Transportation

Kentucky Transportation Center Research Report

University of Kentucky Year 1984

Inspection, Prevention, and Remedy of Suspension Bridge Cable Corrosion Problems

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INSPECTION, PREVENTION, AND REMEDY OF SUSPENSION BRIDGE CABLE CORROSION PROBLEMS

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and

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May 1984
This report discusses methods for visually inspecting cable suspension bridges for corrosion damage. The report discusses how to plan and perform such work, including the locations on cables where corrosion damage is likely to be detected. The report also provides recommendations for assessing the condition of suspension bridge wires. Recommendations also are included for remedial cable repair work should corrosion damage be detected.
The authors would like to thank Mr. Jackson Durkee, P.E. of Bethlehem, PA, for his review of this manuscript.
INTRODUCTION

This is the last of three reports concerning suspension bridges and corrosion. The first report (1) contains background information on suspension bridges including typical corrosion prevention methods employed to protect bridge wire. The second report (2) addresses corrosion mechanisms and contributing factors that lead to corrosion problems in suspension bridge wire.

Many findings of the second report are relevant to this report. The more applicable findings include the following:

1. Bridge wire is subjected to corrosion cracking in common industry-affected atmospheric environments (i.e., the presence of some source of atmospheric sulfur).

2. Galvanized helical strand deteriorates (corrodes) in four stages:
   a) In Stage 1, wire surfaces have a shiny metallic appearance, though some signs of white zinc corrosion product may be visible in spots.
   b) During Stage 2, wire surfaces dull as the zinc corrodes. The wires eventually are covered with the white corrosion product. However, there is no ferrous corrosion under the white corrosion product.
   c) In Stage 3, signs of ferrous rust are visible on wire surfaces. The zinc coating is almost completely consumed. Random wire is cracking possible in this stage.
   d) During Stage 4, ferrous rust stains or displaces most of the white corrosion product on wires. Wire surfaces become very rough and pitted. Wire cracking is anticipated at this stage of deterioration.

3. Long-term contact with atmospheric moisture promotes wire deterioration and cracking processes.

4. Galvanizing on the wires must be locally depleted by other corrosive mechanisms prior to corrosion cracking.

At the time of the second corrosion-related cable problem on the General U. S. Grant (US 23) Bridge over the Ohio River between Portsmouth, Ohio, and South Shore, Kentucky, most authorities responsible for maintenance of cable suspension bridges were somewhat unaware of potential problems posed by cable corrosion. Some had performed internal inspections of main cables or suspenders. However, most authorities were satisfied with external visual inspections and, perhaps, occasional painting of cables.

Unfortunately, information concerning bridge corrosion problems is sparse. Therefore, suspension bridge authorities have lacked guidelines for inspecting and maintaining their structures. The purpose of this report is to provide broad recommendations for inspecting suspension bridges in a thorough yet economical manner. This report also contains preventative and remedial maintenance procedures, when problems are detected in the cable corrosion protection system or when the wires are damaged by corrosion. When consultants are used to perform cable inspections or to recommend additional maintenance, this report should provide bridge engineers with a basis for determining the adequacy of
that work.

Three suspension bridges over the Ohio River were inspected during the course of this work: the General U. S. Grant (US 23) Bridge at Portsmouth, Ohio; Roebling's Ohio Bridge (KY 17) at Covington, Kentucky; and the Maysville Bridge (US 68), Maysville, Kentucky. The General U. S. Grant Bridge (hereinafter referred to as the Portsmouth Bridge) was inspected during its closure, prior to the second cable replacement operation on that bridge (1978-79).

PROBABILITY OF DAMAGE
OR FAILURE DUE TO WIRE CORROSION

To conceptually assess the possibility of corrosion damage to bridge wires and eventually to the structure itself, it is of benefit to examine a common service-life chart (Figure 1). The dished-out shape of the curve defines survivability of the structure with time. That curve, also called the "bathtub" curve, demonstrates that a period of low failure probability is bounded by areas of higher risk.

Because of the relatively low number of cable bridges (suspension and cable-stayed) in service and the relatively few corrosion failures, ordinate values are not indicated. However, the probability of bridge failure or closure due to major corrosion problems would not exceed one or two percent, worldwide, based on historical data.

Shortly after a cable structure is completed, it may be severely damaged, or fail, due to a poorly designed or improperly applied or installed corrosion-protection system. Included in this would be a failure to accommodate, by design, for an unusually corrosive environment such as that at the Lake Maricaibo (Venezuela) Bridge. Other examples include the Hidalgo-Reynosa Bridge (Hidalgo, Texas) collapse (1939), the early Roebling-bridge anchorage-corrosion problems, and the Portsmouth Bridge first cable corrosion problem (1940).

Commonly this type of failure is not directly related to poor maintenance, but rather to poor maintainability. In the case of the Hidalgo-Reynosa Bridge, the anchorages were buried in concrete and subsequent corrosion damage was undetectable. On the Kohlbrand Bridge (Germany), potential corrosion problems were detected early, but follow-up remedial work was ineffective. The fault with that structure probably was in initial design features, including the use of bare wires.

The span of "incubation" failures in suspension bridges usually is not more than 15 years. Delineation between that type failure and the horizontal portion of the curve is rather arbitrary for large and infrequently constructed structures such as suspension bridges. It is obvious that for small temporary bridges such as short-span, unstiffened suspension bridges in eastern Kentucky, a short incubation life would be expected since the anticipated service life is also brief.

