with a tolerance of 0.076mm (0.003 in.) Tests performed on the wire indicated the actual diameter of the galvanized wire varies between 4.88 mm (0.192 in.) and 5.00 mm (0.197 in.). The wire was originally manufactured in coils of 762 meters (2,500 ft). After galvanizing, the wire was spliced to lengths of 30,480 m (100,000 ft.) and wound with uniform tension on wooden reels, 1.83 meter (6.0 ft.) in diameter, for shipment to the bridge site.

Construction of the bridge superstructure by the American Bridge Company commenced on April 2, 1929, and was completed near the end of August, 1930, when the bridge was opened to traffic. The construction period was about 17 months.

Spinning of the main cables occurred over a 13-week period, beginning on December 2, 1929. This phase of the work was performed through the winter months. Final wrapping and painting of the cables was not completed until August, 1930; therefore, some portions of the main cables were exposed to varying environmental conditions for a period of about 8 months. The construction procedures used for spinning the cables were the methods commonly used for building suspension bridges in this era.

Upon completion of the spinning process, all the adjusted strands were compacted to a cylinder 425 mm (16-3/4 in.) in diameter using two triangular framed yokes. Each yoke contained three 267,000 N (30-ton) hydraulic jacks. The cable was compacted at intervals of 900 mm (3 ft) and seized with eight turns of soft wire until final wrapping. Prior to compacting the cables, the tin seizing bands on the outer strands were removed as much as possible.

The next phase of the cable construction was to place the 282 cable bands on the compacted cable at the desired locations. Prior to placement of the cable bands, the cable was cleaned and coated with red lead. The cable bands were secured with six to ten 44.5 mm (1-3/4 in.) diameter bolts. The longitudinal joints between casting halves were caulked with oakum, saturated with red lead and closed with caulked lead. After all the steelwork had been erected for the bridge, the main cables were protected between cable bands by painting with red lead and machine wrapping with 3 plies of No. 9 soft annealed galvanized steel wire. The electrically operated wrapping machines were to maintain a tension of about 495 N (100 lbs) on the wrapping wire. Short sections of the cables adjacent to the cable bands and the backstay sections at the anchorages were wrapped with hand-operated devices. The completed cables were painted with three coats of lead and oil paint.

CABLE INSPECTIONS

PHASE I – PRELIMINARY INVESTIGATION

As stated earlier, short lengths of the cable were unwrapped in 1969, 1981 and 1982. The 1969 openings indicated little if any corrosion. The areas unwrapped in 1981 and 1982 revealed indications of more active corrosion. In November 1986, nine main cable locations were selected for unwrapping and examination. These locations were at the low points, near mid-length between low points and the towers, and in the west anchorage adjacent to the splay castings. One or two plies of wrapping wire were removed over a length of 100 to 350 mm (4 to 14 in.) at the locations, to view the outer wires (see Figure 2). White zinc corrosion residue and brown and black steel corrosion residue were found in varying degrees at eight of the nine locations. The corrosion products were confined to the very bottom, and/or the lower northern sides of the cable circumference. There was some minor loss of wire section, in the form of flat spots or “pitting", noted on some of the outer wires.

The exposed wires at the selected location near the mid-point of the south cable in the center span (low point) were observed to be more extensively corroded than the wires at the other locations. As shown in Figure 3, a decision was made to unwrap a length of 2.0 m (6-1/2 ft.) at this location and probe with wooden wedges. The cable was probed with hardwood wedges at four positions on the circumference; the top, bottom and sides. The wedges were driven to a depth of 50 to 75 mm (2 to 2-3/4 in.). Extensive corrosion of the zinc coating was observed on the outer wires between the 2:00 o'clock and 9:00 o'clock positions on the cable perimeter. The most significant wire section loss was observed on the underside of the cable at the location of the black residue formed by the corrosion process. The visible surfaces of the outer wires on the upper portions of the cables appeared in good condition; however, the red lead coating on the wires was dry and brittle and could be easily brushed from the cable. White zinc oxidation residue from the galvanizing was noted on all visible interior wires at the four positions probed. Some brown steel corrosion residue was noted on interior wires at three of the four positions, but no significant loss of wire section or broken wires was visible.

