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SAFETY APPRAISAL OF SUSPENSION BRIDGE MAIN CABLES

Contractor's Report from a Workshop in Newark, New Jersey
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Executive Summary

A suspension bridge represents a significant capital investment for any owner, and most often is of such importance to a region's transportation system, that replacement is not an acceptable alternative. Most of the components of suspension bridges can be adequately maintained and/or rehabilitated while the structure continues to carry traffic. However, the main cables are the primary load carrying components and replacement, although technically possible, is rarely considered feasible. Replacement of the entire structure is even less acceptable. Beyond the effect on traffic, the primary concern is that collapse of structures of this magnitude and importance absolutely must be prevented.

Suspension bridges in the U.S. have cables that range in diameter up to 36 in. and consist of up to about 28,000 individual wires each. Some are constructed of pre-formed structural strands, but the majority are spun-in-place from individual wires laid parallel. Therefore, spun-in-place cables receive the most attention when discussing suspension bridges. The large number of wires in a parallel wire cable is both an advantage and a disadvantage. It is an advantage in that it provides significant internal redundancy to the structural system, allowing repair or replacement of individual damaged wires. It is a disadvantage in that it is very difficult and costly to determine the extent of deterioration occurring within the cable that could affect its load carrying capability. Guidelines and techniques to determine the significance of the various numbers of internal cable wires with various levels of deterioration are lacking. Defining the scope of the problem and the research needs to address the problem were the goals of this Workshop.

Because of their importance and capital investment, suspension bridges are usually designed for service lives of 100 years or more. The main cable should have a service life comparable to the main structure. In practice, it is necessary that the main cable be designed and detailed to be inspectable and maintainable. Existing cable inspection techniques involve selecting portions of the cables that are judged to be most vulnerable to whatever deteriorating condition that may exist, uncovering the cables, separating the wires by use of wedges to allow visual inspection of the cable interior wires, and possibly removing some sections of individual wires for testing. From this very limited sampling of wire conditions, an assessment is made as to the remaining load carrying capacity of the cable. The reliability of this approach is questionable, and it may be less than adequate. Furthermore, in the anchorage areas where wire corrosion is often more severe, it is not feasible to separate wires for visual inspection or to take samples of wires.

Because of the cost and time involved with this cable inspection and evaluation technique, it is usually performed only after a bridge has been in service for many years. Further cable inspections may be made at intervals of several years, and may be at different locations. However, it should be noted that there are many suspension bridges older than 30 years whose cables have not been subjected to any significant level of inspection.

Recognizing that a life comparable to the main structure is the goal for the cables of these bridges, owners need to be assured that the structural capacity is adequate on the basis of procedures for cable inspection and evaluation more rational than those in common use. They need to be assured that repair procedures, if required, will provide a significant increase in life to justify the investment required. Finally, they need better data to support any indication that replacement of the main cables is required.

To provide the owners with reasonable answers to the above considerations, the participants in this Workshop developed a list of research needs for providing improved non-destructive inspection and evaluation techniques. Such research will provide owners with a better definition of what factors affect cable integrity; with improved means of interpretation of inspection results to provide more confidence in cable strength assessment; and with repair or rehabilitation procedures and technology that will extend cable life as much as possible. These projects should provide owners with more reliable information on the actual condition and strength of the key members of their suspension bridges -- the main cables; and with useful information on cable maintenance and rehabilitation procedures.

I - INTRODUCTION

The customary process of condition and strength appraisal of suspension bridge cables in the U.S. and other countries has been questioned by leading authorities and experts. These concerns are generated by the knowledge that existing cable inspection and appraisal techniques are, at best, cursory, partly because of the sheer magnitude of the problem -- there are many, many miles of individual wires in a typical parallel wire cable. Further, and of prime importance, adequate techniques, equipment and guidelines for performing cable inspections are lacking.

By letter dated 20 December 1997, Jackson Durkee, Consulting Structural Engineer, Bethlehem, Pennsylvania, wrote to Robert Skinner, Jr., Executive Director of the Transportation Research Board, Washington D.C., and expressed his concerns about inspection and appraisal techniques for suspension bridge cables in the United States (See Appendix D). Durkee stated: “The available evidence points clearly to the stark fact that the main cables of many major U.S. suspension bridges are indeed in questionable condition.” His conclusion was, “...the U.S. needs a research project to identify and investigate the factors relevant to the strength and adequacy of suspension bridge main cables, and to develop these factors into a logical and suitable procedure to appraise cable safety aspects.”

M. Myint Lwin, Bridge Engineer for the Washington State Department of Transportation (WSDOT), submitted a Research Problem Statement to NCHRP containing similar concerns which has been endorsed by the AASHTO Bridge Subcommittee. In addition to the endorsement of the AASHTO Bridge Subcommittee, the Chairs of the TRB Section C committees, and the chair of TRB Committee A2C02 Steel Bridges, endorsed this project at the TRB Annual Meeting in Washington, D.C. in January 1998.

The first stage problem statement as set forth by Lwin states:

- Evaluate factors that affect long-term performance
- Develop models for predicting remaining service life
- Evaluate NDT methods
- Develop inspection and evaluation manual
- Field test the manual
- Conduct workshop on the use of the manual
- Finalize manual and provide commentary

Lwin's problem statement became the basis for moving forward in addressing suspension bridge cable assessment, and resulted in the establishment of this NCHRP 20-07 task; and a Steering Committee was established to address this issue. The Steering Committee decided that a workshop would be the best way for the initial approach to this problem, and NCHRP finalized the plans. On November 16 & 17, 1998 a “Workshop on Safety Appraisal of Suspension Bridge Main Cables” was held at the Hilton Gateway Hotel in Newark, New Jersey to define the scope of the problem and address potential solutions through specific research needs statements; and to a lesser extent, attempt to define potential funding sources to conduct the research projects. The list of participants included representatives of suspension bridge owners from the U.S., England and Scotland, consulting engineers who specialize in suspension bridge design and inspection, metallurgists, corrosion engineers, and others who could contribute to development of methods for assessing the conditions of suspension bridge main cables. Most of the case studies reported on cables constructed of individual parallel wires; however, some reported on cables made of locked coil strands. In addition, some presentations included information about suspender ropes, and cable anchorages metalwork. Because parallel wire cables are the predominant type of cable construction for long span suspension bridges, the research statements are directed toward that type of cable.

The goals of the Workshop were defined as:

- Expand knowledge of cable inspection techniques
- Expand knowledge of cable evaluation procedures
- Identify problem areas
- Recommend research tasks
- Recommend funding sources

II - SCOPE OF PROBLEM/STATE-OF-THE-ART

The Workshop began with a series of presentations covering the pertinent subjects.

INSPECTIONS

Representatives of suspension bridge owners and inspecting engineers reported on the results of cable inspections and assessments of many suspension bridges in the U.S. and Great Britain. Although many of the case studies identified cable anchorage corrosion to be a serious problem, it was agreed this is not the problem to be addressed as a part of the Workshop in that the solution is already known i.e., keep water away from cable splay saddles and anchorage eyebars and remedial measures are underway or have been successfully carried out on many bridges.

For all the suspension bridges discussed, it was reported that, at the very least, a complete visual inspection of the cable exterior covering has been carried out. These visual inspections resulted in reports of breaks in the covering, water and other material leaking from the cable, usually at cable bands, and various levels of deterioration of the cable covering material.