In the horizontal "expected-life" portion of the curve, failures (or corrosion problems) may be termed "catastrophic failures." Such failures are commonly attributed to poor maintenance and inspection. However, design and construction factors usually contribute to those problems. Maintenance and inspection may only prevent such problems from becoming severe. Examples of "catastrophic" bridge problems include the Silver Bridge at Point Pleasant, West Virginia (not
Figure 1. Generalized Service-Life History of Suspension Bridges.
Those failures occurred some 40 years after the main structural elements (eyebars and cables) were installed. Those bridges were not exceptionally old for suspension bridges nor were they considered approaching the end of their useful service lives (the restored Portsmouth Bridge is now in full service). Based on histories of the Wheeling and Ohio (KY 17) bridges, the "expected life" of a suspension bridge may approach or exceed 200 years and may be limited in utility only by the structural capacity of the bridge. However, maintenance must be ongoing for structural preservation.

It is important to consider those factors that control "on-line" corrosion failures of suspension bridge wires. This report will offer a basis for remedial and preventative measures for cable-wire corrosion, with the aim of extending the safe service lives of suspension bridges.

In the past, main cables have been commonly protected by a two-stage corrosion protection system consisting of a wrapping system (usually galvanized wire wrapping and common structural paint) and a zinc coating on the wires. As indicated by the Portsmouth Bridge cable corrosion problems (1940 and 1978), there obviously are limitations with the system.

Conventional wire-wrapping systems result in the hundreds of miles of potential seams. If the wrapping wire becomes slack, due to poor construction or thermal expansion, the seam will open, allowing water to enter the cables. More likely, corrosion of wrapping wire on the upper portion of the cables will create passages for rain to enter the cables. Common structural paint is somewhat permeable and, more importantly, it possesses poor flow characteristics once it has set. Any disturbance in the underlying wrapping wire will cause the paint to fracture, creating a gap. This allows moisture to contact the wrapping wire and possibly enter the main cables.

Unfortunately, breaches in the upper portion of the wrapping system often do not possess corresponding failures on the lower portion of the cables. Entrained water is retained by the wrapping on the underside of the cables and capillary action in the wire strands. Generally, water will gravitate to lower portions of the cables unless it is removed by an effective drainage system or is retained by capillary action in the strands.

If the conventional cable corrosion-protection system is to be effective, cables must be inspected frequently for signs of damage on the upper wrapping surfaces. Also, cables must be painted much more frequently than normal structural members. Some larger suspension bridges have maintenance crews regularly assigned to cable maintenance and painting.

It should be noted that, prior to the third cable installation on the Portsmouth Bridge, the cables on that structure lacked handrails. Maintenance personnel could not walk the cables to assess the integrity of the wrapping. Instead, they were forced to visually inspect the cables from the towers or from the bridge deck. At the time of closure (1978), the Portsmouth Bridge wire wrapping showed an extensive level of deterioration that was not properly evaluated from those distant inspections.

Durability of cable wires depends greatly upon the integrity of the wire galvanized coating. The coating is affected by moisture and...
corrodants that may enter the cables and be retained. Moisture entrainment may occur in several different ways.

Water may be trapped in the cables during construction, prior to completion of the wrapping process. Small amounts of moisture may be entrapped in helical strands or on the wire surface prior to the wrapping process. This may be important, since initial corrosion activity can affect subsequent corrosion behavior of the wires.

Prior to the second cable replacement of the Portsmouth Bridge, chaulky random patches of white rust were visible on new strands sitting on reels, though the bulk of wire was in a Stage 1 condition. Those patches were in early Stage 2 deterioration. Ungalvanized wire, used in a Kentucky-owned post-tensioned segmental bridge, was observed on reels, prior to installation, covered with ferrous rust. It would be desirable to protect such wires with waxes, paints, or slushing oils at the wire manufacturing plants to minimize such occurrences.

Openings in the cables, designed or otherwise, may allow moist air to enter. During cool periods, such as evenings, moisture can condense on the cables and subsequently evaporate during the warmer daylight hours. Sheltered surfaces such as interiors of cables become wet less frequently than fascia surfaces due to condensation/evaporation cycles. However, sheltered surfaces require more time to dry and subsequently may have a longer time of wetness. Evaporation of condensed moisture from inside cables is affected by conduction, convection, and radiation. Angles of exposure to sunlight have an important influence on the time of wetness. In some cases, the resulting corrosive action has been more severe than total immersion (3). Increasing accumulations of corrosion products and other detritus on the wires promote condensation. That increases the time of wetness of the wires and may tend to increase the severity of any corrosive mechanisms.

The third possibility is the direct entrainment of large quantities of water due to failures in the cable wrapping. In that case, the time to failure of the wires will be rapid once the wire zinc coating has been consumed. The longer entrained water is retained in close contact with the wires, the greater the chance for corrosion cracking (Figure 2). Also, large quantities of retained water will continuously condense and vaporize, due to extreme daily temperature fluctuations within the cables. That action will create large areas of Stage 3 and Stage 4 deterioration on the strands and segments of strands adjacent to those that are continually immersed. The entrainment of large quantities of moisture leads to the cathodic protection action of the galvanizing and the resulting cathodic charging of hydrogen into wires at locations where ferrous corrosion is occurring.