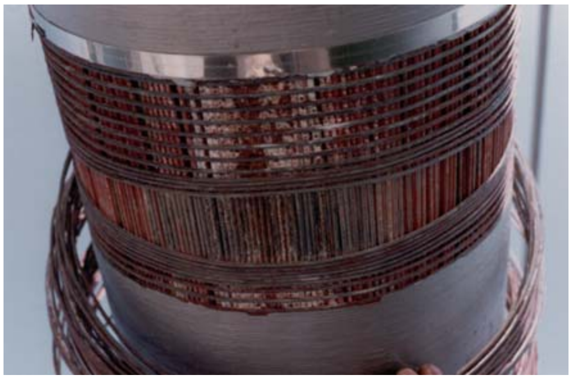

FIGURE 2 – PARTIAL REMOVAL OF WRAPPING WIRES – NOTE CORROSION RESIDUE

FIGURE 3 –EXPANDED INSPECTION AREA - NOTE CORROSION RESIDUE

Shortly after the start of rewrapping operations at the center span location, an outer cable wire broke on the inboard side of the cable perimeter at about the 4:00 o'clock position. Examination of the fracture surfaces revealed black corrosion residue on over 50 percent of the wire cross-section. The remaining portion of the fracture surface appeared clean and brittle in nature. The portion of the wire fracture surface with the black residue was originally located toward the center of the cable and not visible during the initial examination. Both ends of the fractured wire were removed from the main cable for additional evaluation, and an additional five wires, approximately 1.7 m (5-1/2 ft.) in length, were removed at various positions on the cable perimeter for additional observation and testing. This was the first instance that a main cable wire was found broken on the bridge.

A significant observation made during the examination was the presence of circumferential cracks in the paint coating on the wrapping wire. Since construction, the cable surface had been repainted many times with oil-based paint, resulting in an increased thickness. The minimum paint thickness over the wires was measured between 0.7 and 0.8 mm (27 and 32 mils), and between the wires, 1.1 mm (45 mils). The underlying older layers of paint had become brittle, and the cracks developed as a result of the normal movement of the cable under load and temperature. It was noted in subsequent inspections that the cracks reappeared soon after each painting.

PHASE II – 1987-89 - PRELIMINARY INVESTIGATIONS

In 1987 and 1989, five additional locations on the main cables were unwrapped over varying lengths and the wires spread with wooden wedges driven to depths ranging from 60 to 150 mm (2-1/2 to 6 in.). At two of the locations, a suspender rope and cable band were removed for the inspection. The suspender ropes were replaced with new ropes. The original ropes were tensile tested in the laboratory and found to have satisfactory remaining strength.

The field observations were generally the same as those noted in 1986; the most significant corrosion residue and wire deterioration existed on the lower half of the cable perimeter with some steel surface corrosion visible on the inner wires. The average loss of wire diameter due to corrosion on the outer wires at the bottom of the cable sections was approximately 0.38 mm (15 mils). The average depth of section loss on the inner wires was measured to be about 0.13 mm (5 mils), and the maximum cavity depth was measured to be about 0.76 mm (30 mils) (see Figure 4). These inspections revealed that corrosion had affected wires throughout the cable cross-section in a non-uniform manner. Deterioration ranged from minor oxidation of the zinc coating on the wires to local depletion of the zinc and steel corrosion causing uniform loss of section in the form of flat spots or local cavities, accompanied by a black corrosion product. Broken wires were discovered both internally and on the cable circumference while unwrapping or driving the wooden wedges.

The fracture surfaces of the broken wires were similar to those discovered in the earlier examinations, and were characteristic of stress corrosion cracking (see Figure 5).