In addition, in many cases some of the cable wires have been subjected to visual inspection, where selected portions of the cable were uncovered. Typically, hardwood wedges were inserted into the cable to separate the wires so that a visual inspection could be made of the surface condition of the visible portions of interior wires. Where surface cracking of wires, loss of zinc coating (if used), corrosion products, or other concerns were observed, broken wires would generally be cut out and sent to a testing laboratory for examination of broken surfaces and strength evaluation. Based on this type of inspection, a factor of safety or possibly a better term would be the working load factor for the cable was typically determined. Cable design factors of safety (FS) were stated to vary from 2.4 to 4.0 for various bridges. After determination of a new FS based on interpretation and extrapolation of the inspection data, an assessment is commonly made as to the adequacy of the cable.

The detailed results of the cable inspections and assessments presented as a part of the case study presentations, indicated clearly that *there are no standard guidelines for cable inspectors to follow, nor is there a recognized procedure for assessment of cable condition and strength.*

Most of the reported inspections of suspension bridge cables used a corrosion scale for cable wire condition and assessment similar, if not identical, to the following. Hopwood developed a corrosion scale for galvanized structural strand (Reference 5, page 7) as follows:

1. As new condition. Zinc coating has typical bright metallic appearance.
2. Good condition. Exposure to atmosphere has given zinc a dull-gray appearance. If white film is removed, no rust is evident on surface.
3. Much of wire is covered with a thick white zinc corrosion product. When this is scraped off, wire surface reveals rust and pitting. Wire breakage is possible during this stage.
4. Wire is severely rusted and pitted, with speckled brownish-red and white appearance.

It was questioned whether this scale adequately includes the effects of fatigue, stress corrosion, hydrogen embrittlement and ordinary corrosion. It obviously would not apply to cables made up of non-galvanized wires.

Results of one inspection indicated stage 3 to 4 corrosion exists 2 in. to 3 in. into the cable. Another inspection disclosed rust coming through the cable covering, generated as a result of non-galvanized wire straps that were applied before the original cable covering was installed.

An associated problem with uncovering a cable during inspection is the need to re-establish the cable covering system to as good or better condition than existed before. This problem has led to research and testing of new materials to replace older materials such as red lead paste that may no longer be acceptable. New products must be compatible with the existing products in order to ensure that accelerated corrosion does not result. One product proposed for use under new wire wrapping and currently undergoing laboratory testing is an epoxy/75% zinc dust compound that is being used in some European suspension cables in lieu of red lead paste.

The cost, complexity and uncertainties of doing cable inspections with current procedures clearly point out the need for better non-destructive examination (NDE) techniques that can look through the various materials used for cable covering and penetrate far enough into the body of the cable to provide meaningful information.

A review of existing NDE technology indicates that there are three promising techniques to assist in cable inspection and evaluation: magnetic flux leakage, acoustic emission (AE), and radiography (RT). Each has advantages and disadvantages. Magnetic flux leakage equipment provides the capability of evaluating interior wires without uncovering the cables, but is limited to 2 in. to 5 in. depths. However, it cannot look under cable bands and cannot be used at cable saddles. Acoustic emission offers the prospect of continuously monitoring cables, determining when individual wires break. There are commercial AE systems already on the market that will provide this information, but they will not of course provide an assessment of the cable condition prior to system installation; AE will only document activity (broken wires) after installation. RT also is limited in its ability to inspect beyond certain depths, the depth of penetration being a function of the power applied, which in turn means heavier equipment and the possibility of having to restrict access to the area, or even the bridge, during the RT operation. There are also corrosion sensors and global positioning sensors that could assist in monitoring changes in cable condition, but they do little to provide reliable assessment of existing conditions.

CORROSION MECHANISMS

Cable wire deterioration was reported as being caused by one or more of the following: hydrogen embrittlement, stress corrosion, and/or corrosion caused by water (possibly acidic due to acid rain) intrusion. Stopping water intrusion and the related corrosion may initiate other forms of corrosion, such as microbe induced corrosion. If sulfur (i.e., acid rain) is present, it could result in creation of hydrogen, aggravating hydrogen embrittlement.

Environmental effects play an important role in embrittlement phenomena but are not well understood in the case of suspension bridge cable wires. For example, it is known in general that the fatigue life of steel is reduced as the corrosion rate increases; this is called corrosion fatigue. Similarly, nitrates, caustic and carbonate/bicarbonate water-based solutions cause stress corrosion cracking of constructional steels. Stress corrosion cracking is not caused by hydrogen. The embrittlement of steels by absorbed hydrogen is known as hydrogen embrittlement. The important point is that each of these phenomena is driven by a different stimulus: corrosion fatigue by increased rates of general corrosion; stress corrosion cracking by anodic dissolution in the presence of nitrates, caustics or carbonates; and hydrogen embrittlement by processes which introduce atomic hydrogen into the steel. All of these phenomena depend intimately on the level of stress, which is present, the metallurgy of the steel, and the chemical nature of the environment. Each is a thermally activated process which means that embrittlement may occur at low stresses but may require a very long period of time for crack initiation and propagation. Part of the total stress can, and will probably be, residual stress attributable to the wire manufacturing and installation processes. If a crack formed as a result of environmentally induced embrittlement is arrested before it reaches the critical size, the wire will not fracture.

Since the Brooklyn Bridge (completed in 1883), most suspension bridge cable wire has been galvanized to provide corrosion protection. It was reported that the high strength wires, when galvanized, are more susceptible to hydrogen embrittlement than non-galvanized wires. Non-galvanized wires are known to have a significantly reduced life in a humid environment.

By far the most common cable protection system used for suspension bridge cables starting with the Brooklyn Bridge has been painted wire wrapping, which consists of (a) red lead paste applied to the cable wires, (b) a wrapping of galvanized wires, with adjacent wires in tight contact, and (c) several coats of paint. In recent times red lead paste has been designated an environmental hazard.

When an existing cable protection system is removed to perform cable inspection, it is necessary to ensure that replacement materials do not adversely interact with existing materials. Environmental restrictions may prohibit use of red lead when re-covering a cable. In certain cases linseed oil has been injected into the cable for corrosion protection. An epoxy with 75% zinc dust paste has sometimes been used in lieu of red-lead.

FATIGUE

Damage to wires is also caused by load-induced fatigue, corrosion fatigue, and fretting fatigue. Residual stresses in the wire, resulting from uncoiling during the erection process, may aggravate the fatigue stress ranges, which are normally very low in a suspension bridge cable. The fatigue crack-propagation rate in cable wire is not known. It is felt that because live load stress ranges in cables are usually very low, fatigue will be a concern only after the wire has lost a significant section. The unknowns include the fatigue resistance of cables with multiple wires, the threshold of fatigue-crack propagation in bridge wire, the crack propagation rate in bridge wires, and environmental effects on the preceding.

EVALUATION OF CABLE STRENGTH

For U.S. suspension bridges the gross cable-wire diameter (including zinc coating) has typically been 0.196 in and the specified minimum wire ultimate strength 225 ksi. The number of wires per cable varies from about 5000 to about 28,000.