When only average amounts of atmospheric moisture contact the wires, the depletion rate may be similar to average corrosion rates observed in direct atmospheric exposure tests conducted by various technical societies (4). Class A galvanized coating has a maximum coverage of 1.0 ounce of zinc per square foot of uncoated wire. In rural atmospheres, zinc will deteriorate at a rate of 0.06 ounce per square foot per year, yielding a minimum safe life of 17 years. That estimate appears conservative based on previous inspections of the exposed helical strand on small, unstiffened suspension bridges at Tram and Sutton in eastern Kentucky. In an industrial atmosphere, the rate may increase to between 0.1 to 0.4 ounce of zinc per square foot per year, yielding a short safe life. That indicates the need to preclude entrainment of atmospheric
Figure 2. Portsmouth Bridge Cable, Main Span, Downstream, Showing Results of Wrapping Failure (1979).
moisture and corrodants in the cables.

Sulfur gases and acidic industrial pollution have the most detrimental effect on galvanized coatings. Galvanizing also will corrode abnormally in contact with water that does not have access to free air. While corrosion of steel usually is more pronounced at higher temperatures, zinc corrodes more rapidly in the winter, especially in the presence of sulfur compounds (5).

"On-line" failures may be expected in older bridges employing marginal designs or materials. That type failure may have occurred on the Charleston, West Virginia, suspension bridge in 1904. Many suspension bridges constructed around the time of the Civil War were allowed to corrode and decay to the point of closure at the turn of the century. However, by that time, the bridges were functionally obsolete. That also has been the fate of the Laub-built suspension bridges in the Ohio Valley in more recent times.

ASSESSMENT OF CONDITION OF SUSPENSION BRIDGE WIRE

A suspension bridge may contain miles of main cables. Superficially, the prospect of cable inspection and wire assessment would appear to be a formidable task. However, with the proper approach, the work may be completed in a minimum amount of time and at a reasonable cost. That may be achieved by careful initial visual inspections of exterior cable surfaces followed by selective internal examinations pinpointed by the initial inspections.

The exterior condition of cable wrapping will have a direct bearing upon the integrity of the underlying wires. Gaps or cracks in either the upper portions of the wire wrapping or band packing may allow rainwater to penetrate the cables and initiate corrosive attack of the wires.

Small-scale failures (Figures 3 and 4) in cable corrosion protection systems can degenerate rapidly, leading to massive water-entry problems. As noted in an article on the Kohlbrand Bridge (6), "The coating (plastic) originally showed only hairline cracks. Later, though, rain soaking in from the top permeated the cables 'like a drain-pipe' from the top to bottom."

Those gaps can be observed readily in wire wrapping as radial cracks in the wrapping paint on the top portion of the cable. Such disturbances can be detected by inspectors walking the cables. Another sign of potential problems is deterioration of paint on the upper portion of cables due to either wrapping wire corrosion or poor maintenance painting. Gaps in the band packing may occur with time, due to either relaxation (stretching) of cable-band retaining bolts or by service-induced compaction of the strands. Most band packing on older suspension bridges is driven lead wool that does not have the ability to flow with slight changes in the band-gap separation.

Other superficial irregularities on the undersides of cables may indicate locations where corrosion damage is probable. Rust or rust stains on the undersides of cable wrapping may be a sign of either poor maintenance painting or corrosion of the main cable wires. In either case, those locations merit more extensive examinations. Such signs are usually not evident unless severe corrosion damage has taken place.
Figure 3. Early Paint Failure on Topside of the Cable Wrapping; Maysville Bridge (1980).

Figure 4. More Extensive Paint Deterioration on Cable Wrapping; Maysville Bridge (1983).
When a large quantity of water is entrained in the cables, water stains may also be evident on the lower portions of the cables (Figure 5). Another less obvious indicator of corrosive attack is chipping of paint on the undersides of cable wrapping that may be covered with paint from recent topcoats (Figure 6). On the bottoms of cable bands, rust stains emanating from the packing or between the band edge and wire wrapping, loose or dislodged band packing (packing pop-outs) (Figure 7), and dripping water from band areas are signs of candidate locations for wire assessment. To detect water dripping from cables, it is advisable to inspect cables on a day following a heavy rain. That can be accomplished from the bridge deck using a pair of high-powered binoculars.

Provision for drainage in caulking on the undersides of vertically split bands has been an inconsistent practice in the past. Some suspension bridges have drainage gaps at every band location. Others have gaps at the lowest points in the main span. Still others have none at all.

Debris may flow down to bands from more elevated portions of cables. That action may cause small drain holes to become clogged, rendering them ineffective. Since corrosion products and other debris may bridge or clog drain holes, the function of small drains should be questioned. When stable caulking exists on the underside of cable bands, water may still be retained in the band area and wire corrosion damage may occur adjacent to and under those bands. Possible warning signs in those situations are rust stains or chipped paint, as previously enumerated. At least a few of those locations should be included in any wire-corrosion assessment.

The following observations may be useful in planning more extensive cable wire examinations:

1. Water entrained in cables will generally settle to low points of cables (i.e., to points near midspan and near cable bents. When cable deterioration is severe, those general locations probably will show the most extensive cracking, except for points under cable bands.

2. Locations along main cables near towers usually will be in better condition than lower portions of the cables. There are several reasons for this. Since there are fewer panel lengths of cable above those locations, there is little chance for water drainage from higher points. Also, due to the greater cable inclination, entrained water would be held in strands by capillary action for a shorter time than at less inclined locations.

