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Suspension bridge cable evaluation and maintenance

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ABSTRACT: Inspection and maintenance of suspension bridge cables requires specialized expertise. After the first thirty years of the bridge's life the main cables should be unwrapped and the interior wires or strands should be inspected in-depth at selected locations. NCHRP has established guidelines for the inspection and evaluation of suspension bridge cables. These guidelines include inspection protocols and techniques for the capacity evaluation of the cables. New products for maintaining the cables and extending the expected service life of the bridge are being utilized by owners of suspension bridges throughout the world. The use of dehumidification systems to dry out the cables is now in place on numerous bridges. This paper will present details of the techniques and procedures now utilized around the world to inspect and evaluate suspension bridge cables. Examples of recent projects will be cited.

1 INTRODUCTION

1.1 *Main Cables*

Since the Brooklyn Bridge was built in New York City in the late 1800's virtually all main cables of major suspension bridges have been constructed of high strength galvanized steel wire. Until the mid-twentieth century, all large suspension bridge cables were air spun by pulling one or more pairs of wires at a time from one anchorage to the other and adjusting each wire to theoretically share the load equally with the others. In 1969, the Newport Bridge in Rhode Island was constructed using shop-fabricated parallel wire strands (PPWS), the method that has now gained favor for many new bridges.

Since John A. Roebling pioneered the art of suspension bridge design, the main cables of suspension bridges have typically been protected by a tight covering of soft wire wrapping bedded in a sealing paste, usually red-lead (Pb_3O_4) in linseed oil, and coated with paint. Some exceptions are notable, such as the Newport and Bidwell Bar (Oroville, California, U.S.A., 1965) Bridges where glass-reinforced acrylic was used, and the William Preston Lane Bridge (Maryland, U.S.A., 1973) where neoprene sheet was used.

Recognizing the advantage of using an impervious covering on the cables, a number of U.S. suspension bridges have been retrofitted with elastomeric coverings placed over the existing wrapping wire. There are now a number of bridges in Europe and Japan that use a dry-air injection system in conjunction with an elastomeric wrapping to ensure that no moisture can enter the cables. Some suspension bridges have also been constructed using twisted strands. The inspection is significantly different for this type of bridges and is therefore not covered in this paper.

1.2 *Guidelines*

Based on the experience of bridge owners and consultants familiar with this field of expertise, the Federal Highway Administration (FHWA) developed guidelines for these special inspections that include some basic descriptions of how to open and wedge cables: Federal Highway Administration Guidelines for "Inspection of Fracture Critical Bridge Members for Cable Suspension Bridges", FHWA-IP-86-26, 1986.

An expanded report; NCHRP Report 534, "Guidelines for Inspection and Strength Evaluation of Suspension Bridge Parallel-Wire Cables" was developed with a concentration on the computational methods used to estimate remaining cable strength of a corroded cable. The NCHRP guidelines were published in 2004 and describe today's standards for bridge inspection. They include recommendations on when to inspect, where to inspect, how many samples to extract, etc. to achieve statistical accurate cable strengths from the inspection results.

2 PREPARATIONS

2.1 *Exterior Inspection and review of existing data*

First the main cable is externally inspected. Inspectors walk the cable to find out if there is anything notable visible on the exterior of the cable. They look primarily for compromises in the protection of the wrapping. Rust stains, beads of water, peeling paint, cracks, are indications of a compromised wrapping system with potential water infiltration. At times large patches of paint have peeled off or long cracks have been discovered in elastomeric wrapping, exposing corroding wires below and allowing water and humidity to infiltrate the interior.

What is learned during the exterior inspection, from earlier inspection and testing reports become the bases for the decision of where to open the cable for the interior inspection It is also advisable to inspect the cable near the midpoint of the mid span. The low point of the cable is often near the splash zone from the roadway and where water tends to gravitate towards. Often the quarter points are chosen since there is where the largest movements are in the cable. Sometimes the cables are inspected near the bents; at the tower tops and splay castings. Those openings require some additional planning since they include the removal of the shrouds. The main objective is to find the worst section of the cable since the overall strength is not larger than the worst section. The cable walk often also include a visual inspection of the sheaved part of suspenders, cables bands, caulking, handropes, stanchions, saddles, splay castings, cable strands, and associated hardware in the anchorages.