Calculation of the factor of safety was questioned as a proper way to assess cable strength, since there is no model for cable failure. Consider a cable 4000 ft. long containing 15,000 wires. Such a cable would contain 60,000,000 feet of wire. Uncovering a 10 ft. length of cable, and wedging down 5 in. at 8 points around the circumference, would expose one side of only 4000 linear feet of wire, or 0.007% of the total length. In addition, assuming that visually good, and usually non-tested, wires possess the original load carrying capability can also be questioned, since we do not have a good understanding of the mechanism causing wire distress.

Strength of cables has to be determined statistically, based on individual representative wire samples. The need for defining what is a representative sample was stressed throughout the session. Probability based detection methods are needed to establish confidence in the results of an inspection. Further, it must be kept in mind that we do not have a reliable structural model for the failure of a suspension bridge cable made up of several thousand individual wires.

III - NEEDED RESEARCH

The papers presented in the opening sessions of the Workshop took note that available evidence indicates the following:

- some suspension bridge main cables have deteriorated significantly;
- many cables have never been subjected to any internal inspection;
- comprehensive inspection procedures have not been defined;
- relating cable inspection data to cable strength is vague;
- cable safety factor is a vague concept, and calculated values have no clear meaning;
- failure of any wire-cable suspension bridge would constitute a catastrophe and call into question the integrity of all other suspension bridges.

To develop a means to obtain answers to the above concerns, the participants were assigned to four breakout groups to define research needs statements. Prior to retiring to the breakout groups, a brainstorming session was held to provide participants the opportunity to express their thoughts on key issues. These ideas were tabulated and provided the basis for breakout group discussions. The breakout groups were charged to develop statements of research needs that will result in adequate inspection guidelines, testing criteria, and strength assessment techniques for use in inspections of suspension bridge cables.

The breakout groups developed research problem statements as detailed in Appendix B. Participants were asked to prioritize the research statements. The six highest priority research problems are listed below.

I-1: Priority #1 **Develop Cable Inspection, Sampling and Testing Guidelines**

Develop standards for cable inspection including sampling and testing guidelines. These should provide greater reliability for cable inspections and allow comparison of cable conditions from one bridge to another.

E-1: Priority #2 **Develop a Model to Predict Strength of Cables with Various Levels of Wire Damage**

There are types of wire deterioration occurring in cables that individually may be understood, but collectively, need further study. A cable strength model that encompasses all forms of wire deterioration at various levels is needed to properly assess cable integrity.

I-2: Priority #3 **Establish Inventory of Past Cable Inspections, Conditions Reported, and Strength Evaluations**

A large amount of data has been collected over the years from cable inspections, but has not been catalogued for study. Analysis of results of past inspections will allow a comparison of the procedures and provide assistance toward establishing guidelines.

C-1: Priority #4 **Develop Understanding of the Effect of Cable Environment on Strength**

Deterioration of cables occurs for a number of reasons. To evaluate cable integrity, a better understanding of the effects of the environment is required.

F-1: Priority #5 **Effect of Fatigue Damage on Cable Integrity**

The influence of dynamic loads on wires and cables is not fully understood. There is a need for development of a cable fatigue model to ensure that fatigue damage is correctly assessed.

C-2: Priority #6 **Evaluate Effectiveness of Cable Corrosion Protection Systems**

The standard cable corrosion protection system has been of questionable effectiveness over the years in minimizing cable deterioration. However, newer systems such as plastic types of covering may be more effective. There is a need to evaluate the various systems.

IV - FUNDING SOURCES

NCHRP

NCHRP is funded by contributions by the State Departments of Transportation. These funds offer the opportunity to pursue preliminary studies that might develop guidelines for more extensive projects. A research project in the amount of $500,000 for studying cable condition and evaluation has already been submitted to the NCHRP. If approved, work would start in the year 2000.

National Science Foundation

Research funds are available from the NSF, but they generally limit their grants to research determined to be fundamental in nature. Development of an NDE collar may fall in this category.

Pooled Funds

Under current Federal-aid highway legislation, individual states were provided significant increases in research dollars. Many states do not have the administrative structure in place to effectively utilize this increased funding level. Pooling some of these funds from a number of states provides an opportunity to leverage the funding by allowing bigger contracts to better address the scope of the above problem statements. Pooled-fund projects can be administered by the FHWA or by an individual state.

IBTTA

The International Bridge, Tunnel and Turnpike Association has a research responsibility. Most suspension bridges are toll facilities, and therefore, the owners would be members of the IBTTA. International bridge owners are also a part of the IBTTA.

Cooperative Agreements

The owners of suspension bridges consist of both public agencies and toll authorities, in the U.S. and abroad. As such, many of the funding sources listed above would generally be restricted to use by one of these two sets of owners, and further limited to a given country. The opportunity to combine funds from these different owners, domestically and internationally, allows leveraging of the funds available. Cooperative agreements have been used very successfully for other research projects. A cooperative agreement might be executed between the participating parties outlining the level of funding participation, in-kind contributions, technical responsibilities and voting rights. Overall project management could be by one of the cooperating agencies (e.g. IBTTA), or by an independent body such as NCHRP.

V - CONCLUSIONS

The Workshop clearly achieved its goals. The participants shared their experiences of many years of suspension bridge design, inspection, and evaluation. The research statements developed define the work needed to ensure safe and uninterrupted service from the main cables of these landmark structures.

It may be noted that neither the safety nor the short-term serviceability of any suspension bridge was questioned during this Workshop. The research projects outlined should provide development of the tools and procedures necessary to ensure that the minimum required level of safety can be continued over the long term.

APPENDIX A

Workshop on
Safety Appraisal of Suspension Bridge Main Cables
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APPENDIX B

RESEARCH PROBLEM STATEMENTS

Inspection

Research Project I-1

Title	**Develop Bridge Cable Inspection, Sampling and Testing Guidelines**
Problem Statement	There are no standardized procedures for performing suspension bridge cable and wire inspections. Because of the lack of reliable NDE techniques, there is a need to establish the number and location of wire samples. Guidelines for cable inspection, wire sampling and wire testing are needed to assure uniformity and reliability.
Objective	Task A - Review current practice, both domestic and international. Task B - Recommend standard practices for inspecting, sampling and testing of suspension bridge cable wires to include: • Sampling techniques - when, where, how many? • Wire testing (mechanical and chemical) specifications • Length-retraction measurements • Cable band tension • NDT/ evaluation tools • Format for reporting inspection and testing results
Urgency	Inspection priority I - 1

Research Project I-2

Title	**Establish Inventory of Past Cable Inspections, Conditions Reported, and Strength Evaluations**
Problem Statement	Suspension bridges in the U.S. and other countries have been built to various design and construction criteria. There are various types of cable corrosion protection systems in use. Inspections performed on these cables have varied; some have consisted only of external visual inspection while others included uncovering and opening up the cables for a visual assessment of internal wire conditions at limited locations. The determination of where to look varies by inspection agency. When to look is another variable. Analysis of the results of past inspections will allow a comparison of the procedures used and provide a better basis for establishing guidelines for future inspections.
Objective	Collect and organize cable inspection data from bridge owners and gather information from the literature, and evaluate and interpret it.
Urgency	Inspection priority I - 2