3. At cable locations intermediate between greatest cable inclination and horizontal lay, band drain areas and the upper surfaces sides of the cable wrapping should be closely examined before selecting wire-corrosion assessment locations. When no significant exterior signs of damage are evident, a few intermediate locations should still be subjected to wire-corrosion assessment. Recent painting of cables may hide many potential signs of wire corrosion.

4. Wire damage by uniform corrosion, and perhaps cracking, may be
Figure 5. Water Stain on the Underside of the Downstream Cable; Maysville Bridge (1983).

Figure 6. Signs of Paint Chipping, Lowerside of the Downstream Cable; Maysville Bridge (1983).
Figure 7. Pop Out and Rust Stain on Cable Band of the Maysville Bridge (1980).
more severe on one end of the bridge near a more pollution-prone environment or oriented northward (Figures 8 and 9). In the latter case, those northward portions of cables will have a longer time-of-wetness (7).

Once an exterior survey of cables has been completed, a decision can be made regarding the extent of wire-corrosion and number of locations required to obtain an accurate picture of the wire condition. If the enumerated indicators are not present, at least four locations (between intermediate and horizontal cable lay) per cable should be inspected. Cable damage along the Portsmouth Bridge second cables varied due to random failures of wrapping and cable drains (Figure 10).

To properly assess the corrosion condition of wires in main cables, direct visual inspection is necessary. That requires removing the main cable cover, which is usually wrapping wire. The Kentucky Department of Highways inspection port is a useful tool for performing internal inspections. Ports are placed over the wrapping and become permanent installations on the cable (Figure 11). They eliminate the necessity for unwrapping an entire panel length of cable covering to inspect interior wires.

After an inspection port is installed, the lid on the bottom of the lower cover half can be removed for periodic inspections, allowing a good view of the lowest cable stands. Occasionally, the drain plug can be removed to determine the extent of moisture leakage into the cable (after a rain, or randomly to inspect for condensation).

The condition of the wire is closely related to the quantity of water entrained in the cables. Moisture contact is exacerbated by debris and surface rust on the wires. Wire failure due to corrosion cracking will begin once a certain level of deterioration is reached. The main objective of wire-corrosion assessment is to inspect cables, determine the level of degradation, and conduct required remedial work before the critical level of deterioration is reached. The rapid increase of corrosive cracking on the Portsmouth Bridge second cables detected by inspections from 1975-1978 verified the need for detailed internal inspections.

At locations other than bands, corrosive damage generally will be worse at the lowest portion of the cable at the bottom most, outer strands (at points along the panel between bands). At locations where cable inclinations are greatest, the lowest portion of the cable, along the panel, will usually show the "worst-case" cable deterioration; however, that is not always true. For uniform corrosion damage, this would be correct, except for lower cable band locations where no damming has occurred at a lower band drain. In those instances, corrosion damage may be more severe at the more elevated band. There only nominal draining might take place across a dammed upper band drain. At such locations, the time of wetness will be greater than on the lower band, especially at the lower outer strands at points situated just below that more elevated band.

When a localized inspection of cable between the panel points reveals a critical level of wire degradation, further inspections should be conducted on areas adjacent to, and possibly lower than cable bands that adjoin a panel segment of cable where critical wire corrosion is first detected. Portsmouth Bridge inspections indicated those locations would be among the first to exhibit corrosion cracking. An easy method
Figure 8. Portsmouth Bridge Second Cables, Main Span, Downstream, Facing North (1979).

Figure 9. Portsmouth Bridge Second Cables, Main Span, Downstream, Facing South (1979).
Figure 10. Corrosion Survey on the Portsmouth Bridge Prior to Recabling in 1979.
NOTES
1. SPOTTED RUST ON ALL PORTIONS OF CABLE.
2. ONLY SPOTTED RUST ON LOWER PORTION OF CABLE.
3. SECTIONS MONITORED BY MODIESKI AND MASTERS & ODOT PRIOR TO CLOSURE.
4. CABLES FROM SPLAY SADDLE TO ANCHOR ASSEMBLIES IN GOOD CONDITION.
5. UPPER STRANDS IN GOOD CONDITION.

LEGEND, CABLE COND. PRIOR TO BAND REMOVAL.

- BREAKS, N=QTY, M=20+.
- RUST.
- NO RUST, SLIGHT ZINC CORROSION.
- ZINC CORROSION.
- SEE NOTES.

Figure 10. (continued)
Figure 11. Inspection Port for Access to Interior of a Main Cable.
of inspecting those areas would be to remove packing (caulking) on the underside of the cable bands. Then, the strands or wires on the bottom of the cables could be inspected visually (possibly with the aid of a borescope). Packing on the underside of the bands serves no good purpose and may be harmful. The lower caulking should be removed from each band to provide for improved drainage. Some cable-band designs have lips on one band-half that may render this work ineffective.

When corrosion damage is detected at an inspection port prior to completion of the installation, inspection-port bands may be removed and the wrapping stripped from the cable for the entire panel length. Then, a corrosion assessment can be made on the cable segment exposed along the entire panel and adjacent to the bands. Wire wrapping may be replaced with a neoprene sheet/chlorinated rubber paint system or new wrapping wire when corrosion damage is not sufficiently severe to warrant further remedial action. While cable wire is unwrapped, the strands or wires may be pryd apart, using brass or wooden wedges to avoid damaging the wires. Then, some of the interior strands or wires may be visually inspected. The interior strands and wires will probably be in better condition than the outer lower strands and wires.