FIGURE 4 – REPRESENTATIVE CORROSION "PIT"

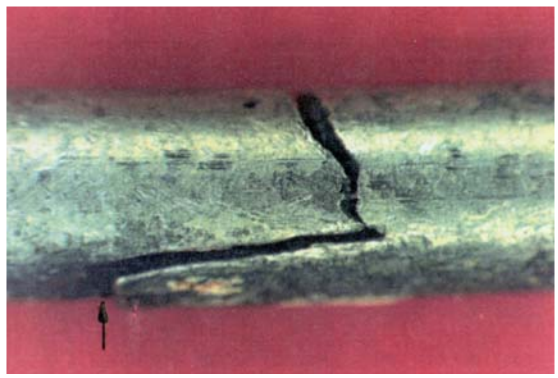

FIGURE 5 – TYPICAL FRACTURE

The greatest concentration of localized cavities or pits on inner wires was noted on the upper half of the cable cross-section. These pits appeared to occur on the upper surfaces of the wire at locations that trap moisture between the wires and were located more toward the center of the cable.

The fractographic examinations performed on the broken cable wires removed from the cable indicated the failures were most likely the result of stress corrosion cracking. Stress corrosion cracking is defined as the formation of a crack due to the combined effects of corrosion and high tensile stress. High-strength steel, such as bridge cable wire, is subject to stress corrosion cracking in an environment of moisture and anions, such as chlorides, sulfates and nitrates. The presence of significant amounts of these anions was found in the corrosion product and/or water samples analyzed in the laboratory. These contaminants were most likely brought into the cable by rainwater penetrating cracks in the paint coating.

The chemical composition of the wire was found to be within original specifications, and the average tensile strength of 1,470 MPa (213,200 psi) was close to the 1,482 MPa (215,000 psi) minimum specified. The total elongation in a 10-inch gage length for the tensile specimens generally ranged between 2-1/2 and 3 percent. This percentage is less than the 4 percent originally specified; however, the average percent reduction in area (23 percent) was close to that specified for wire placed in other bridges constructed in the same era. The detailed examination of the wire fracture surfaces revealed characteristics that strongly suggest stress corrosion cracking as the mechanism of crack propagation, although corrosion fatigue characteristics were observed on the surfaces.

A recommendation was made to perform a large-scale examination of the cables for the purpose of establishing a comprehensive base condition and to perform more extensive laboratory testing and analyses of wire samples. It was concluded that the data obtained from a more thorough, systematic investigation would help to formulate a better judgment regarding the future service life of the cables, and allow the rate of deterioration to be determined after future examinations.

A recommendation was also made to measure the actual stress ranges in the cable by strain gaging cable elements (wires and anchorage eyebars). Actual stress ranges are typically lower than calculated ranges, thereby improving service life estimates.

PHASE III & IV – 1990-1993 DETAILED INVESTIGATION & .REHABILITATION

In 1990-1992, contracts designated as Phases III & IV, were tendered by the Authority. The purpose of Phase III was to examine approximately 20 percent of main cable length by unwrapping and probing, and to obtain representative wire samples for closer examination and laboratory testing. Fifty-six panels (length of cable between cable bands) were unwrapped and 17 cable bands were removed. At all the unwrapped locations, the cable was probed to a minimum depth of 150 mm (6 in.) towards the center, at a minimum of four positions on the circumference (top, bottom and both sides). Including the perimeter wires, this number of probes exposed about 9 to 10 percent of the cable wire for examination. At the locations where a cable band was removed, the adjacent two panels were completely unwrapped. Therefore, at each of these locations approximately 12 m (40 ft.) of continuous cable was exposed for examination. Following the completion of Phase III, Phase IV was begun resulting in the remaining panels of the cables were unwrapped, inspected, oiled, and a new type of cable protection applied.