Research Project I-3

Title	**Develop an Externally Mounted, Portable NDE Collar System for Inspecting Main Cables of Suspension Bridges**
Problem Statement	Broken, cracked and/or corroded wires in the main cables of suspension bridges can be detected only by removing the cable covering system. This limits the extent of bridge cable wire that reasonably can be inspected. Even with the removal of the covering, only a small portion of a very limited number of the wires can be visually inspected. Current NDE equipment used for this purpose (Magnetic Perturbation Cable) is very cumbersome and cannot inspect at saddles or under cable bands, and also offers only limited depth of penetration into the cable. Better lightweight NDE equipment that can be used without removal of the cable covering is needed.
Objective	Develop a lightweight non-destructive evaluation tool that provides a high degree of reliability for detection of broken, cracked and/or corroded wires in the main cables of suspension bridges, without having to remove the cable covering system.
Urgency	Inspection priority I - 3

Research Project I-4

Title	**Develop NDE Methods for Exposed Bridge Cable Wires**
Problem Statement	When cables are uncovered for inspection, sometimes followed by “wedging down” to expose internal wires, conditions ranging from what appear to be essentially new wires, to surface pitting and corrosion, to broken wires, are often found. Even in the new condition state, there may be small, invisible cracks that may reduce wire capacity. Corroded but unbroken wires have an unknown capacity. Current technology is of only limited usefulness for this purpose, and more definite information is needed to provide an accurate assessment of remaining wire strength. In addition, current practices usually involve removing and testing of wires, which obviously is a destructive technique. There is a need for improved capability to detect and quantify damage in bridge wires after they have been exposed, but not removed, using non-destructive evaluation techniques.
Objective	Develop non-destructive methods to detect and evaluate damage in exposed bridge wires after the cable covering has been removed.
Urgency	Inspection priority I - 4

Research Project I-5

Title	**Develop Monitoring System for Bridge Cables**
Problem Statement	At best, cable wire inspections are usually limited to a very small percentage of cable length, and a very small percentage of the wires within the cable at the selected inspection locations. It would be beneficial to be able to detect precursors to cable wire adverse conditions and damage before wires break, and to ensure that inspections are made at critical locations and at the proper time intervals, by means of some form of continuous monitoring system.
Objective	Develop a long term, continuous cable monitoring system, possibly based on the use of sensors placed along the cable length and at various positions within cable cross sections, to detect wire damage precursors.
Urgency	Inspection priority I - 5

Corrosion

Research Project C-1

Title	**Develop Understanding of the Effect of Environment on Cable Strength**
Problem Statement	Corrosion in suspension bridge cables can be caused by water intrusion (with or without chloride ions); stress corrosion can occur at locations different than areas of water induced corrosion; residual stresses present since the time of cable construction may be driving stress corrosion; hydrogen embrittlement may be occurring; and fatigue stresses, either load induced or from fretting, may exacerbate the effects of residual stresses and/or corrosion. Metallurgical knowledge of these phenomena has been derived, for the most part, from studies not associated with suspension-bridge cable wire. It is imperative to understand the effect of each of these phenomena, including driving forces or mechanisms, to allow evaluation of remaining wire strength.
Objectives	Task 1: Assess wire strength at varying levels of the above phenomena, and determine which, if any, aggravate the effect of others. Task 2: From the results of Task 1, determine wire strength at varying levels of these phenomena, independently and in combination. Task 3: Develop recommendations for reducing the effect on cable strength of the above phenomena.
Urgency	Corrosion priority C-1

Research Project C-2

Title	**Evaluate Effectiveness of Cable Corrosion Protection Systems**
Problem Statement	The primary corrosion protection system that has been used for suspension bridge cables consists of using galvanized wire, coating the compacted cables with red-lead paste, then wire-wrapping with galvanized wire and painting the whole. The effectiveness of corrosion protection systems has varied.

Cable inspection involves removal of part or all of the protection system to expose some portion of the wires. Red-lead paste is considered to be environmentally unacceptable. There is no data base for selecting an adequate replacement for red-lead. In other countries procedures such as injection of dry air, nitrogen, or polymers have been used to augment the primary protection system. There is very little, if any, data to support long-term life predictions of these systems. To ensure continued long-term serviceability of cables, the various cable protection systems should be evaluated.

Objective

Evaluate the effectiveness of various cable protection systems and procedures, including, but not limited to, the following:

1) Painted wire wrapping
2) Plastic covering
3) Cathodic protection
4) Injectable oils, dry air, nitrogen, polymers, etc.
5) Corrosion Inhibitors

Urgency

Inspection priority C-2

Fatigue

Research Project F-1

Title

Effect of Fatigue Damage on Cable Integrity

Problem Statement

Reliable models to assess the effect of fatigue damage on the life of suspension bridge cables do not exist. Hardly any data exist on the basic fatigue properties (crack growth and thresholds) of wires in various stages of deterioration.

Objective

Develop a procedure to detect fatigue cracks in bridge wire and to determine their effect on wire strength.

Task 1: Data collection

(a) Perform literature search and collect wire samples that may exist to identify possible fatigue crack initiators.
    - assess flaw sizes of in-service broken wires
    - identify cause
(b) Acquire service stress measurements.
    - obtain any existing data
    - develop guidelines to obtain additional measurements

Task 2:Experimental program

(a) Carry out an experimental program to determine the fatigue and fracture properties of cable wire.

(b) Determine the fatigue crack growth threshold of cable wire in un-corroded and corroded wires.
    - assess impact of R ratio
    - assess environmental impact
    - assess effect of mechanical properties on crack growth

(c) Determine fracture toughness.

(d) Evaluate effect of protective treatments on crack growth.

Task 3: Establish capacity.

(a) Establish fatigue resistance and residual capacity of fatigue damaged wire and cables.
    - relate cable behavior to wire test results
    - evaluate wire splices
    - evaluate anchorage conditions
    - evaluate splay areas
    - evaluate wrapping and crossed wires
    - determine capacity of fatigue damaged cable

Task 4: Develop prediction models of fatigue damage and life.

Urgency	Priority F - 1

Evaluation

Research Project E - 1

Title	**Develop Models to Predict Strength of Cables with Various Levels of Wire Damage**
Problem Statement	There are no accepted models for translating cable-wire deficiencies as found during a cable inspection, into cable remaining strength. The factor of safety commonly calculated following a cable inspection appears to have little or no meaning, because (1) factor of safety is a design concept, and (2) there is no convincing structural model of how a suspension bridge cable containing thousands of wires would fail. A cable rating concept is needed, along with a statistically based model to account for the effects of various forms of wire deterioration.
Objective	Develop a cable rating concept, along with a structural model to predict capacity of a cable having wires in various stages of deterioration. The model must account for the following cable wire conditions: • broken wires • stress/strain distribution in wires across the cable diameter • wires cracked but not broken • wire secondary stresses • significance of various wire corrosion mechanisms
Urgency	This will drive all other research; Priority E - 1

Research Project E - 2

Title	**Develop Procedures for use by Cable Inspectors When Performing Condition Surveys of Cables**
Problem Statement	There have been many inspections performed on suspension bridge cables over the years, each of which has resulted in data acquisition using various procedures. As a result of lack of standard guidelines for obtaining data along with samples of deteriorated wires, and lack of uniformity in the reporting format, much of the data has not been suitable in respect to the state-of-knowledge of cable conditions.
Objective	Develop specifications and guidelines for data acquisition to include: • Sampling techniques - when, where, how many? • Wire testing specifications (mechanical and chemical) • Cable-band bolt tension • NDT/ evaluation tools • Formats for reporting inspection and testing results
Urgency	Evaluation priority E - 2