Wire breaks may be more difficult to detect in parallel-wire cables than in helical-strand cables. Broken wires in a helical strand will splay outward due to residual stresses imparted during fabrication. To check for broken wires in parallel-wire cables, the following steps are suggested:

1. Make a prying tool from a medium-sized screwdriver. Grind the tip of the screwdriver to a chisel point and then slightly round the sharp edge. Other edges of the screwdriver also should be slightly rounded to avoid damage to wires.

2. Locate areas of obvious wire corrosive damage on the lower portion the strand. Look for zinc corrosion product "white rust", ferrous rust, and dark spots on the lower outer strands (Figure 12). Also, examine the wires and strands of recently unwrapped cables for signs of dampness. Along the panel length, test locations adjacent to the cable bands.

3. To check for breaks, insert the screwdriver between the wires. Some light rapping with a hammer at the base of the handle may be required. Once the screwdriver tip has penetrated into the wire bundle about the length of one wire diameter, the inspector should attempt to gently pry the wire outward away from the strand. If the wire is almost or completely cracked, it should break free, exposing the fracture.

If wire breaks are encountered at one location, there is a good probability that similar breaks will be present along adjacent panel lengths and possibly at similar locations on the other main cables.

At the anchorages, the first place to look for signs of corrosion is at the splay saddle (Figure 13). Entrained water may settle to the saddle and wash corrosion products onto the splayed strands inside the anchorage. The second important location is at the anchorage assembly. Excessive corrosion or broken wires inside strand socket assemblies may warrant remedial work. For conventionally spun parallel-wire strands, tangent points at the mounting shoes and looped portions of the strands should be closely inspected. No attempt should be made to pry the wires apart at those locations. Broken wires at the tangent portion of the
Figure 12. "Dark Spot" on the Maysville Bridge Cable at an Inspection Port.

Figure 13. Splay Saddle inside Anchor House of the Maysville Bridge.
strands should readily fray outward from the strands. It may be desirable to temporarily remove nonessential seizings near those locations to determine whether wires have broken.

Moisture conditions in the anchor houses and the level of corrosive degradation of wires inside the anchorages should be noted. When signs of wire corrosion damage and excessive anchorage moisture are both present, remedial steps should be taken. Even when corrosion damage is limited to a few wires, the seriousness and potential for further damage should not be underestimated. At those locations, coatings that may retain moisture should not be employed.

Corrosion stages for galvanized parallel wire are the same as for helical strand. Bright uncoated wire will show uniform corrosion (rust) or a dark surface corrosion product prior to corrosion cracking. With uncoated wire, the greatest damage will probably be loss of section rather than corrosion cracking. Wrought-iron wire also will be more prone to corrosion damage resulting in loss of section.

Visual inspection will provide sufficient insight into the condition of main cables in most circumstances. In some cases, the use of other corrosion-monitoring techniques may be desirable. Sometimes chemical analyses of entrained water samples to determine the presence of unusual corrodament or metal ions may be useful. Probes may be embedded in cables to provide remote monitoring of electrochemical potentials that might reveal uniform corrosion or a potential for corrosion cracking. Other types of remotely monitored probes can detect the presence of moisture in cables and measure the time of wetness. Galvanic current tests also would provide similar useful information (8). Resistivity tests may be useful for determining the impermeability of nonmetallic cable-wrapping systems (9).

Nonvisual, nondestructive test methods also may be employed to inspect wires, ropes, and strands. However, those methods have not been frequently employed. Radiography has been used to detect fatigue cracks in small electrical cables (10). That method would be difficult and expensive for inspecting main cables. X-ray computed tomography (CAT scanning) shows potential for inspecting wires at end-fitting locations (11). Ultrasonic testing of wires using rod waves generated by magnetostrictive excitation is possible. Pulse-echo testing using angle probes also is feasible. However, very little work has been done in those fields (12). Eddy-current methods possibly may be useful in detecting cracks and measuring metallic coating thicknesses. Equipment capable of performing this general type of work has been developed, though no specific wire tests have been reported. Magnetic-flux methods have been used to detect cracks on mine and elevator wire ropes. That equipment has been in use for several decades and may be of interest for tests of newly fabricated wires and structural strand and also for suspender strand and ropes (13). Literature mentions that magnetic tests were employed on the heat-treated wire used in the Mt. Hope and Ambassador bridges (14). However, there is no record of subsequent use of that method on cold-drawn wire.

Another technique that has potential is acoustic-emission testing. This method has been used to monitor cables of a lift bridge in California and also has been employed in tests on wire rope (15). Recent field work has demonstrated the suitability of an advanced acoustic emission system for detecting cracking in areas of high mechanical noise (16). That work has shown that acoustic emission
methodology may be applicable to test problem locations difficult to monitor by visual examinations (i.e., main cables under bands and on suspender ropes at end fittings).

Other specialized forms of corrosion monitoring that may prove useful include electrical resistance and electrical potential tests (17, 18). Those methods would measure changes in resistance and voltage due to the presence of cracks or loss of section along wires. Additional research is needed to determine the suitability of any of the aforementioned nondestructive methods to test wires.

