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**Contractor's Final Report: Phase I--Technology Review**

# Nondestructive Methods for Condition Evaluation of Prestressing Steel Strands in Concrete Bridges

## Final Report
## Phase I: Technology Review

**Prepared for:**

National Cooperative Highway Research Program
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# DISCLAIMER

## ACKNOWLEDGMENTS

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# ABSTRACT

This report contains the findings of a study performed to determine whether a practical and economical method for quantitative nondestructive condition evaluation of bonded prestressing systems in highway bridges exists. The report provides a comprehensive summary of a global technology review made to identify NDT methods developed in the time period commencing in 1990. The noted NDT advances of the decade, which possessed some potential for assessing strand condition, were characterized and evaluated based on technical, accuracy, operational, logistical, safety, and other factors. The contents of this report will be of interest to bridge maintenance engineers, researchers, and others concerned with assessing the condition of concrete bridges and the degree of strength and serviceability impairment created by deteriorating prestressing systems.

# SUMMARY

Although the durability performance of the nation's 100,000 prestressed concrete bridges is considered satisfactory, the age of an appreciable share of these assets is approaching the common design service life of 50 years. The current state of the art in concrete bridge condition evaluation relies on visual inspection. However, deterioration in prestressing strand or tendon condition is not always reflected by distress visible on the concrete surface. Further, the effect of deterioration of prestressing steel is more disruptive than that of mild reinforcement. Strand, due to its high mechanical strength and metallurgical characteristics, is smaller in cross section than conventional reinforcing steel and is proportionally more impaired by loss of section. The material is also susceptible to less common and less predictable forms of deterioration such as stress corrosion, hydrogen-assisted cracking, corrosion fatigue, and fretting corrosion.

Methodology for prestressed concrete bridge condition evaluation, therefore, could be revolutionized through the development of accurate, quantitative nondestructive test methods for strand in pretensioned and posttensioned structures. Though believed to be difficult to achieve, means for routinely and precisely detecting the presence and extent of deterioration of embedded steel have been sought since the early 1970s. Researchers have investigated diverse techniques such as magnetic, radiographic, acoustic/ultrasound, radar, thermographic, eddy current, electrochemical, and acoustic emission.

This NCHRP research study examined and summarized advances in nondestructive test (NDT). In addition, the technological horizon was assessed to identify candidate methods that would permit identification of loss of cross sectional area in strand attributable to corrosion and cracking. Organized as a two-phase program, the research was intended (a) to identify and select a promising, recently devised technique suitable for strand evaluation in pretensioned and posttensioned components and (b) to develop a practical, cost-effective NDT tool.

In the study, a global technology review identified some promise among the data interpretation and operational refinements in several methods studied in the research. Recent development in Switzerland of a nondestructive test method for strand based on electrical time domain reflectometry (TDR) was also noted. The latter technique relies on the strand itself as a sensor through which high-frequency electrical pulses are sent. Impedance discontinuities caused by physical anomalies along the strand result in partial reflection of the pulse. These reflections are sensed by commercially available TDR equipment used for fault detection in power and communication cables. However, the long-term Swiss research into the TDR method, which coincided with the schedule of this NCHRP study, concluded that the measurement technique is not suitable for use in the bonded prestressing systems.

Review of recent refinements in NDT methods led the research team to conclude that the current state of the art will not permit an evaluation of the embedded prestressing strand's condition as precisely and broadly as sought in the NCHRP project goals and within the project constraints. However, the research team, in collaboration with members of the NCHRP 10-53 Research Panel, identified recent improvements in the equipment and data-gathering features of the magnetic flux leakage method. These advances could, with experimental correlation and refinements in automated data interpretation techniques, be adapted to successful automated NDT of strand in pretensioned standard girders. Pretensioned standard girders represent roughly one-third of the concrete bridge inventory. Thus, even within the constraints of its present limitations, the magnetic flux leakage technology as configured would be of considerable benefit and potential. The team recommended that an experimental effort be instituted in the second phase of the study, and a second phase research plan was developed. Additionally, the

researchers formulated recommendations for developing low-cost, preplaced, passive sensor systems for new prestressed construction to fulfill future quantitative condition evaluation needs for strand. This approach may have relevance, since the growing population, variety, and complexity of prestressed concrete bridge structural systems may far outpace the public transportation sector's resources for effective utilization of NDT methods.