2.2 *Contract Documents*

The access to the interior of the cable requires construction crews. The consultants prepare the contract documents for bidding by qualified contractors to provide work platforms, labor, tools, equipment and materials necessary to remove the existing wrapping, assist in driving wedges for the inspection; remove sample wires, splice in replacement wires, and finally re-compact and re-wrap the cables.
Since the project requires special competence, the interior inspection of the main cable is often done separate from the rest of the normal bridge inspection. However the rest of the suspender system is often included in these types of projects. Suspenders (hangers) and their connections are often inspected and a few suspenders removed for testing. Also cable band bolts are removed, inspected and retightened. Anchorages are inspected and broken wires are repaired. The project can also entail rehabilitation and implementation of improved details of the suspender components.
Part of this phase is to prepare the specifications for wire testing and solicit proposals from qualified testing labs.

3 INTERIOR MAIN CABLE INSPECTION

3.1 *Method of Inspection*

The internal inspection of the main cables should follow NCHRP Report 534 “Guidelines for Inspection and Strength Evaluation of Suspension Bridge Parallel-Wire Cables” with some modifications that are appropriate.

The major steps of a typical internal inspection are as follows:

- Install platforms, including enclosure to contain led debris.
- Inspect wrapping system
- Measure the cable diameter
- Remove wrapping wire.
- Clean surface with wire brush and vacuum up debris.
- Drive one line of wedges, inspect and extract sample. Repeat until all wedge lines have been inspected.
- Compact cable
- Apply protective paste and rewrap cable.
- Paint

3.2 *Inspect wrapping system*

With the inspection platform in place the exterior of the cable can be closer examined. Any irregularities and breaches in the wrapping system can explain some of the deficiencies within. The exterior should therefore be documented and photographed.

3.3 *Measure the cable diameter*

Before and after removing and installing the wrapping wire the circumference should be measured to monitor that the cable is properly compacted and that no abnormalities exists. Diameter measures shall also be taken if the main cables are discovered to be not perfectly round. A varying diameter could become an issue during compaction and wrapping of the cables.

3.4 *Wedging the cable*

The cables are wedged at eight locations around the circumference corresponding to 12:00, 1:30, 3:00, 4:30, 6:00, 7:30, 9:00, and 10:30 clock positions. For cables larger than 24 inches in diameter the number of wedge lines would be larger.

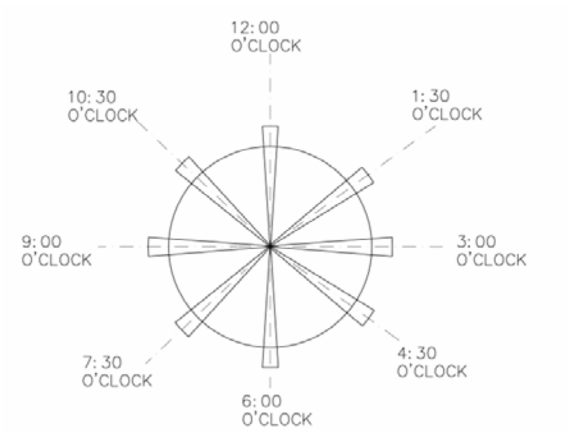

Figure 1: Wedging Pattern

The inspected panels should be unwrapped from band to band to allow driving of wedges to proper depth. A brass wedge is initially used to open up the wedge line at the center of the panel. Thereafter pairs of plastic wedges are driven down into the cable, expanding the wedge line towards the cable bands. The tips of the wedges should eventually reach the center of the cable. Instead of driving one wedge line at a time, several lines have been wedged at some bridges before the inspection. It reduces inspection time but should not be counted on in the contract documents. It creates higher stresses among the wires.

3.5 *Determining the wires' corrosion stages*

It has become standard practice to classify wire corrosion grades as:

- Stage 1 – No Corrosion (spots of zinc oxidation)
- Stage 2 – White zinc corrosion product present (on entire surface)
- Stage 3 – Occasional spots of ferrous corrosion (up to 30% of surface)
- Stage 4 – Larger areas of ferrous corrosion (more than 30% of surface)

The basic definitions have been adopted by the FHWA. The additions in parentheses above are proposed clarifications included in the NCHRP Guidelines.Wire conditions are recorded at normally four locations along each wedge line. Each wire in the grove along that quarter length is rated for its worst corrosion stage.