In the event cracking is detected at locations outside the anchorages, it would be imperative to unwrap large portions of the cable and inspect for further wire breakage. At that time, assessment of the general wire condition (Stages 1-4) throughout the cable would probably be more important in determining the nature of future remedial action than would be the extent of the wire breakage (which will probably be concentrated on lower strands, except at cable bands).

Unwrapping main cables should not be avoided for fear of damaging underlying wires. If the wires have experienced Stage 3 or worse corrosion, no further damage may occur in a reasonable time period. When a single panel length of cable is completely unwrapped, it may be desirable to erect a temporary cover using plastic sheet and steel bands. That cover would not have to be stout nor would it have to be completely waterproof.

REMEDIAL AND PREVENTATIVE MEASURES

Once the condition of cable wires has been completely assessed, the structural integrity of the bridge may readily be determined. When a large number of wire fractures is detected, and when many of the remaining wires are subject to Stage 3 and Stage 4 corrosion, it may be advisable to consider closing the bridge and condemning or recabling it (as with the Portsmouth Bridge).

In their report on the Portsmouth Bridge second cables (19), the Battelle investigators stated that, even if a large quantity of entrained moisture could be prevented, the action of the corrosion products on the unbroken but corroded wires on the main cables of that bridge would be hydroscopic (water absorbing) and those corroded wires would eventually fail. The Battelle researchers were of the opinion that corrosion products had already been laced with crack-producing corrodatants. They suspected that condensation-related moisture would be sufficient to interact with the corrodatants in the existing corrosion product and with applied stresses, causing failure. Residual stresses imparted in the helical stranding operation were considered debilitating by the Battelle investigators.

If the bulk of the wires in main cables show Stage 2 corrosion, even when some advanced corrosion and broken wires are detected on lower strands, the condition of the bridge may not be critical. This is especially true of bridges that have large-diameter main cables. If bright-steel or wrought-iron wire is present, corrosion cracking may not be as significant as loss of section due to uniform corrosion. However, when some wire-corrosion damage is evident, a need for prompt remedial work is indicated.
The object of remedial work is to prevent further entrainment of water in the cables and possibly to preclude atmospheric moisture from condensing on the wires. Also, in the case of parallel wire cables, it may be desirable to repair breaks by splicing new wire segments. That has been done in several instances, most recently on wires of the Wheeling Bridge (20).

If corrosion damage is evident, it must be assumed that the cable wrapping or upper band packing has failed. Therefore, those leaks should be sealed or new wrapping or packing should be installed. A decision on the extent of work may, in part, be based on finances available and also on the condition of the wrapping system and packing in place. If the wire wrapping system is badly corroded, it may be desirable to replace the wrapping with a neoprene/chlorinated-rubber system (21). If the present wrapping is in good condition, it may be useful to clean the wire wrapping by abrasive blasting and subsequently coat it with a paint system possessing good sealing and flowing properties, such as acrylics or high-build chlorinated rubbers (22). The paint should be light-colored to maintain a cooler temperature inside the cable. That would suppress ferrous corrosion reactions within cables during warm periods.

Prior to other remedial work, it may be desirable to renovate the bands. First, band bolts should be retorqued. Lead-wool packing on the topside of the band should be redriven and/or replaced or top-coated with high-grade silicone caulk (Figure 14). On the underside of horizontally split bands, a large drain hole should be created in the space between the band-halves by removing most of the lead-wool packing or caulk (Figure 15). Edges between the wrapping and bands should be resealed by redriving the lead-wool or more preferably by using a silicone caulk. Prior to caulking, the bands should be cleaned by abrasive blasting and top coated with an impermeable paint system.

It would be desirable to remove excess corrosion products such as white zinc corrosion product and rust. However, if abrasive blasting is employed, care should be exercised to ensure that zinc coating is not removed from good strands and that all debris resulting therefrom is flushed from cables before they are resealed. Perhaps, cleaning with mild acids, such as phosphoric acid, having inhibitors to prevent hydrogen penetration into the wires, might be desirable. That should be followed by washing with a neutralizing solution. Mechanical cleaning would only be effective on the external portions of the outer strands. Liquid cleaning would be more thorough. However, tests would be required to ensure that cleaning compounds would not pose a threat to the wires.

To protect ferrous surfaces exposed after cleaning operations, zinc-enriched compounds or paints could be applied in a touch-up operation. Those compounds are routinely applied on damaged areas during cable installation operations. Inspections of the Maysville Bridge cables revealed that a heavy cover of red-lead paste is an ideal long-term intimate protection for the outer wires and strands of main cables. On older bridges, which originally employed those coatings, the red lead would probably be in poor condition. It would be desirable to rehabilitate those coatings; however, United States EPA regulations may prohibit the use of red lead. The use of zinc-dust primer or zinc-chromate coatings might provide additional protection to corrosion-susceptible outer strands. Another possibility would be to inject
Figure 14. Pliable Caulk Used on the Portsmouth Bridge Third Cable Installation (1979).

Figure 15. Cable Band Showing Lack of Packing on the Lower Gap; Portsmouth Bridge Third Cable Installation (1979).
plastic or other inert compounds into cables to fill all interstices and thus prevent water from contacting the wires, regardless of the condition of the wire wrapping or the band packing. Those compounds have been employed on new bridges, but, probably not on existing structures.