# CHAPTER 1

# INTRODUCTION

## Project Description and Goals

This NCHRP research program sought a practical, economical method for quantitative nondestructive condition evaluation of concrete- or grout-encased prestressing strand in highway bridges. The method was to have the ability to measure loss in strand cross-sectional area attributable to structural aging and degradation.

A methodical, quantitative, field-applied engineering basis for evaluating and maintaining the prestressed concrete bridge infrastructure's reliability has long been pursued. Availability of a nondestructive testing or imaging technique could consolidate and simplify the application of periodic measurements and inspections of prestressed concrete bridges.

Overall, the research program attempted to identify and evaluate recently developed techniques and technology-driven refinements of methods formerly shelved or rejected. NCHRP objectives were met by implementing Project 10-53 within the following scope of activities:

- A comprehensive global technology review of relevant NDT methods was made.
- Promising candidate methods were evaluated, selected, and categorized.
- A study report (at the end of the first phase of research) addressing the selected candidate methods and recommending future research direction was issued.
- A detailed research plan to validate and develop the primary goals for the NDT technology through bench-scale, full-scale, and field-test protocols was prepared.

This document presents the research team's Phase I study report. It documents the feasibility of various NDT systems based on scientific examination of the state of the art. This Phase I report also presents an assessment of the technology horizon with respect to promising nondestructive testing and evaluation concepts and documents the research team's recommendations for future research.

The review was conducted by the Structural Laboratory staff of Construction Technology Laboratories, Inc. (CTL) with the assistance of Dr. David Whiting of the CTL Materials Research and Consulting Group, and subcontractors SRI International and Cordec International, Inc. In carrying out this study, the team considered practices and technology from Canada, Germany, Switzerland, the United Kingdom, France, Italy, India, the Netherlands, Norway, and the United States and drew on the expertise and experience of the investigators.

## Function of Prestressing Reinforcement

Most concrete bridges in this country consist of prestressed concrete in two predominant fabrication/construction categories: pretensioned and posttensioned. The geometric cross sections and design/construction procedures used represent a broad range of possible structural design configurations. Common to all of these is the role of the prestressing reinforcement. This component can take the form of either cold-drawn, high-strength wire or wire helically wound to form strand and rolled high-strength threaded bars. Prestressing strand for bridge construction is typically supplied with a tensile strength of 270 ksi.

In bridges, this reinforcement element provides the concrete structure with a means for counteracting tensile stress resulting from service loads and with the needed capacity for the strength limit state. Consequently, the prestressing reinforcement's quality and its protection against deterioration processes are paramount to attaining functional and safety requirements. Design of prestressed members provides directly for several forms of durability measures such as dense concrete cover; corrosion-mitigating grout systems; and innovative, proprietary, full-length corrosion barriers integrated with anchorage systems for posttensioned structures. Additionally, structural details and standards have been developed and introduced by AASHTO and various industry organizations such as PCI (Prestressed Concrete Institute), PTI (Posttensioning Institute), ASBI (American Segmental Bridge Institute), and ACI (American Concrete Institute) to manage the effects of prestressing reinforcement's heightened susceptibility to certain aging mechanisms such as fatigue, fretting, and time-dependent, inelastic changes in concrete structure components.

Assessment of an existing concrete bridge structure's ability to function, therefore, must consider the condition of the embedded prestressing reinforcement. The nation's prevailing bridge management strategy relies on fixed-interval inspections and computation of bridge load ratings. These inspections generally consist of visual observation of the structural features visible to the unaided eye. Further, no effective means exist for quantitatively measuring condition of the strand. No methodology for integrating results of such measurements into the strength and serviceability rating computations has been devised. Ideally, a technique that noninvasively examines prestressed reinforcement in concrete and generates data regarding residual strength of the aged reinforcement would fill that need. In turn, confidence in the safety and reliability of the infrastructure would be raised, the maintenance philosophy for bridges would evolve into a more reliable and accurate form, and highway infrastructure rehabilitation and replacement expenditure allocations would be much more systematic.

## Available Prestressing Reinforcement Evaluation Techniques and Methodologies

Approximately 13 years ago, the Transportation Research Board and the National Academy of Sciences commissioned NCHRP Project 10-30, "Nondestructive Methods for Field Inspection of Embedded or Encased High Strength Steel Rods and Cables." This program and several other initiatives around the world succinctly identified the state of the art for NDT systems for evaluating condition of prestressing strand. The various techniques possessing prospective relevance for the strand system included magnetic methods, radiographic methods, acoustic/ultrasonic methods, radar, thermography, eddy current methods, tomography, and vibration monitoring techniques.