The primary goals for performing these Phases were as follows:

1. Determine if the cables were in short-term danger and estimate the Factor of Safety.
2. Determine if traffic-related fatigue was an important parameter in the development of wire cracks.
3. Determine the cause(s) of the wire corrosion and cracking.
4. Provide a planning level estimate of remaining cable life and recommendations for future maintenance and repairs.
5. Establish a database for comparison with future cable inspections to begin to establish the rate of deterioration.

During and after a cable length was prepared for examination by the contractor, the following data was recorded by the engineer;

1. The presence of moisture and the types and limits of corrosion product on the cable circumference upon initial unwrapping (white, black, brown or orange corrosion residue).

2. The point of fracture of all broken wires, with respect to location along the cable, position on the circumference and depth in the cable.
3. The length of the gap between broken ends of wires.
4. The nature of the wire fracture surfaces, with regard to type of corrosion product present, and the orientation of the initial point of fracture with respect to the wire curvature.
5. The extent of corrosion and wire section loss, especially the size of pits or cavities on internal wires.

Field Observations

The field inspection confirmed the findings of the earlier examinations that the exterior and interior longitudinal wires of the cable bundle had suffered deterioration in a non-uniform manner throughout the majority of the cable length. The condition generally ranged from wires that had no apparent deterioration to wires that had random loss of the zinc coating and steel (ferrous) corrosion, resulting in uniform loss of section, pits or cavities, cracks and failures.

A very small percentage of wires were observed to have failed. Of the approximately 60 single panels (5.8 m (19 ft.) ± between cable bands) of cable unwrapped and examined in Phase III, only five or more broken wires were found in three panels of the north cable and nine panels of the south cable. The maximum number of in-service broken wires found in a panel was 16. Approximately 50% of the broken wires discovered were located on the bottom surface of the cable, and the remaining were found located throughout the other portions of the cross-section. Examination of the fracture surface of the in-service broken wires revealed that nearly all the wires contained a heavy black oxidation residue on at least 50% of the surface, indicating this portion of the crack existed for a significant number of years (see Figure 8). The remaining portion of the fracture surface for a majority of the broken wires was judged to be moderately or lightly corroded. This area indicated the fracture had occurred in the more recent past. The exact age of the initial crack areas, or the final fracture areas could not be determined. The in-service broken wires exhibited very little, if any, reduction of area (necking) at the fracture sites.

The broken wires had no significant offset between ends. This suggests that the wires are redeveloping load by friction with other wires and are not unloaded for a very long length. The condition of the cable wires under the cable bands, collars and rocker casting covers was no worse, and, in most cases was better than the general condition of the wires between cable bands.

Apparent Cause of Corrosion

Deterioration of the wire galvanized coating and ferrous corrosion of the wire is attributed to moisture penetrating the cable cover and moisture vapor condensing within the wire bundle. The infiltration and concentration of pollutants from the air has increased the corrosive effect of the moisture. Laboratory testing revealed the amount of zinc originally deposited on the wires complied with the original specifications.

The initiation sites for cracks in the wire were found at locations where the zinc coating was depleted and ferrous corrosion was in progress, but were not found at deep pits or cavities in the wires. All crack initiation sites were located on the inside of the wire residual curvature (See

Figure 6). This is most likely related to the additional tensile stress caused by straightening the wire.

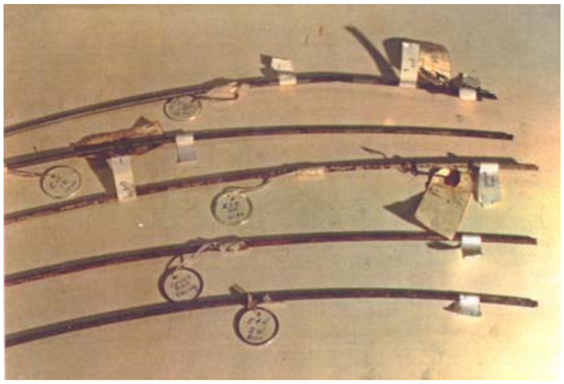

FIGURE 6 – SAMPLES OF REMOVED WIRE (NOTE RESIDUAL CURVATURE)