Suspender rope corrosion problems are difficult to correct, and generally that damage is confined to the lower portion of the rope or strand. When wire rope is employed, it would be difficult to completely seal the suspender for its entire length. Chlorinated rubber paints on suspender ropes may not be desirable, since it may retain moisture in the rope or strand and damage the underlying wires. Inspection of suspender rope from the Ohio Bridge indicates proper maintenance painting with common structural paint would preclude corrosion damage.

The key to protecting against corrosion cracking is to prevent corrosion cracks from forming rather than increasing the stress-corrosion fracture-toughness properties of the wires. On new suspension or cable-stayed bridges, the ideal cable protection would provide corrosion "protection in depth" by employing 1) an outer wrapping system that would be essentially moisture impermeable and resistant to atmospheric degradation, 2) a corrosion-inhibiting inner sealant that would fill the interstices between wires or strands, and 3) an intimate coating for each wire that would provide localized protection for those instances when other levels of protection might fail.

On typical modern suspension bridges, main cable wires have two of those three protective systems. In the past, that protection was considered sufficient. However, the service lives of bridges are constantly being extended. Indeed, many large American suspension bridges have probably exceeded their original design service expectations. Due to increasing construction costs, it would be difficult to contemplate costs of replacing many of those old, yet serviceable, structures. For large new bridges, designers should always anticipate service lives extending beyond 50 years. While the initial cost of a bridge with a "protection-in-depth" system may be more expensive than for a bridge employing two-stage protection, benefits in structure survivability and durability would greatly exceed additional initial costs.

Bare wires should never be installed on bridges except where the wires are directly cast into concrete in redundant structural members such as prestressed concrete deck girders. Experience with the Kohlbrand cable-stayed bridge indicated the life of uncoated wires may be relatively short.

While protective metallic coatings such as zinc may have some adverse effects on wire failure, usually that would occur only after years of neglect (23-26). During the same time period, uncoated wires would fail many times over due to general corrosion.

Zinc coating on wire will remain protective as long as it is in the Stage 2 condition. No corrosion cracking will occur, as was noted by Pollard (27). Thereafter, depleted galvanized wires may be a liability and attempts to extend the service life of a bridge having grossly deteriorated zinc-coated wire (Stage 3 and Stage 4) may be hazardous unless extensive remedial work is undertaken. Apparently, Thul (28) felt bare wire was more desirable since he found no instance of corrosion cracking. However, bare suspension bridge wire has suffered corrosion cracking in several instances.
Galvanizing results in a slightly larger wire bundle; however, the slight increase in cable diameter and weight necessitated by this coating is offset by advantages, including a longer potential service life. Depletion of the zinc coating may be monitored without hazarding loss of structural integrity. Also, during times of fiscal shortfalls, added deterioration of galvanizing may be countenanced. Monitoring coating stability also will allow for an orderly schedule of maintenance to rehabilitate or preserve cables. When rust is detected on bare wires, the structural integrity has been affected and scheduling of repairs becomes more critical.

CLOSURE

Some designers contend that cables of stayed bridges should be constructed in an economical manner to lower construction costs. They believe that stay cables may be replaced in the future at reasonable costs. History indicates that is not the case. Eventual replacement costs of main cables and stays often exceed costs of the original structure. For instance, the cost of the Portsmouth Bridge second cable replacement was about $10 million. The cost of placing new stays on the Lake Maricaibo Bridge was about $50 million. As Burke noted, low-cost structures are not always bargains (29).

In addition to suspension bridges and cable-stayed bridges, there are a number of new economical bridge designs that rely on high-strength wire to achieve construction cost savings. It seems only logical to return a portion of that savings to the structure in the form of a suitable corrosion-protection system for the wire. While the original cost may be reduced somewhat by using cheap wire protection, it will eventually have to be paid out in terms of frequent inspections and repairs resulting from use of an ineffective corrosion-protection system. In terms of design logic, it would be more desirable to have long-lasting wires coupled with a replaceable or restorable wire corrosion-protection system. The net result of a comprehensive wire corrosion-protection system is a structure that is reasonable in cost, yet, very durable.

When properly designed and maintained, suspension bridges have served extremely well. Those bridges have shown good adaptability in contending with heavier service loads. At least three 1,000-foot main-span American suspension bridges have served for 100 years or more. That may well be the standard to which bridges may have to be built in the future.

RECOMMENDATIONS

The following recommendations pertain to the three major Kentucky-owned suspension bridges.

1. Consideration should be given to altering the traffic flow on the Kentucky and Ohio banks to reduce live loads on the Ohio, Maysville, and Portsmouth (US 23) bridges. These recommendations are contained in Reference 30.
2. Consideration should be given to replacing present paint on the Ohio and Maysville bridges with more water-impermeable coatings.

3. The strength of the Maysville Bridge truss should be reevaluated using deflection theory. Consideration should be given to upgrading the bridge by eliminating the interior sidewalk and using the resulting space for widening the traffic lanes. An enclosed sidewalk could be attached to the side of the truss. If necessary, the deck support system also may be upgraded by adding additional crossbeams. The sufficiency rating of the bridge may be upgraded considerably by those measures. If properly renovated, the bridge may serve for another 50-100 years at a reasonable financial outlay.

4. Cable corrosion-protection schemes for any proposed cable-stayed bridges should be closely reviewed for suitability. The lessons of the Portsmouth Bridge should be applied when considering corrosion-protection systems that provide marginal security at insignificant initial savings.