Figure 2: Inspecting the 3:00 o'clock wedge line

Figure 3: Cutting a sample wire for retraction measurements

3.6 *Removing samples and measuring the retractions*

During the inspection wire samples should be extracted for lab testing. Samples should be taken from the cables in the following distribution among the corrosion stages: The locations where the samples are taken should be evenly distributed among the inspection locations and within the cable section. Approximately one wire is extracted from each wedge lines to achieve a representative sample population. The ratio of samples should also follow the distribution of the corrosion stages defined in the NCHRP. After the sample is cut a new wire should be spliced onto the cut ends to appropriate tension. Each specimen will be cut into specimens that will be tested for strength and material properties.

During the sampling, the wire retractions are measured. The retraction measurements are directly correlated to wire tension and the wire retractions into the cable bands are indicative of the development length of cracked and broken wires. These values are used in the cable strength calculation if cracked and broken wires are found. A new wire is then inserted with a pressed-on ferrule at one end and a pressed-on turnbuckle on the other end. Holding on to two wire ends, a come-along is used to tension the wires so that the installed turnbuckle could be tightened.

3.7 *Cable recompaction*

Cable recompaction start at one of the cable bands and proceeded towards the other cable band. The compactor normally consists of a segmented steel ring with four – 100 ton center hole hydraulic jacks operating simultaneously to constrict the ring. The jacks were equally pressurized through a manifold and a hydraulic pump powered by compressed air. Compaction intervals and temporary seizing band spacing are determined in the field based on the degree of expansion of the cable after wedging. Cable circumference measurements are taken after pressurizing the compactor and after banding and releasing the compactor in order to monitor the relaxation of the bands and to ensure that the original diameter was not exceeded. At certain instances the repairs in the cable are so plentiful that the diameter is affected.

3.8 *Waterproofing paste*

Due to environmental concerns with the handling and disposal of lead-based materials such as the traditional waterproofing red lead paste, oil-based zinc paste has been specified for the protection of main cables in the last few decades. Today there are two formulations of water proofing paste that are normally specified for US bridges; Elettrometall and Grikote-Z. Elettrometall cures to flexible rubbary state and Grikote-Z remains pasty. These pastes have excellent properties with regard to cable protection, and there use will provide a much higher degree of protection than the traditional red lead paste.

3.9 *Cable rewrapping*

The wrapping machine is normally pneumatically powered and consists of two main parts – the saddle which sits on top of the cable and acts as the base for the machine and the flyer which houses the wrapping wire spools and rotate around the saddle. The machine should be capable of winding the wires with a minimum tension of 300 lbs around the cable. The wrapping wire tension is maintained by torquing the spool nuts to the proper level and thereby creating friction between the underside of the spool and a brake pad attached to the surface of the flyer. The wrapping wires are usually round zinc-coated steel wire, soft-temper, Class A coating, No.9 Gauge, meeting the requirements of ASTM A641 and shop coated with linseed oil.

Figure 4: Cable compactor

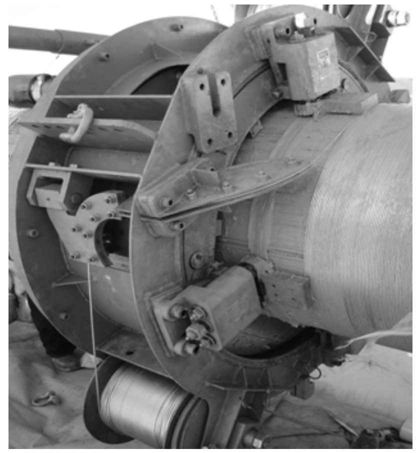

Figure 5: Wrapping Machine

3.10 *Painting*

Traditionally suspension bridge cables were protected with the same paint system used for the steel structure. More recently water-based acrylic coatings that contain highly elastic polymers and cure to a rubbery coating have been used for painting suspension cables. Because of their ability to sustain up to 200% elongation without cracking or peeling, they have been successfully used for the maintenance painting of wire wrapped cables on many existing suspension bridges and new bridges. In addition, these coatings have proved to have a long life in other applications, especially in environments where superior salt water and chemical resistance are required. One of such materials is the proprietary coating Noxyde, manufactured originally in Belgium and now licensed for manufacture in other countries.

4 TESTING WIRE SPECIMENS

From the sample wires extracted from the cable, specimens are cut into appropriate length for testing. The bulk of the testing is tensile tests that will define the average strength and statistical deviation for the different corrosion stages. These test results will determine the ultimate strength of the cable.

Other tests include zinc coating, wire chemistry, wire fatigue, atomic hydrogen content, surface chemistry and microscopic examinations.

5 CALCULATING CABLE STRENGTH

The conditions recorded at the four locations of each wedge line are later combined into a composite "condition map" for each panel. In these cross sections, the four inspected areas are combined to represent the worst conditions throughout the inspected panel.