In general, the Project 10-30 technology review did not identify an available, effective technique. The study results were not published in the NCHRP report series. Researchers recommended investigation of corrosion-monitoring techniques as a means for attaining study goals, but since the Strategic Highway Research Program was working in this direction, the NDT research was redirected. A second phase of the project theoretically and experimentally investigated evolution of a candidate ultrasonic system for identifying the presence and extent of transverse cracking and corrosion-induced, loss-of-section defects in strand. A prototype test system was developed, but capabilities of this system were deemed to be limited. Results of this research were also not published in the NCHRP report series.

Therefore, at the conception of planning for this NCHRP 10-53 project, no single methodology had been identified and developed that could successfully examine, identify, and characterize consequential changes in condition of strand on a basis that was nondestructive, rapid, and practical. During the course of its proposal research for NCHRP Project 10-53, the CTL team noted the existence of a Swiss-derived methodology using electrical pulses traveling the length of strand for defect detection. Phase I research was identified with the goal of stringent evaluation and potential refinement of this method as well as exploring other methods on the NDT technology horizon with the assistance of SRI International's scientists.

# CHAPTER 2

# CONDITION ASSESSMENT NEEDS FOR EXISTING PRESTRESSED CONCRETE BRIDGES

## Historically Prevalent Aging and Degradation Mechanisms

Overall, the historical performance record of 100,000 prestressed concrete bridge structures in the United States is generally considered satisfactory. Nevertheless, the effect of prestressing steel deterioration and rupture has severe consequences in terms of the strength and projected reliability of a concrete bridge. Additionally, deterioration of embedded prestressing strands is not necessarily reflected in surface distress in a structure, and the prestressed concrete component of the nation's infrastructure has matured to the point where remaining useful life and durability assessments need to be made more frequently. Therefore, the need for nondestructive means for establishing integrity of prestressing tendons has never been greater.

Techniques capable of noninvasive examination of condition and integrity of prestressing strands have been sought for decades. Prior research efforts in this field, including NCHRP programs, though identifying methods with promise, did not result in widespread implementation of a reliable, practical technique.

Federal Highway Administration surveys in 1987 and 1992 of 20 major in-service structures representative of the prestressed concrete component of the nation's highway infrastructure supported and highlighted the need for design for serviceability. These surveys of pretensioned and posttensioned superstructures of various configurations and environmental exposures found no evidence of serious prestressing reinforcement corrosion or other systemic degradation.(1,2) However, these and other studies by the highway bridge engineering research community led to the formulation of recommendations related primarily to minimization of the number of deck joints; more durable, protective concretes and coatings for anchorage components; improved deck and joint drainage systems to redirect passage of aggressive solutions from corrosion-susceptible components near girder ends; and implementation of more effective deck joint maintenance programs.(2)

Nevertheless, prestressed concrete structures have displayed certain premature performance impairments worldwide. Szilard,(3) in a 1969 survey, noted that corrosion of prestressing reinforcement was and would continue to be the predominant form of unexpected damage to structures, whether accidental or deterioration/aging-based.

In 1975, the Australian Water Resources Council published the results of a wide-ranging study on the performance of prestressed concrete structures worldwide. It was intended to assess the performance of Australian prestressed structures and compare it with that of structures elsewhere.(4) The work was prompted by premature multiple failures of prestressed, wire-wound pipelines and tanks and helped establish improved specifications for prestressing wire and concrete/mortar and other protective coatings.

Citing the criticality of corrosion protection for prestressed concrete pressure vessels for nuclear reactor containments, Griess and Naus(5) studied the corrosion behavior of high-strength prestressing steels in 1978, reviewing several incidents of prestressing steel failures in nuclear pressure vessels in the United States, France, and the United Kingdom.

Schupack(6) conducted a performance survey covering the period of 1950 to 1977, concluding that the noted failure incidence rate of 200 tendons out of the estimated worldwide prestressing steel consumption of 30,000,000 tons was negligible. However, a study performed in 1982(7) reported that 50 structures with tendon corrosion were noted in the period between 1978 and 1982. Ten of these reportedly displayed brittle fractures suggestive of environmental cracking phenomena. In 1992, Ciolko et al.(8) summarized structural evaluation and failure analysis data from U.S. prestressed concrete pipeline failures, estimating based on industry and water utility records that more than 60 such pressure pipelines had failed in the United States, leading in most cases to complete pipeline replacement or relining. The heightened susceptibility of prestressing wire to accelerated corrosion was a common factor.