Some recommendations are presented for potential future research. In the US, there are approximately 60 wire-cable suspension bridges having spans exceeding 500 feet. Service lives of those bridges range from 15 to 130 plus years. The median life of American suspension bridges is about 40-50 years. The bridges are subject to a myriad of atmospheric and loading environments.

Since suspension bridges are owned by many different authorities, the quality of inspection and maintenance probably varies. If a fraction of those bridges require recabling, the costs would be an enormous drain on highway rehabilitation funds.

It is not unreasonable to anticipate "catastrophic" or "on-line" corrosion-related problems on other suspension bridges, based on observations of the Maysville and Portsmouth bridges. The following facts appear relevant:

1. The Maysville Bridge cables have steadily deteriorated despite the original employment of red lead on all strands (a corrosion-protection feature probably not present in most American suspension bridges).

2. The environment of the Portsmouth Bridge is not unusual.

3. Consistent or higher atmospheric sulfur levels may be expected in the future due to the increased use of coal as an energy source (31).

4. Most US suspension bridges are approaching an advanced age.

5. Drainage of most suspension bridge cables is probably inadequate.

6. The corrosion-protection systems employed on many suspension bridges are probably marginal at present maintenance levels.

The following work is necessary to provide suspension bridge owners with adequate information to adequately deal with potential corrosion
problems:

1. Conduct a questionnaire survey of suspension bridge owners to obtain construction details, service histories, present inspection and maintenance procedures, traffic and loading analyses, and environmental analyses. From those data, suspension bridges could be grouped by areas of commonality.

2. Perform detailed cable examinations on specific bridges in each group to assess the potential for corrosive attack. Wrapping wires on main cables of certain bridges should be partially removed and underlying cable wires inspected for corrosion and cracking.

3. Develop nondestructive test methods to periodically inspect bridge cables for cracking. The purpose would be to eliminate catastrophic failures. Methods should not require unwrapping the cables. Acoustic-emission monitoring is the most promising method. Three-dimensional radiography (computed tomography) shows potential for inspecting end fittings.

4. Formulate rational suspension-bridge cable-inspection procedures that could be adopted by bridge owners to meet their specific requirements.

Presently, there does not appear to be other major difficulties with suspension bridges. If a program such as outlined were initiated, greater assurance could be gained, not only in the reliability of existing bridges, but also in the durability of new cable-stayed designs, which offer many economic advantages. Additionally, corrosion problems in some bridges may be detected and remedied before expensive recabling is required.

REFERENCES


21. American Bridge Division, "USS Elasto-Wrap System of Cable


APPENDIX

CHECKLIST FOR ASSESSMENT OF CORROSION DAMAGE TO SUSPENSION BRIDGE MAIN CABLES

A. EXTERIOR CABLE SURVEY
1. Review drawings of the bridge, including major components such as bands and anchor assemblies.
2. Inspect cables externally by performing the following tasks:
   a. Walk the cables to check condition of paint, locate any gaps in the wrapping, and inspect the band packing.
   b. Inspect the underside of the cables with binoculars to check for rust stains, water leakage from the cables, chipped paint, and band packing pop-outs.
   c. Check for presence of drains in the packing on the underside of the bands.
3. Note all wrapping disturbances or signs of possible corrosion problems in the cables on sketches of the bridge.

B. CABLE INTERIOR WIRE CORROSION ASSESSMENT
1. Review exterior cable survey sketches to select portions of the main cables to be subject to interior inspection. Rank severity of indications as follows:
   1. rust stains,
   2. water leakage from the cables,
   3. chipped paint on undersides of the cables,
   4. band pop-outs
   5. paint or wrapping failures on topside of cable (those can be the most important indication if the failures are severe).
2. Select at least four locations per cable for interior wire corrosion assessment (the locations should vary along each cable -- select at least one location near midspan of the bridge for each cable).
3. Install cable inspection port or alternatively strip all wrapping from the cable along a panel (band-to-band) at each designated inspection location.
4. Visually inspect the interior wires and strands.
5. Note and record the progression of corrosion on the wires.
   a. If Stage 3 or 4 corrosion exists, inspect the lowest outer strands for corrosion cracking in the wires.
   b. If Stage 4 corrosion is detected, consider stripping the remaining wrapping from the panel, if the inspection port is employed, and also consider stripping the wrapping from adjacent panels.
   c. If Stage 4 corrosion is detected, consider inspecting interior strands by wedging the lower strands apart.
   d. If cracked wires are detected, unwrap the adjacent panels and inspect them for broken wires.
6. Reseal the cables.
7. Review the inspection results and determine the need for more extensive inspections or remedial work.
C. ANCHOR HOUSE INSPECTIONS
1. Review drawings of the anchorages and details.
2. Inspect exterior of anchor house including cable entrance (usually the splay saddle).
3. Inspect the interior of the anchor chamber for signs of excessive moisture.
4. Examine the splay saddle for signs of washing of debris or rust from the cables.
5. Determine the corrosion condition of the wire in the anchor chamber.
   a. If Stage 3 or 4 corrosion is detected, closely inspect the wires for corrosion cracking.
   b. Inspect the strand socket openings for signs of wire corrosion (if prestranded wire is employed).
   c. Inspect wires along the looped ends, including tangent points at the strand shoes (if spun wire is employed).
   d. Record corrosion damage found on the wires and signs of excessive moisture in the anchorage chambers.
6. Review the inspection results to determine the need for further inspection and remedial work.