There are three methods for strength calculations described in the NCHRP guidelines. The most common one used is the Brittle-Wire Model, which is described below.

The cable strength modeling is developed utilizing the wire strength for each grade of wire. This approach requires knowing the number of wires in each category and the number of broken wires. Though the exact numbers of wires in each grade are not measurable directly, the number of wires in each category can be estimated from interpolation of the field inspection findings.

Because only one panel is normally inspected at each location, the assumption is made that the adjacent panels are in the same condition as the inspected panel. This is important because broken and cracked wires in the adjacent panels affect the strength of the inspected panel to an extent dependent on the number of cable bands needed to redevelop the broken wire's full strength. The redevelopment length is determined based on the retraction measurements taken when samples are cut and by observing the separation between ends of wires found broken in place.

In computing the cable strength, broken wires are first taken out of the section. The number of remaining wires in each category is then computed by multiplying the total remaining number of wires and the percentage of wires of each category. The cable is then theoretically incrementally loaded and at each step of the loading, the ratio (R) of wire breakage (probability of wire breakage) is computed by using the Probability Density Function for the wires in each category. The number of wires broken is obtained by multiplying the R ratio by the number of wires in a certain group. The total number of remaining wires from each group times the load in each wire at that particular step is the corresponding total cable load.

At the beginning when the theoretically applied wire load is small, the R ratio computed from the probability distribution functions is small and hence very few wires are broken. The total cable load increases almost proportionally with the wire load during this stage. At the later stages when the wire load is large and many are breaking, the total cable load decreases rapidly with increasing wire load. Therefore there is a peak value for this continuous loading process which is the estimated cable strength.

6 PROTECTION METHODS

6.1 *Oiling*

The recent practice in the United States has been to treat damaged cables by oiling and rewrapping them for their entire lengths. This entails major construction work and installation of work platforms below the cables to provide access. The existing wrapping is removed panel by panel, wedges are driven into the cable and oil (usually linseed oil with or without additives) is poured into the wedged grooves. The cables are then rewrapped, usually with wire and a sealing paste and sometimes with a neoprene overwrap.

6.2 *Dehumidification*

6.2.1 *Anchorage Installations*

Metal corrosion is a common problem in the anchorages of suspension bridges and it is promoted by both water leakage, and excessive air moisture in the anchorage chambers. It is probable that contamination from pollutants is also a contributing factor to the corrosion observed in the anchorage.

The decrease in the relative air humidity may be achieved by either raising the air temperature thereby increasing the amount of water vapors that the air can contain before becoming saturated, or by removing moisture from the air through dehumidification. Although the same result is obtained by either method, heating the air has been tried and proved to be impractical; it promotes the development of molds, algae, and bacteria, and demands high levels of energy consumption, which can be expensive. On the other hand, industrial dehumidification methods are extensively used in storage facilities for materials and products, and for the protection of electrical and electronic equipment, among other things. Equipment with a reliable service performance, suitable for permanent installation, and of the size needed in bridge applications, is readily available. (The use of dehumidification as a method for protecting steel bridges against corrosion was pioneered in Denmark as early as 1970, when the Second Little Belt Bridge was constructed with the inside of the boxed cross section coated only by a shop applied primer, and the interior of the superstructure was dehumidified. The same system was used for the corrosion protection of the superstructure for the Farø-Falster Bridge, opened in 1985, and the Great Belt East Bridge, opened in 1998, both in Denmark).

Dehumidification of suspension bridge anchorages has gained acceptance with both bridge owners and bridge designers, and it has been incorporated in the design of a number of new bridges:

- the Askøy Bridge in Norway, opened in 1992;
- the Great Belt East Bridge in Denmark, opened in 1998;
- the Akashi Kaikyo in Japan, opened in 1998; and
- the Tsing Ma Bridge in Hong Kong, opened in 1997.

Dehumidification has also adopted for corrosion protection in the anchorage of a number of existing suspension bridges:

- the four anchorages of the Forth Road Bridge, in Scotland,
- the Humber Bridge in England, anchorage dehumidification installed in the 1980's;
- the two westerly anchorages of the Bear Mountain Bridge over the Hudson River, New York,
- the Hennepin Bridge in Minneapolis, Minnesota;

- the Benjamin Franklin Bridge in Philadelphia, Pennsylvania;
- the Mid-Hudson Bridge in Poughkeepsie, New York;
- the George Washington Bridge in New York City;
- the Verrazano-Narrows Bridge in New York City; and
- the Bronx-Whitestone Bridge in New York City.