Major Suspension Bridges*

Bridge	Location	Year	Span	Design Engineer	Superstructure Contractor	Notes
Messina Strait	Sicily - mainland Italy		10827	Stretto di Messina, SpA		Under design
Akashi Strait	Kobe-Naruto Route, Japan	1998	6529	Honshu-Shikoku Bridge Authority		Shop fabricated PWS cables
Izmit Bay	Turkey		5538	Anglo Japanese Turkish Consortium Kvaerner, Enka, IHI, MHI, NKK	Design engineer	Under design. Design, build, operate, transfer.
Great Belt (East Bridge)	Denmark	1998	5328	COWIConsult	Coinfra SpA - SDEM	Concrete towers
Humber	Hull, England	1981	4626	Freeman Fox	British Bridge Builders	
Jiangyin	Jiangyin, China	1999	4544	Highway Planning & Design Institute - Yongyi University - Jiangsu Province-Mott MacDonald	Kvaerner Cleveland Bridge	Shop fabricated PWS cables. Concrete towers. Under construction.
Tsing Ma	Hong Kong	1997	4518	Mott MacDonald	Anglo Japanese Construction JV	Highway & railway
Verrazano Narrows	New York City	1964	4260	Ammann & Whitney	American Bridge - Bethlehem - Harris	
Golden Gate	San Francisco	1937	4200	Joseph B. Strauss, Charles Ellis	Bethlehem - Roeblin	
Höga Kusten	Veda, Sweden	1997	3970	Kjessler & Mannerstråle - COWIConsult	Scandinavian Bridge Joint Venture	Concrete towers
Mackinac Straits	Mackinaw City, Michigan	1957	3800	Steinman	American Bridge	
South Bisan-Seto	Kojima-Sakaide Route, Japan	1988	3609	Honshu-Shikoku Bridge Authority	Mitsubishi - IHI -Nippon Steel - Kobe Steel - Yokogowa - Kawasaki	Shop fabricated PWS cables. Highway & railway
Fatih Sultan Mehmet (Bosporus II)	Istanbul	1988	3576	Freeman Fox	IHI - Mitsubishi - Nippon Kokan	
Ataturk (Bosporus I)	Istanbul	1973	3524	Freeman Fox	Hochtief - Cleveland	
George Washington	New York City	1931	3500	O. H. Ammann	McClintic-Marshall - Roebling (1931); Bethlehem(1962)	Lower deck installed 1962

Bridge	Location	Year	Span	Design Engineer	Superstructure Contractor	Notes
Kurushima No. 3	Onomichi-Imabari Route, Japan	1999	3379	Honshu-Shikoku Bridge Authority		Shop fabricated PWS cables. Under construction
Kurushima No. 2	Onomichi-Imabari Route, Japan	1999	3346	Honshu-Shikoku Bridge Authority		Shop fabricated PWS cables. Under construction
25 de Abril	Lisbon	1966	3323	Steinman	American Bridge(1966); Consortio Teja(1998)	Highway & railway. Additional cables and lower deck installed 1998
Forth Road	near Edinburgh, Scotland	1964	3300	Freeman Fox	A.C.D. Bridge	
North Bisan-Seto	Kojima-Sakaide Route, Japan	1988	3248	Honshu-Shikoku Bridge Authority	Kawasaki - Hitachi Mitsubishi - IHI	Shop fabricated PWS cables. Highway & railway
Severn	near Bristol, England	1966	3240	Freeman Fox	Associated Bridge Builders	
Shimotsui-Seto	Kojima-Sakaide Route, Japan	1988	3084	Honshu-Shikoku Bridge Authority	NKK - Mitsui - Nippon Steel - Kobe Steel - Miyaji	Highway & railway
Xaling	Yangtse River, China	1996	2953	MBRDI - Wahan	3rd Construction - MBEB	Shop fabricated PWS cables. Concrete towers
Boca Tigris	Guangdong Province, China	1997	2913	Highway Planning & Design Institute	Gordon Wu - Hopewell	Shop fabricated PWS cables. Concrete towers
Ohnaruto	Kobe-Naruto Route, Japan	1985	2874	Honshu-Shikoku Bridge Authority	Mitsubishi - Kawasaki - Nippon Steel - Kobe Steel - Yokogawa - Miyaji	Shop fabricated PWS cables. Highway & railway
Tacoma Narrows	Tacoma, Wash	1950	2800	Washington Toll Bridge Authority - Dexter R. Smith	Bethlehem - Roebling	
Askϕy	Norway	1992	2789		Monberg & Thorsen	
Kami-Yoshinogawa	Kochi Prefecture, Japan	1971	2733	Yokogawa - Miyaji	Design engineer	1 PWS Cable, 1 aerial-span cable. Plastic cable covering
Innoshima	Onomichi-Imabari Route, Japan	1983	2526	Honshu-Shikoku Bridge Authority	Hitachi - NKK - Nippon Steel - Kobe Steel - Kawada	Shop fabricated PWS cables.
Akinada	Japan	1996	2461			

Bridge	Location	Year	Span	Design Engineer	Superstructure Contractor	Notes
Hakucho	Hokkaido Prefecture, Japan	1996	2362			Shop fabricated PWS cables.
Angostura	Ciudad Bolivar, Venezuela	1967	2336	Sverdrup & Parcel	American Bridge	
Kanmon Strait	Honshu - Kyushu, Japan	1973	2336	Japan Highway Public Corporation	Mitsubishi - IHI - Nippon Steel - Kobe Steel - Yokogawa - Miyaji	Shop fabricated PWS cables.
West Bay	San Francisco - Oakland	1936	2310	C. H. Purcell - G. B. Woodruff	American Bridge	Two 2310 ft. spans
Bronx-Whitestone	New York City	1939	2300	O. H. Ammann - A. Dana - L. S. Moisseiff	American Bridge	
Pierre Laporte	Quebec City	1970	2190	Demers-Vandry-Gronquist	Janin - Cleveland -Dominion	
Delaware Memorial I	Wilmington, Del.	1951	2150	HNTB	American Bridge	
Seaway Skyway	Ogodensburg, N.Y.	1960	2150			
Delaware Memorial II	Wilmington, Del.	1968	2150	E. Lionel Pavlo	Bethlehem	
Gjemnessundet	Krifast, Norway	1992	2044	DOPR	Selmer Moere - Sterkoder - Linjebogg	
Walt Whitman	Philadelphia	1957	2000	Ammann & Whitney - Modjeski & Masters	Bethlehem - America Bridge	
Tancarville	Le Havre, France	1959	1995	Baudin Chateauneuf - CFEM	Design engineer	Concrete towers
New Lillebaelt	Little Belt, Denmark	1970	1969	Ostenfeld & Jonson	Monberg Thorsen	Concrete towers
Kurushima No. 1	Onomichi-Imabari Route, Japan	1999	1969	Honshu-Shikoku Bridge Authority		Shop fabricated PWS cables. Under construction
Rainbow	Tokyo	1993	1870	Metropolitan Expressway Public Corp.		Shop fabricated PWS cables.
Ambassador	Detroit	1929	1850	McClintic-Marshall	Design engineer	
Hakata-Oshima	Onomichi-Imabari Route, Japan	1988	1837	Honshu-Shikoku Bridge Authority	Sumitomo - Mitsubishi - Miyaji - Yokogawa	Shop fabricated PWS cables.