Reflecting on the dangers of complacency resulting from reliance on favorable statistical conclusions of surveys of prestressed concrete structures worldwide and focusing on the specific lessons derived from failed prestressed bridge structures, Podolny(9) issued cautionary guidance to bridge designers in 1992. He emphasized that the consequences of corrosion and rupture of prestressed reinforcement in bridges are so severe from the public safety and economic impact perspective that unusually stringent corrosion-prevention methods are required for prestressing steel. Podolny observed that it was only in the last one and one-half decade that the industry has begun to understand the role that environment and the many forms of corrosion have on the reliability of prestressing reinforcement. In the research team's opinions, Podolny's most compelling argument for caution is based on the 1985 failure of the posttensioned segmental Ynys-y-Gwas Bridge in Great Britain. Although the structure had been inspected 10 times over its 32-year life, including 6 months prior to catastrophic collapse under self-weight, no external evidence of corrosion had been noted, and no warning signs of distress had been revealed.

Examination of failure remnants indicated, however, that the wires in grouted posttensioning tendons had been consumed by corrosion to the point of tensile overload. Benefits of the availability of a prestressing reinforcement NDT method to complement visual condition survey methods in the case of structures like this are obvious.

## NDT Implementation for Inspection and Maintenance Practice

Projecting the experience from the historical performance trends should guide the selection of nondestructive structural evaluation tools. As the average age of prestressed concrete bridge inventory increases, this may lead to challenges for future NDT identification and measurements.

For example, currently undiagnosed corrosion mechanisms will need to be detectable by NDT techniques. Increases in highway traffic load levels and volumes due to economic growth may accelerate rates of damage. Changes in prestressing strand metallurgical composition brought about by manufacturing process upgrades, new supply sources, or incorporation of strand coatings may influence susceptibility to corrosion.

These and yet-to-be discovered degradation mechanisms will face the bridge maintenance engineer. Strand- or tendon-focused NDT methodology, slated for incorporation as a routine maintenance inspection tool in bridge management, would therefore need to discern loss-of-section corrosion, environmental cracking phenomena (stress corrosion), fatigue cracking, and wire rupture.

Procedurally, data acquired from strand NDT programs would be analyzed to assess residual strength and serviceability of component structural members. To avoid repetition of the elaborate effort necessary for 100-percent inspection at each interval, sampling strategies rationalizing smaller lots of alternating individual components may be carried out.

All strands in each chosen girder or other component selected for inspection would be scanned over their entire length for anomalies. The structural significance of defects would be evaluated on the basis of computations made to assess remaining strength. The process would guide rehabilitation or replacement decisions by comparing structural condition of elements noted among inspection intervals of record and by assessing the adequacy of the bridge span or segment with respect to strength and serviceability thresholds.

# CHAPTER 3

# APPROACH TO TECHNOLOGY REVIEW

Identifying and reviewing new NDT technologies for condition assessment of prestressing strand was considered critical to the successful conduct of Phase I of the NCHRP 10-53 project. Thus, the first research phase concentrated on not only assessing the relevance of technological advances for improving previously identified test methods, but also intensively seeking new, untried methods. The work in this phase was completed within the scope of the following three-task effort.

## Task 1 - Review Recent and Emerging NDT Technology

CTL carried out a comprehensive global review of available current literature and identified recent developments applicable to locating defects in prestressing strand. Emphasis was placed on efforts of the last 5 years. CTL researchers used the resources of the following libraries and sources of information:

- Portland Cement Association (PCA) Library
- SRI International Library
- Northwestern University Library
- John Crerar Library (Chicago)
- Linda Hall Reference Library (Kansas City)
- Defense Technical Information Center

Additionally, the following on-line engineering databases were used to complete the search:

- INSPEC
- Mechanical Engineering Abstracts
- METADEX
- Aluminum Industry Abstracts,
- SciSearch
- Dissertation Abstracts Online
- Aerospace Database
- Engineering Materials Abstracts
- ICONDA
- Dialog
- Compendex
- STN
- TRIS
- NTIS

Results of search "hits" in the form of 650 titles and abstracts were reviewed. Promising information sources were identified. To ensure that a time interval-created gap in reviewed technologies between this project and the predecessor NCHRP 10-30 projects did not occur, information dating back as far as 10 years was considered. Forty research reports and articles were catalogued, reviewed in detail, and summarized for technical evaluation and report preparation purposes.