The installations of dehumidification equipment noted above have been generally designed to maintain relative humidity levels between 35-40%. Research regarding corrosion of bridge wires and relative humidity is somewhat limited. However, there is ample research into the correlation of humidity and corrosion of steel. Research has also shown that at relative humidity levels of 40%, corrosion will initiate. The corrosion rates will accelerate as the relative humidity increases and is further amplified by the presence of contaminants.

6.2.2 *Dehumidification Installation*

All reported bridge applications of dehumidification as an anticorrosion measure have used the desiccant wheel type equipment. The same type of equipment is used in military long-term (static) storage installations for the US Army and Navy. Reportedly, hundreds of dehumidification (desiccant) systems have been used in military applications since 1958, limiting corrosion in storage areas to negligible amounts.

An effective dehumidification system for the anchorage chambers, similar to a passive storage installation, features the following characteristics:

- dehumidification only - nearly all the moisture in the anchorage chamber is from latent heat (humidity).
- not required to cool the air - it is more desirable to heat it, thereby increasing the amount of water vapor that the air can contain.
- restricted access to the space - infrequent personnel visits, limited ingress of moist air from door opening or from people.

6.2.3 *Sample Dehumidification System*

<u>System Specifications</u>
(for George Washington Bridge – size of equipment is based on volume of air within the anchorage enclosures to be processed)

Flow rate: 600-2250 scfm (Standard Cubic Feet Per Minute)
Moisture removal: 30 lb/hr (~3.5 Gal./hr.), 75°F, 50% RH at 1125 scfm
Reactivation: electrical
Dimensions: 75”x31”x62” (LxWxH)
Wheel Diameter: 21” for HCD 1125, 30” for HCD 2250 (Munters / Cargocaire, USA)
Wheel Rotation: 8 to 10 RPH (Revolutions per Hour) for both models
Weight: 660 lb max
Utilities: 480V/3/60
Heater Consumption: 24 KW
Unit Consumption: 36.0 A

The heart of the system is a honeycomb wheel made of a solid, insoluble titanium/silica gel, which acts as desiccant. Silica gel is inert, stable, and non-toxic. In particular, it is resistant to acids and sulfur products found in combustion products. It is possible to wash the desiccant wheel with a hose, without jeopardizing its structural integrity. An example of a desiccant is the little gel packs that come with cameras.

The desiccant dehumidification process is unlike cooling based systems. Instead of cooling the air to condense its moisture, desiccants attract moisture from the air by creating an area of low pressure at the surface of the desiccant. The pressure exerted by the water in the air is higher, so the water molecules move from the air to the desiccant and the air is dehumidified and becomes warmer.

If the desiccant surface is cool and dry, its surface vapor pressure is low, and it can attract moisture from the air, which has a high vapor pressure when it is moist. Once the desiccant becomes wet and hot, its surface vapor pressure is high, and it will give off water vapor to the surrounding air.

The Process Air is circulated from the enclosure, through the desiccant wheel where the moisture is drawn out of the air, and collected on the wheel. The Reactivation Air is drawn in from outside fresh air, is filtered, heated, circulated through the desiccant wheel, and is brought back outside the system. The process of heating the air allows the surface vapor pressure of the desiccant to rise allowing the desiccant to release the moisture and be drawn to the Reactivation Air Outlet.

6.2.4 *Background and System Description for Main cables*

A comprehensive study on the corrosion protection of existing suspension bridge cables was performed during the selection of the high strength wires for the Akashi Kaikyo Bridge. Starting in 1988, the interior of the main cables of several existing bridges on the Honshu-Shikoku crossing were inspected, including the area under the cable bands, and some cables were found to have corroded surfaces because of insufficient protection against water. Ammann & Whitney was engaged by the Honshu-Shikoku Bridge Authority to conduct an in-depth study of the mechanics of cable corrosion.

This investigation revealed that the conventional corrosion protection is not always sufficient to prevent water intrusion. Water can enter the cable through discontinuities in the outer wrapping, or through water vapor carried by the air passing in and out of the cable as the atmospheric pressure varies, for example through the openings at the bottoms of the cable bands. Air entrapped in the voids between the wires inside the cables contains water that evaporates as the temperature rises, and condenses when the temperature falls. Internal surfaces were wet as a result of water seepage increasing from sides to the bottom, and decreasing toward the top. At the cable bands the wires were in relatively good condition with only zinc corrosion at the bottom. The measurement of relative humidity inside the cables showed that in most parts the humidity was always high, regardless of outside temperature, whereas at the cable bands the level of humidity was similar to the outside.