Bridge	Location	Year	Span	Design Engineer	Superstructure Contractor	Notes
Yong Jong Grand	Yong Jong Island, Korea	2001	1804	Yeoshin Corp.	Samsung - Hanjin	Highway & railway. Self anchored. Underconstruction.
Throgs Neck	New York City	1961	1800	Ammann & Whitney	American Bridge - Bethlehem	
Tokyo Harbor	Tokyo	1994	1772	Metropolitan Expressway Public Corp.	Mitsui - Kawasaki - Yokogawa - IHI	Shop fabricated PWS cables.
Benjamin Franklin	Philadelphia	1926	1750	Modjeski - Webster - Ball	Bethlehem - America Bridge - Keystone	
Kvalsund	Hammerfest, Norway	1977	1722			
Skiomen	Narvik, Norway	1972	1722	Arild & Grove	Erik Ruuds Mek. Verksted	
President Mobuto Sese Seko	Matadi, Zaire	1983	1706	IHI Consortium	Design engineer	Shop fabricated PWS cables.
Emmerich	Emmerich, Germany	1964	1640	H. Homberg	Hein Lehmann	
Bear Mountain	Peekskill, N.Y.	1924	1632	H. C. Baird - F P. Witmer - H. D. Robinson	Bethlehem	
Williamsburg	New York City	1903	1600	L. L. Buck	Pennsylvania Steel - Roebling	Highway & rail
Wm. Preston Lane, Jr. Memorial I	Chesapeake Bay, Md.	1952	1600	Greiner - Dexter R. Smith	Bethlehem	
Newport	Narraganset Bay, R.I.	1969	1600	PBQ&D	Bethlehem	Shop fabricated PWS cables. Plastic cable covering
Wm. Preston Lane, Jr. Memorial II	Chesapeake Bay, Md.	1973	1600	Greiner	American Bridge	Shop fabricated PWS cables. Plastic cable covering
Brooklyn	New York City	1883	1595	John A. Roebling	Design engineer	Highway & railway
Lion's Gate	Vancouver, B.C.	1938	1550	Monsarrat & Pratley	Dominion Bridge - Hamilton Bridge	
Sotra	Bergen, Norway	1971	1535			
Hirado Ohashi	Hirado Island, Japan	1977	1526	Nagasaki Prefecture	Mitsubishi - Nippon Steel - Sasebo	

Bridge	Location	Year	Span	Design Engineer	Superstructure Contractor	Notes
Vincent Thomas	San Pedro, Calif.	1963	1500	California Division of Highways - G. B. Woodruff	Kaiser - Yuba - Roebling	
Mid-Hudson	Poughkeepsie, N.Y.	1930	1495	Modjeski & Moran	American Bridge	
Manhattan	New York City	1909	1470	L. L. Buck - L. S. Moisseiff	Phoenix Bridge - Terry & Tench	Highway & railway
Angus L. MacDonald	Halifax, Nova Scotia	1955	1447		Dominion Bridge	
Male Kap Shui Mun	Hong Kong	1997	1447	Mott MacDonald		
A. Murray Mackay	Halifax, Nova Scotia	1970	1400	Pratley & Dorton	Canadian Bridge	
Triborough	New York City	1936	1380	O. H. Ammann - A. Dana - L. S. Moisseiff	American Bridge	
Alvsborgsbron	Gothenburg, Sweden	1966	1370			Concrete towers
Hadong-Namhae	Pusan, South Korea	1973	1325	Nippon Steel - IHI	IHI	
Baclan	Bordeaux	1967	1292			Concrete towers
Amu-Daria River	Turkistan	1964	1280			
Cologne- Rodenkirchen	Cologne	1954	1240	H. Homberg; Rendel Palmer & Tritton	Strabag - Thyssen(1954); Cleveland (1992)	Widened by adding tower legs and cables 1992
St. Johns	Portland, Ore.	1931	1207	Robinson & Steinman	Wallace Bridge - Roebling - La Pointe	
Wakato Narrows	Kitakyushu City, Japan	1962	1204	Japan Highway Public Corporation	Yokogawa	Widened to 4 lanes, additional cables installed 1990
Mount Hope	Mount Hope Bay, R.I.	1929	1200	Robinson & Steinman	Bethlehem - Keystone	
International	Ogdensburg, N.Y.	1960	1150	Modjeski & Masters - P. L. Pratley	American Bridge	
Hercilio Luz	Florianopolis Island, Brazil	1926	1114	Robinson & Steinman	American Bridge	

Bridge	Location	Year	Span	Design Engineer	Superstructure Contractor	Notes
Bidwell Bar	Oroville, Calif.	1965	1108	Calif. Dept. of Water Resources	Bethlehem	Plastic cable covering
Varodd	Kristiansand, Norway	1956	1106			
Tamar	Saltash, England	1962	1100			Concrete towers
Deer Isle	Penobscot Bay, Maine	1939	1080	Robinson & Steinman	Phoenix Bridge	
Rombaks	Nordland, Norway	1964	1066			Concrete towers
Maysville	Maysville, Ky.	1931	1060	Modjeski, Masters & Chase	Roebling - Bethlehem	
Ile D'Orleans	Quebec City	1936	1059	Monsarrat & Pratley	Dominion Bridge	
John A. Roebling	Cincinnati	1866	1057	John A. Roebling (1866); Wm. Hildenbrand (1898)	John A. Roebling(1866); Wm. Hildenbrand(1898)	Widened to 4 lanes, additional cables installed 1898
Dent	Orofino, Idaho	1971	1050	HNTB	Fought	
Otto Beit	Chirundu, Zimbabwe	1939	1050	Freeman Fox	Dorman Long	
Cologne-Mülheim	Cologne	1951	1034	M.A.N.	Design engineer	
Mampimi	Mampimi, Mexico	1900	1030	Henry G. Tyrrell	Wm. Hildenbrand	
Wheeling	Wheeling, W Va.	1849	1010	Charles Ellet	Design engineer	First bridge span in the world to exceed 1,000 ft;destroyed by wind1854, Rebuit (by Ellet) 1856
Bidwell Bar	Oroville Gorge, Calif.	1854	1010			Moved to new location 1965
New Elizabeth	Budapest	1965	984	Uvaterv - Fömterv	Ganz-MAVAG - Massanyi - Fekete - Vogt	
Konohana	Osaka	1987	984	Hanshin Expressway Public Corp.	Hitachi - Mitsubish	Shop-fabricated PWS monocable
Elizabeth	Budapest	1964	951	A. Czechelius	Mavag-Ganz Metals	