Candidate NDT technologies captured in the literature search and references included the following:

- Induction thermography
- Time domain reflectometry (TDR)
- Reflectometric impulse measurement (RIMT)®
- Ultrasonics
- Vibration-based damage detection
- Microwave radiometry
- In situ stress measurement (strain relief)
- X-ray diffraction
- Pulsed eddy current
- Tomography and radiographic imaging
- Acoustic emission
- Noncontact ultrasound using lasers
- Magnetostrictive sensor (MsS) techniques
- Nonlinear vibro-acoustics
- Power focusing ground penetrating radar

Contacts with NDT practitioners and centers were made. Ontario Ministry of Transport staff were contacted regarding their experiences with prestressing reinforcement NDT techniques, including their specific assessment of the RIMT® technology, which had been attempted on a Sarnia, Ontario, posttensioned bridge structure. This technology had been identified as a candidate method during CTL's proposal research. Recently published Swiss and Italian research results on this technology were sought, reviewed, and catalogued.

Information from FHWA's NDT center was reviewed, as were recent innovations from the Center for Nondestructive Evaluation at Iowa State University and Stevens Institute of Technology. CTL subcontractor SRI International made its contributions to the research; a report entitled "Assessment of the Potential for Using Emerging Nondestructive Evaluation Techniques to Detect Corrosion and Cracking in Prestressing Steel Strands" by Dr. Alfred J. Bahr was received and reviewed in detail (Appendix A here). Dr. Bahr's work in particular resulted in the team seeking research information on previously unidentified methods, namely pulsed eddy current and nonlinear vibro-acoustics. Additionally, a report entitled "Overview of RIMT® Technology for NCHRP Project 10-53" by Cordec International was received and reviewed (this report was included as Appendix B to the agency's original final report and is not included here).

The NCHRP 10-53 Research Panel brought other techniques to the attention of the research team for consideration. Specifically, a proprietary wire break monitoring and detection system called SoundPrint® and a UC-Berkeley-proposed impedance technology for assessing the state of corrosion in reinforcing steel in concrete were identified. Further, Ghorbanpoor's([38]) unpublished development efforts of the past 5 years to improve the practicality of magnetic flux leakage systems were brought to the team's attention by the NCHRP 10-53 Research Panel's FHWA liaison in July 1998. Additionally, developers of a new radar technology with enhanced sensitivity and defect resolution contacted CTL as a result of their review of the Project 10-53 information maintained on the TRB web site.

### Task 2 - Evaluate and Select Candidate Methods

This task focused on evaluating and prioritizing promising methods. The work was conducted within the scope of research team review of noted research NDT advances, development of evaluation criteria, selection of most promising candidate methodologies, evaluation of candidate methods for potential Phase II evaluation, and consideration of Phase II evaluation plans.

The technology review and evaluations of candidate methods were completed approximately 5 months after the research project commenced. At that time, the research team concluded in its project quarterly report that no new advances with significant potential for strand NDT were made within the time interval between the initiation and conclusion of the NCHRP 10-30 project in the following areas:

- Conventional ultrasound
- Acoustic emission
- Radar
- Radiographic imaging
- Linear vibration-based measurements
- Magnetic techniques

The team proceeded, therefore, with rigorous critical assessment of the following candidate techniques:

- TDR
- Nonlinear vibro-acoustics
- Pulsed eddy current
- Impedance measurements

These results and further research recommendations were communicated in May 1998 to the NCHRP 10-53 Research Panel for their consideration in the first of two interim reports. The recommendations included suggested further research and development into strain-relief-based measurement of stress state in concrete and structural sensor development. Considering that little promise existed for strictly attaining the project goals with "recently developed" NDT systems and that the research team's initial recommendations would have constituted a major change in direction of the research, the NCHRP 10-53 Research Panel suggested that the team examine the potential of recent, then unpublished, FHWA-funded developments in magnetic flux leakage NDT systems. Further, the panel sought from the research team a technology summary report that would serve as a guide for future strand NDT researchers.