FIGURE 7 – NOTE CRACKS ON INSIDE FACE

Remaining Fatigue Life

The remaining fatigue resistance of the wire determined from the laboratory fatigue tests, compared with the very small effective stress range found by strain gaging the cable wires under normal car and truck traffic patterns, indicated that the load-induced, and otherwise unassisted fatigue, is not a significant factor in the development of wire cracks.

FIGURE 8 – TYPICAL FRACTURE SURFACE

FIGURE 9 – VIEW OF CABLE BOTTOM, NOTE THE PRESENCE OF MOISTURE

Apparent Cause of Wire Cracks

The most probable cause for cracking in the wires is environmentally induced corrosion. A combination of stress corrosion, corrosion fatigue and hydrogen embrittlement mechanisms are involved. Field observations of the fracture surface shapes and the fractographic studies support stress corrosion and/or corrosion fatigue mechanisms for crack propagation. There has been no evidence found to indicate that the chemical composition of the wire and/or metallographic aberrations specifically initiated wire cracking.

The environmental cracking process cannot be totally stopped as there are certainly additional latent defects developing in the cable. However, it was felt that the rate of deterioration could most likely be decreased by limiting the amount of moisture and pollutants contacting the wires and retarding the corrosion process with inhibitors.

Tensile Tests

In this phase of the investigation, tensile testing was conducted on 15 short samples (each between 500 and 660 mm (20 and 26 in.) in total length) and 53 long samples (ranging between 4.6 and 11.9 m (15 and 39 ft.) in total length). Due to failures below the yield point or the minimum ultimate strength of nine long samples, an unbroken end of these samples was retested. Two samples were tested three times. A total of 64 long specimens were actually tensile tested. Although the long specimen tensile test is not a standard test, the probability of revealing defects in the wire is higher than by using a similar number of short tensile tests.

The tensile specimens failed over a wide range of stresses, depending on the wire condition. Wires with little or no deterioration and no initial crack areas generally failed above the original minimum ultimate stress of 1,480 MPa (215 ksi) and showed normal ductility for cable wire manufactured during the era this bridge was constructed. Of the approximately 46 specimens that failed below the minimum ultimate stress, 25 specimens failed at areas of significant uniform corrosion or cavities, but not at an initial crack area. The average failure stress of these wires was approximately 1,395 MPa (202 ksi), ranging from a low of 1,100 MPa (159 ksi) to a high of 1,635 MPa (237 ksi). These wires also exhibited good ductility. Twenty-one specimens failed at an initial crack in the wire, covered with black oxide. These wires failed at an average stress of 1,080 MPa (157 ksi). The failure stress ranged from a low of 642 MPa (93 ksi) to a high of 1,395 MPa (202 ksi). The wires with initial cracks exhibited negligible ductility at the failure location. A majority of the wires that failed at initial cracks were wires that had been removed from the bottom surface of the cable. Nearly all the specimens that were not removed from the bottom of the cable failed at a stress above 1,300 MPa (188 ksi). The strength testing revealed that the corrosion pits in the wire were not as significant as the crack sites.

Estimated Current Factor of Safety

The maximum stress in the as-built cable was calculated to be 380 MPa (55.7 ksi) under dead load existing in 1987, live load and temperature change. This corresponds to an initial Factor of Safety in the cable of approximately 3.9.