Bridge	Location	Year	Span	Design Engineer	Superstructure Contractor	Notes
Tjeldsund	Bjerkvik, Norway	1967	951			
Gran'Mere	Quebec City	1929	949	Robinson & Steinman	Roebling	
Cauca River	Columbia	1894	940			
Peace River	Alberta, Saskatchewan	1950	932			
Cornwall-Massena International	Massena, N.Y	1958	900	Steinman		
Terenez	Aulne, France	1952	892			
Brevik	Telemark, Norway	1962	892			Concrete towers
Royal Gorge	Canon City, Colo.	1929	880	G. E. Cole	Midland Bridge	
Higashi-Ohi	Kumamoto Prefecture, Japan	1976	866		Kurimoto	Shop fabricated PWS cables.
Kjerringstraumen	Nordland, Norway	1975	853			
Rognonas	Viviers, France	1949	833			
Kamiyoshinagawa	Kochi Prefecture, Japan	1972	832			
Cuscatlan	El Salvador	1943	820	American Bridge	Design engineer	
Dome	Dome, Ariz.	1929	800	Arizona Highway Department	Roebling	
Waldo-Hancock	Bucksport, Maine	1931	800	Robinson & Steinman	American Bridge	
Thousand Islands	Clayton, N.Y	1938	800	Robinson & Steinman - Monsarrat & Pratley	American Bridge	
Kosui Ohdan	Kochi Prefecture, Japan	1983	787			Shop fabricated PWS cables.
Iron Gate II	Rumania - Yugoslavia	1994	787	Victor Popa	Sorin Heinman - ENERGO - MONTAGE	

Bridge	Location	Year	Span	Design Engineer	Superstructure Contractor	Notes
Anthony Wayne	Toledo, Ohio	1930	785	Waddell & Hardesty	McClintic-Marshall	
Mobile River	Alabama	1991	780			
Parkersburg	Parkersburg, W. Va.	1916	775			
Fykesund	Norway	1937	750			
Iowa-Illinois Memorial I	Moline, Ill.	1935	740	Modjeski, Masters & Chase	Bethlehem	
Iowa-Illinois Memorial II	Moline, Ill.	1959	740	Modjeski & Masters	Bethlehem	
South 10th Street	Pittsburgh	1933	725	Allegheny County	American Bridge	
Kirjala Sound	Finland	1964	722			
Fukase	Ishikawa Prefecture, Japan	1979	709	Matsuo Bridge	Design engineer	Shop fabricated PWS cables.
Rondout	Kingston, N.Y	1921	705	Robinson & Steinman	Terry & Tench	
General U.S. Grant	Portsmouth, Ohio	1927	700	Robinson & Steinman	Dravo - American Bridge	Plastic cable covering. Cables replaced 1940 and again 1979 by American Bridge
Fort Steuben	Steubenville, Ohio	1928	689	Dravo	Design engineer	Cables replaced 194[illegible]
Hakogase	Fukui Prefecture, Japan	1967	676			

*This list of major suspension bridges was compiled by Jackson Durkee. The list is maintained by the National Steel Bridge Alliance.

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20 December 1997

Mr. Robert E. Skinner, Jr.,
Executive Director
Transportation Research Board
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Dear Bob,

Re: Safety Appraisal of
Suspension Bridge Main Cables

You will recall that I presented some views to you during the Annual Meeting of the National Academy of Engineering, on 8 October, on the problem of safety appraisal of suspension bridge main cables. You suggested that I send you a letter on this problem.

My thesis on this subject can be stated as follows:

- The parallel-wire main cables of many major suspension bridges in the U.S. appear to be in questionable condition.

- Some suspension bridge main cables have been inspected and appraised in recent years by various engineering organizations, each of which has performed the studies in its own way. It seems likely, however, that the majority of such cables have never received a thorough inspection--however that might be defined.

- On the basis of my limited knowledge of the cable studies that have been performed, it would appear that none of them have taken account of all factors that might need to be considered. Further, the weighting given to the various factors appears to be somewhat arbitrary.

- To my knowledge there is no convincing structural model of how a suspension bridge cable containing thousands of wires would fail. Accordingly, the term "factor of safety" commonly used in respect to the structural integrity of such cables appears to have only limited meaning.

- Most recently I have seen samples of failed cable wires from a well-known major U.S. suspension Bridge, that exhibit what has been termed "square breaks." How widespread, and how serious, this problem might be on the cables of this bridge is not known.

- I am informed that this problem of "square breaks" might exist in The cables of other major suspension bridges, in addition to those of the bridge under review. There is the prospect that this problem could be widespread.
- There seems clearly to be no agreed-upon, recognized procedure to appraise and evaluate the condition, strength and safety of suspension bridge main cables. Accordingly, as individual bridges are placed under review, each engineering organization called upon must perforce develop its own procedures.

My conclusion from all of these considerations, as mentioned to you on 8 October, is that the U.S. needs a research project to identify and investigate the factors relevant to the strength and adequacy of suspension bridge main cables, and to develop these factors into a logical and suitable procedure to appraise cable safety aspects.

Many references could be cited to illustrate the need for a cable safety appraisal procedure, such as the following:

- IABSE workshop "Evaluation of Existing Steel and Composite Bridges," held in Lausanne, Switzerland in March 1997. (See enclosed article from "Structural Engineering International,"Vol. 2 No. 2, May 1997.) The aim of the workshop was to identify promising scientific work and develop evaluation methods what might be suitable for use in structural safety appraisal of these structures. The significant factor here is that even for ordinary structures such as short- and medium-span steel and composite bridges, there is no recognized procedure for structural safety evaluation.
- Paper "Safety Analysis of Suspension-Bridge Cables: Williamsburg Bridge" by Matteo, Decdatis & Billington, Journal of Structural Engineering, ASCE, Vol. 120 No. 11, November 1994. (See copy enclosed.) The objective of this paper was to estimate the safety factor of the corroded

Williamsburg main cables, defined as the ratio of predicted actual remaining strength to calculated maximum force. As I see it, this definition has no real meaning in the absence of a definitive failure model for a large parallel-wire suspension bridge cable. Further, nothing is said in the paper regarding such factors as the effect of transverse pressure (in saddles and under cable bends) on wire tensile strength, the effect of wire kinks at the edges of tightened cable bands, and the local cable bending effect caused by the concentrated vertical loads applied at the cable bands by the suspenders. A review of this paper will disclose a number of other questions: for example, there is no estimate of the frequency at which wires may be breaking, and the effect of such ongoing breakage on future cable strength and "factor of safety."

- Paper "Cable Safety Factors for Four Suspension Bridges" by Haight, Billington & Khazem, Journal of Bridge Engineering, ASCE, Vol. 2 No. 4, November 1997. (See copy enclosed.) This paper reports on the evaluation of the cables of the Williamsburg (1903), Bear Mountain (1924), Triborough (1936) and Golden Gate (1937) suspension bridges. Table 1 of the paper lists 46 U.S. suspension bridges with main spans of 700 ft (213 m) or more, 27 of which (59%) are over 50 years of age. From a review of this paper, several key questions come forward. For example, in no case would I Judge the determination of either the number or the effect of broken cable wires to be persuasive. Nothing is said about the adverse conditions that usually exist within the cable anchorage chambers. Further, it may be noted that in the case of each bridge (see Fig. 3) the "current ductile-brittle safety factor" is significantly less than the "original actual safety factor"; the ratios range from about 83% for Golden Gate on down to about 56% for Triborough. Such losses are highly significant, and must be assumed to exist on most if not all of the older bridges listed in Table 1 and must be assumed to be progressing.