Further testing was done to verify the critical humidity for the corrosion of galvanized wires used on an existing bridge, where zinc corrosion, ferrous corrosion, and deteriorated paste were present with airborne salt in the injected air. This showed that when relative humidity is held below 60%, almost no corrosion occurred even without galvanization and in a salty atmosphere. Removal of salt from the air further improved the results.

Different types of paste, including red lead paste, aluminum phosphate paste, zinc chromate paste, and polymerized organic lead paste were compared experimentally. None of them adequately sealed the main cables, especially in humid and hot weather. It should be noted that the relative humidity in some parts of Japan exceeds 80% in summer time.

A new system for the corrosion protection of main cables was then developed for the Akashi Strait Bridge, consisting of a watertight Neoprene wrapping system, complemented by a dehumidification system. In order to assure water- and air-tightness, a neoprene rubber sheet wrapping was applied over conventional wire wrapping, but the paste was omitted. The air-tightness at the cable bands is the most critical part, and is ensured with sealants containing rubber and silicone.

Dry air is injected from the periphery of cables at intervals of about 140 m (460 feet). The air pressure applied was determined by considering the durability of the sealing materials and the loss of air pressure at intakes and cable bands. These were determined from tests performed on model cables and on-site measurements.

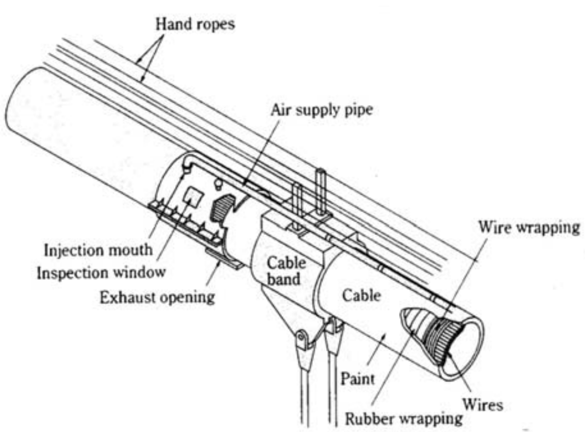

Figure 6: Schematic diagram of dry-air injection system(Figure obtained from “The Akashi Kaikyo Bridge”, a publication of the Honshu-Shikoku Bridge Authority)

Over the years several bridges in Europe and Asia have incorporated dehumidification for the main cables on their bridges. A similar installation is now under design in Maryland for the William Preston Lane Bridges. This will be the first installation of a dehumidification system for the main cables for a bridge located in the United States.

7 INSPECTION RESULTS

7.1 *Practical adjustments to the guidelines*

Even though there are general guidelines, every bridge is different in some ways and the guidelines often need to be adjusted to accommodate those differences. In the Bear Mountain Bridge cables, for example, wires looked like Stage 1 at first impression until several Stage 1 wires were found broken. It was discovered that small corrosion pits had formed locally. To better represent the cable wire population the corrosion stages were revised for this inspection. This meant that each wire had to be not only viewed but also felt to find the small corrosion pits. The inspection became labor intensive but ultimately a better representation of the true cable strength as the lab test ultimately confirmed.

Another unconformity at the Bear Mountain Bridge was the discovery of some wires had lesser tension than the rest. The tensions in these wires were estimated in the field and the strength calculation was revised to accommodate the loose wires.

7.2 *Newer suspension bridges*

The earlier bridges were often designed with a safety factor of 4.0 for the main cables while the more recent bridges are designed with a safety factor as low as 2.25. The older bridges can therefore sustain a higher level of section loss than the newer bridges. A minimum safety factor for the main cables is debatable but 2.0 is often considered. That leaves a bridge with a 2.25 designed safety factor only an 11 % potential degradation before remediation needs to be implemented. This has led to the discovery that not only older bridges need to be inspected but also the not so old.

In 2004 the Forth Road Bridge became the first suspension bridge in Europe to have its main cable opened up to check for signs of corrosion. In 2006 and 2009 the other two major British bridges; Severn and the Humber Bridges, were inspected for their first times. The results of the inspections were that the strengths were sufficient but any further corrosion had to be minimized. All the bridge’s main cables have now been dehumidified or are in the process of being dehumidified. The Humber Bridge is only 29 years old.