Since there was no industry accepted method of determining the remaining strength of parallel bridge cables at this time, the Factor of Safety was estimated by conservatively reducing the number of effective wires in the cable cross-section and the minimum allowable ultimate stress. The method and assumptions used were based on the field observations and laboratory test results and are as follows:

1. At the panel with the highest number of visible broken interior wires (Panel 121-122, south cable), the percentage of broken wires was projected to the remaining cable cross-section. This resulted in a reduction of 222 wires.
2. The 222 broken wires were assumed to be ineffective over a length of three panels. This amounts to an additional reduction of 444 wires.
3. The outer three layers of wire in the bottom segment of the cable and the remaining perimeter wires were assumed ineffective, due to cracks and section loss. This amounted to an additional 414 wires.
4. The maximum allowable strength of the remaining effective wires was reduced to 1,311 MPa (190 ksi).
5. The sagged shape of the cable causes the tensile force to vary slightly along its length. The maximum cable force was used in this projection.

Applying the above conservative assumptions, the Factor of Safety of the cable was estimated to be about 3.0, a reduction of about 22% from the original. The cable was <u>not</u> in short-term danger.

FIRST FIVE YEAR INSPECTION - 1998

As noted above, one of the recommendations made at the conclusion of Phase IV was that portions of the cable should be reopened in approximately five years. In July 1998, a contract was let with the following scope:

1. Ten sections of the main cable were to be unwrapped and inspected to record the condition of the cable and the number of visible broken wires. The ten sections were selected so that portions of the cable that had been opened in all the previous contracts would be inspected.
2. As in the case of Phase IV, seven lines of wedges were to be driven in the upper portion of each cable panel in order to examine interior wires and to add as much corrosion inhibitor as possible, followed by removal of wedges. In addition, samples were taken at four locations to investigate the possible presence of hydrogen producing bacteria.
3. Recompact the cable wires.
4. Apply red lead paste to the outside of the compacted cable wires, followed by rewrapping.
5. Apply a 2.0 mm (8 mill) wet thickness of “Pegarust®” as a primer coat followed by two coats of “Noxyde®” each 2.0 mm (8 mill) wet thickness.

As was the case in the prevous inspections, it was discovered that the cable condition varied between portions that appeared in very good condition with very little deterioration, and no broken wires, to sections that exhibited deterioration in the form of ferrous surface corrosion, wires with corrosion pits or cavities, and a small percentage of visible broken wires. The more inclined portions of the cable, near the towers and the backstay portions between the rocker castings and the splay castings, were generally in better condition. These sections had less or no wire corrosion product and broken wires when compared to the other sections of the cable.

It was observed that the red lead paste that was placed in Phase IV was dried and quite flaky with the exception of the underside of the cables where the red lead paste seemed to have been soaked with the oil. The strands in the lower portion of the cable were well bathed in oil while those in the upper portion of the cable appeared drier. There was evidence of gel throughout the cable, though the lower half was definitely more protected. Unlike the previous phases, no water or moisture was discovered at any of the locations opened.

Results of Bacterial Testing

Because of recent concern regarding the possibility that bacteria living in the suspension bridge cables could be a source of hydrogen, tests for the presence of such bacteria was performed. The results of those tests, performed by Lehigh University, indicated that sulfate-reducing bacteria that would result in hydrogen production are not likely present.

Conclusions

Based on the examinations of the ten panels opened under this first five year inspection, the following conclusions were drawn:

1. Previous contracts had been effective in sealing the cable from water intrusion. No water was discovered in any of the panels opened under this contract.
2. The red lead paste placed under Phase IV was already dry and flaky and separated easily from the wires. Consideration should be given to an alternate material.
3. The corrosion inhibitor placed in the earlier contracts seemed to be performing its intended function. There was reasonably good coverage in the lower portions of the cable cross-section. There was limited coverage in the upper portions of the cable.
4. Active corrosion appeared to have been stabilized. An insufficient number of panels were opened to draw an absolute conclusion regarding this issue.
5. Wire breakage did not appear to have increased; however, the number of broken wires found during each contract cannot be rigorously compared because of different inspection procedures.
6. Bacterial testing revealed no reason to suspect the existence of sulfate-reducing bacteria that would result in hydrogen production.
7. Additional panels of the cable should be opened in five to six years for inspection and monitoring of the wire condition.