The available evidence points clearly to the stark fact that the main cables of many major U.S. suspension bridges are indeed in questionable condition. It is likely that many such cables have never even received a reasonable inspection, however that might be defined. Indeed, it should be noted that it is not even practical to accomplish representative visual inspection and sampling of as much as perhaps 1% of the cable wire. For example, each cable of the second Tacoma Narrows suspension bridge (1950) is about 6000 ft (1800 m) long and contains 8702 wires, making a total wire length of approximately 52 000 000 ft (16 000 000 m). Representative visual inspection and wire sampling of even 1% of this wire--500 000 ft (150 000 m)--would constitute quite an undertaking. Inspection of wires below the cable surface requires "wedging down," while inspection of inner wires in and near the cable bands and saddles is not possible. On the basis of these and other such practical considerations, we must recognize that there is no effective procedure for comprehensive inspection and sampling of wires in a suspension bridge cable. Clearly, the procedures and results will vary depending on what engineering organization carries out the work.

The present unsatisfactory situation with respect to suspension bridge main cables carries certain similarities to that which existed with respect to steel columns in the early 1940s, when Jonathan Jones (of the Bethlehem Steel Corporation) put forward a plea to the structural engineering profession to organize their efforts and develop suitable procedures for column strength appraisal. In a key letter addressed to ASCE in 1941, Jones stated: "I urged and do urge that it is a national necessity that as many as possible of the bodies that are interested in writing formulas for steel columns get together in some kind of central group and carry on the research and analyze the results in a way that will be satisfactory to all." The result was the formation of the Column Research Council (now Structural Stability Research Council) in 1944, sponsored by ASCE under the auspices of the Engineering Foundation.

In summary, we can set forth the following basic considerations:

- Available evidence indicates that the strength of the cables of some of the country's major suspension bridges has deteriorated significantly, Some bridge cables may even be unsafe, however that term might be defined.

- Many such bridge cables have probably not even been given a serious inspection.

- The procedures for accomplishing a comprehensive cable inspection are by no means well defined.

- There is no logical and accepted method for transforming cable inspection data into cable strength data.

- The concept "cable factor of safety" is vague, and calculated values for a given bridge cable have no clear meaning.

- The failure of the main cables of even a "minor" suspension bridge would constitute a catastrophe, and call into question the cables of most other suspension bridges. Suspension bridge main cables are non-redundant components, and when one cable fails the opposite cable will most likely also fail, followed by collapse of the towers and dropping of the suspended deck structure.

In view of these considerations, I see a pressing need for launching a project to develop procedures for safety appraisal of suspension bridge main cables. It appears to me that you and the Transportation Research Board are in the best position to evaluate the priority of such a project in respect to other national engineering needs, and then to determine how the project could be initiated and carried forward.

Yours sincerely,

Jackson

JD:js
Enclosures

Copies: Dr. G. Wayne Clough, Chairman
Civil Engineering Section
National Academy of Engineering

Dr. Wm. A. Wulf, President
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APPENDIX E

BIBLIOGRAPHY

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1. Betti, R., Yanev, B., "Conditions of Suspension Bridge Cables: The New York City Case Study". This paper was presented at the 1999 Annual Meeting of the Transportation Research Board.

2. Csogi, "Manhattan Bridge, Rehabilitation of the Main Cable Eyebars, Cable "C" at the Manhattan Anchorage."

3. Durkee, J.L. & Thomaidas, S.S., "Erection Strength Adequacy of Long Truss Cantilevers", Journal of the Structural Division, *ASCE*, January 1977.

4. Fisher, J., Kaufmann & Pense, A., "Effect of Corrosion on Crack Development and Fatigue Life", *Transportation Research Board Proceedings 1998 Annual Meeting*, Paper #981038.

5. Haight, R.Q., Billington, D.P., & Khazem, D., "Cable Safety Factors for Four Suspension Bridges", *ASCE Journal of Bridge Engineering*, Vol. 2, No. 4, November, 1997, Paper #13321, pp157-167.

6. Hopwood, Theodore. "Ohio River Suspension Bridges: An Inspection Report" Kentucky Transportation Research Program, *Research Report UKTRP-81-6*, June 1981.

7. Kendall, M.H., "Cable Restoration - Brooklyn and Williamsburg Bridges". Proceedings Suspension Bridge Operators Conference, April 17 & 18, 1991, Poughkeepsie, New York.

8. Kendall, M.H. & Sluszka, P. "In-depth Inspection of Suspension Bridge Main Cables and Suspender Ropes". Proceedings Second International Conference on Bridge Management, University of Surrey, Guildford, April, 1993.

9. Matteo, J., Deodatis, G., & Billington, D.P., "Safety Analysis of Suspension-Bridge Cables: Williamsburg Bridge", ASCE *Journal of Structural Engineering*, Vol. 120, No. 11, November, 1994.

10. Matteo, J., Deodatis, G., Billington, D.P., & Stahl, F.L., (discusser), "Safety Analysis of Suspension-Bridge Cables: Williamsburg Bridge. Discussion and Closure". ASCE *Journal of Structural Engineering*, Vol. 122, No. 7, July, 1996.

11. Mayrbaurl, R.M. "Anchorage Repairs on New York City Suspension Bridges", Proceedings International Association for Bridge and Structural Engineers Symposium, San Francisco, California, 1995, Vol. 73-1.

12. Mayrbaurl, R.M., Good, "Re-anchoring a Main Cable on the Manhattan Bridge", Proceedings ASCE Metropolitan Section, November, 1988.

13. Mondello, F.J., “Inspecting and Evaluating New York's East River Suspension Bridge Cables”. Proceedings International Bridge Conference, June 13-15, 1988, Pittsburgh, Pa.

14. Paulson, P., Cullington, D., “Evaluation of Continuous Acoustic Monitoring as a Means of Detecting Failures in Post-tensioned and Suspension Bridges”, Proceedings XIII FIP Congress & Exhibition, May 23-29, 1998, Amsterdam.

15. Perry, R.J., “Estimating Strength of the Williamsburg Bridge Suspension Cables”, *The American Statistician*, August 1998, Vol. 52, No. 3.

16. Robert, J.L., Laloux, R., “Non-destructive Control of Engineering Structure Cables”. Bulletin Liaison Lab Ponts Chauss, 1974/03/04.

17. Sluszka, P. & Hayden, “Inspection, Evaluation and Rehabilitation of Suspension Bridge Cables”. International Association for Bridge and Structural Engineering Symposium, Lisbon 1989, Volume 57/1.

18. Virlogeux, M., “Replacement of the Suspension of the Tancarville Bridge”. This paper has been submitted to the Transportation Research Board for the 1999 Annual Meeting.

19. Yanev, B. “Infrastructure Management Systems Applied to Bridges”, Proceedings International Symposium on Operation and Maintenance of Large Infrastructure Projects, Balkema, Rotterdam, 1998. ISBN 9054109637.

20. Yanev, B. “Keeping a Hold on History”, *Bridge Design and Engineering*, Third Quarter, 1998.

21. Yanev, B. “The Management of Bridges in New York City”, *Engineering Structures*, Vol. 20, No. 11, 1998.

22. “Acoustic Monitoring System”, Quasar Concept, LCPC, Paris.

    This is not a technical paper, but provides a description of this equipment to provide real-time monitoring of suspension bridge integrity.

23. “Seismic Performance of Long-Span Suspension Bridges in the United States”, by Subcommittee on Seismic Performance of Bridges, IABSE Symposium, San Francisco, August 23-35, 1995.

24. “SoundPrint - Continuous Structural Monitoring”, PURE Technologies, Calgary, Alberta, Canada. This is not a technical paper, but provides a description of this equipment to locate failures in high-tensile steel wire, strand or cable.