SECOND FIVE YEAR INSPECTION -2003

In 2003, Modjeski and Masters began the second five year inspection of selected portions of the cables. This inspection continued through 2004. A contractor was hired to provide equipment, labor and materials to:

1. Unwrap 11 panel sections of the main cables.
2. Classify the exposed wires using the Hopwood scale in anticipation of the use of NCHRP 534 for determining factor of safety at some point in the future.
3. As in the case of Phase IV and the first five year inspection, drive seven lines of wedges in the upper portion of the cable, assist the on-site engineers in the inspection of the exposed interior wires, and add 16 gallons of corrosion inhibitor, followed by removal of the wedges at each cable panel to be investigated.
4. Re-compact the cable wires.
5. Apply a zinc-rich paste, “GRI-KOTE Z®, complex 2C”, a substitute for red lead paste, to the outside periphery of the cable followed by rewrapping the cable sections.
6. Apply a 2.0 mm (8 mill) wet thickness of “Pegarust®” oil-based primer followed by two coats of 2.0 mm (8 mill) thickness of “Noxyde®” paint.
7. Check the tension in the existing cable band bolts at each of the two ends of each of the 11 panels (22 cable bands).

On site engineers recorded the condition of the cable and wires, took wire samples, and recorded the number of visible broken wires.

As in the previous cable investigations, the cable condition varied between portions that appeared to be in very good condition with little deterioration and few broken wires to portions that exhibited corrosion, section loss and pitting with a small percentage of broken wires.

The red-lead paste that was placed under the previous wrapping contracts was generally dry and brittle. There were two locations previously re-wrapped under Phase III, where the red-lead paste was found to be relatively soft and pliable. In general, the interior wires appeared to have been well bathed in Prelube® at one point, but the remaining Prelube® residue was somewhat pasty or gelled.

Unlike the previous five year inspection, water was found at four panels: three of the six panels of the south cable, and one of the five panels of the north cable. In the first location water was found to be trapped between the wrapping wire and the red-lead paste coating the main wires. At the second location a very small amount of water was found within the interior upon wedging (at one of the top set of wedges). At the third location, up to one gallon of water was found trapped within the upper cable band. At the forth location water was found running from the lower cable band upon unwrapping and where there was extensive corrosion on the wires at the underside of the panel.

Various levels of Stage 3 corrosion (brown rust on the individual wires of up to 30% of the surface area) were found at most cable panel sections. There were some isolated areas of Stage 4 corrosion (brown rust on areas of individual wires covering over 30% of the surface area accompanied by section loss). Areas of Stage 3 and 4 were more predominately found in the sections of the south cable that were closer to the low points of the cable (mid-span and near the back-spans). Panel sections on the north cable tended to be in better condition than those on the south side.

Also as found under previous investigations, the greatest concentration of wire corrosion product was found on the bottom surface of the cable between the cable bands. This is the area where moisture has historically collected and remained in contact with the wires for longer periods of time.

Areas where the red-lead paste was either thin or not present (gaps in the lead paste cover) were also areas where corrosion was more prevalent. The exterior cover of red-lead paste that was placed under the previous wrapping contracts was generally dry and brittle. There were two locations, previously re-wrapped under the first five year inspection, where the red-lead paste was found to be relatively soft and pliable. Because the red lead paste in general was found to be dry and brittle, a zinc-rich paste, “GRI-KOTE Z®, complex 2C”, was used as a substitute for red lead paste on all the panels opened under this phase of the project.

It was common to find a Prelube® residue along the bottom of the cable sections that was visible upon the unwrapping of each section, indicating that the Prelube® had penetrated the various cable sections and settled out along the bottom. In general the Prelube® residue was somewhat pasty or gelled.

Another common finding was a white powdery substance, presumably oxidation residue from the galvanizing, which could be easily wiped away. In general, the galvanizing was splotchy and a darker gray at the exterior of the cable sections with various degrees of oxidation.

Conclusions

Based on the examinations of the eleven panels opened under the second five year inspection, the following conclusions can be drawn:

1. Previous contracts have not been as effective in sealing the cable from water intrusion as originally thought. Water was discovered in several panels opened under this investigation.
2. Though there were two areas that the red lead paste placed under previous contracts remained pliable, most locations, as in the past, were dry and flaky. This confirmed the decision to use the zinc-rich paste, “GRI-KOTE Z®, complex 2C”, as a substitute for red lead paste. Performance should be verified in subsequent inspections.
3. The corrosion inhibitor placed in the earlier contracts seems to be performing its intended function. There is reasonably good coverage in the lower portions of the cable cross-section. There is limited coverage in the upper portions of the cable.
4. Active corrosion continues to appear slowed, but not necessarily stopped due to the intrusion of water.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The nearly forty years of investigations of the condition of the main cables of the Mid-Hudson Bridge, coupled with other investigations not described in this report, have led to the following general conclusions and recommendations regarding parallel wire bridge cables:

- The primary cause of deterioration of main bridge cables is the intrusion of water. Through careful attention to details, the amount of water entering the cable can be limited, but not stopped completely. Therefore efforts such as those made on the Akashi Bridge to dehumidify the interior of the cables appear to be a promising approach for newer bridges.
- Since much of the damage experienced by wires comprising cables is the result of hydrogen embrittlement and stress corrosion cracking and since it is generally accepted that there is a relation between these two phenomena and high sustained loading, additional research needs to be performed in this area. Many of the newer suspension bridges in the world are using higher strength wire carrying higher sustained loads than the bridges built in the early part of the 20th century.
- Suspension bridge cables should be inspected on some regular basis. The method and procedures used from bridge to bridge should be standardized in order for results to be compared. A method to do this was outlined in NCHRP Report 534 – “Guidelines for Inspection and Strength Evaluation of Suspension Bridge Parallel-Wire Cables” released in late 2004.

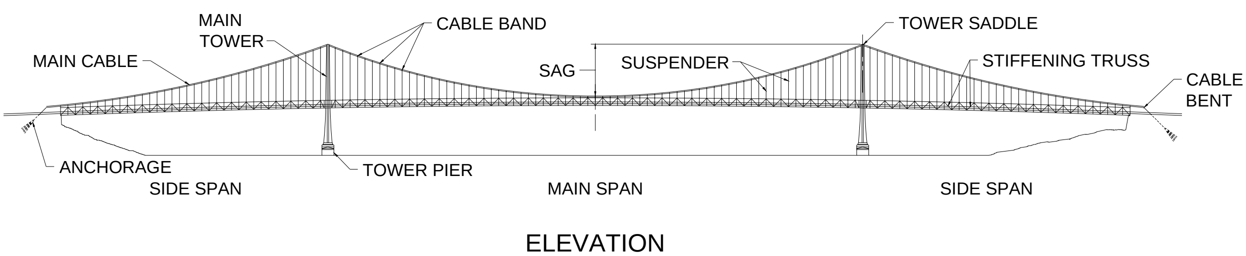

FIGURE 10 – GENERAL ELEVATION IDENTIFYING THE MAJOR COMPONENTS

NEXT STEPS AT THE MID-HUDSON BRIDGE

The third five-year inspection of the cables at the Mid-Hudson Bridge is presently scheduled for tender in the spring of 2009. The determination of the remaining strength of the cable will utilize the methodology outlined in NCHRP 534. The data used in the application of NCHRP 534 will come from both the second and third five-year inspection.. When finished the condition of the cables of the Mid-Hudson Bridge will be one of the most historically documented in the world. Just as the methods used to inspect the cables have changed with the passage of time, the determination of the condition of the main cables continues to change and improve as assessment methodology evolves.