### Task 3 - Furnish Report

The Phase I research was documented in two draft interim reports dated May 1998 and September 1998 and in this final report. The interim reports provided detailed descriptions and assessments of candidate methods in terms of potential practicality and reliability with recommendations for Phase II. This final report was intended to document the Phase I research and provide future researchers with direction, since Phase II was not pursued.

# CHAPTER 4

# REVIEW OF TECHNOLOGY

Several technologies with relevance for strand flaw detection and a few with the potential for indirectly evaluating the presence and extent of deterioration-induced damage to a structural component were identified and studied. The research results reviewed below represent the most recent data gleaned from the literature surveys conducted by CTL. Most have been investigated and applied in one form or another to reinforced concrete or reinforcement since approximately 1970, with the exception of pulsed eddy current, nonlinear vibro-acoustics, and TDR. All the technologies the research team evaluated are discussed below. Chapter 5 presents the research team's evaluation of the techniques.

## Ultrasonic Defect Detection

The University of Manchester Institute of Science and Technology (UMIST) performed a comprehensive research effort sponsored by the National Research Council (NCHRP 10-30) in the late 1980s and early 1990s. This research was aimed at development of nondestructive test and evaluation methods to detect the deterioration of prestressing steel tendons embedded in concrete. The case of seven-wire strands inside metal ducts was of particular interest. Based on a survey of various technologies available at the time, UMIST researchers identified ultrasonic testing and corrosion rate monitoring techniques as having the most potential for obtaining information on embedded prestressing steel. Since the latter technology was at the time the subject of Strategic Highway Research Program study, UMIST efforts concentrated on adaptation of ultrasonic techniques for strand evaluation. This effort consisted of theoretical analyses as well as experimental work. A prototype system was built, which included rolling transducers and incorporated advanced signal processing techniques.

Ultrasonic waves can travel relatively long distances along prestressing strands when those strands are suspended in air. However, when a strand is embedded in concrete, signal attenuation limits the distance of wave penetration to one or two meters. Aggregate sizes that are comparable to the wavelength of the ultrasonic signal result in large-scale scattering or "grain noise."

Subsequent to completion of the NCHRP 10-30 project, the UMIST researchers(10) attempted refinements in their previous effort by introducing digital deconvolution analysis of ultrasonic signals for the purpose of assessing the condition of prestressing steel. The authors report in 1992 that the frequency response of the steel strand can be calculated through deconvolution analysis of input and output signals. The first parts of the ultrasonic signals ("prewaves") are used. They report that the frequency response of strand is very sensitive to small amounts of corrosion.

Duncan, Gaydecki, and Burdekin(11) of UMIST also reported in 1996 on an Ultrasonic NDT prototype system for detection of voids in grouted tendon ducts. They introduce a track-mounted scanning system ("CANDI") which consists of two 430 kHz side-by-side rolling transducers that travel along the beam. The received signals are analyzed in the frequency domain using a multiple frequency band correlation technique. The test specimen used for prototype development and typical transducer signals are shown in Figures 1 and 2. A small void in grout reflects higher frequencies, while a major void reflects most of the spectrum.

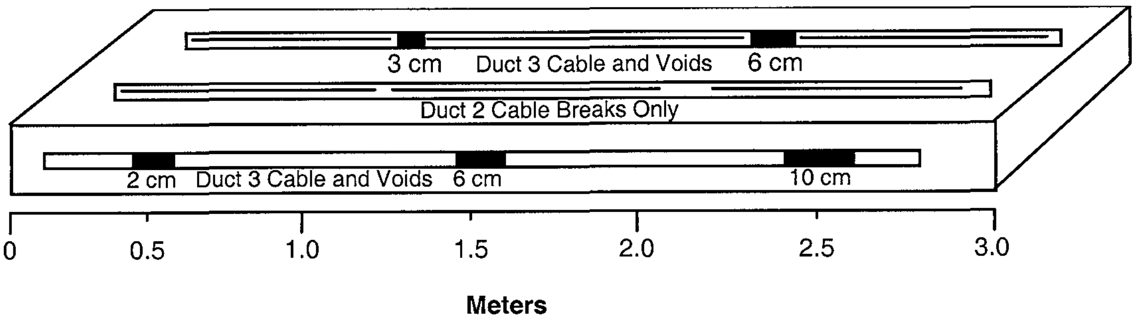


FIGURE 1 SCHEMATIC DIAGRAM OF THE TEST BEAM

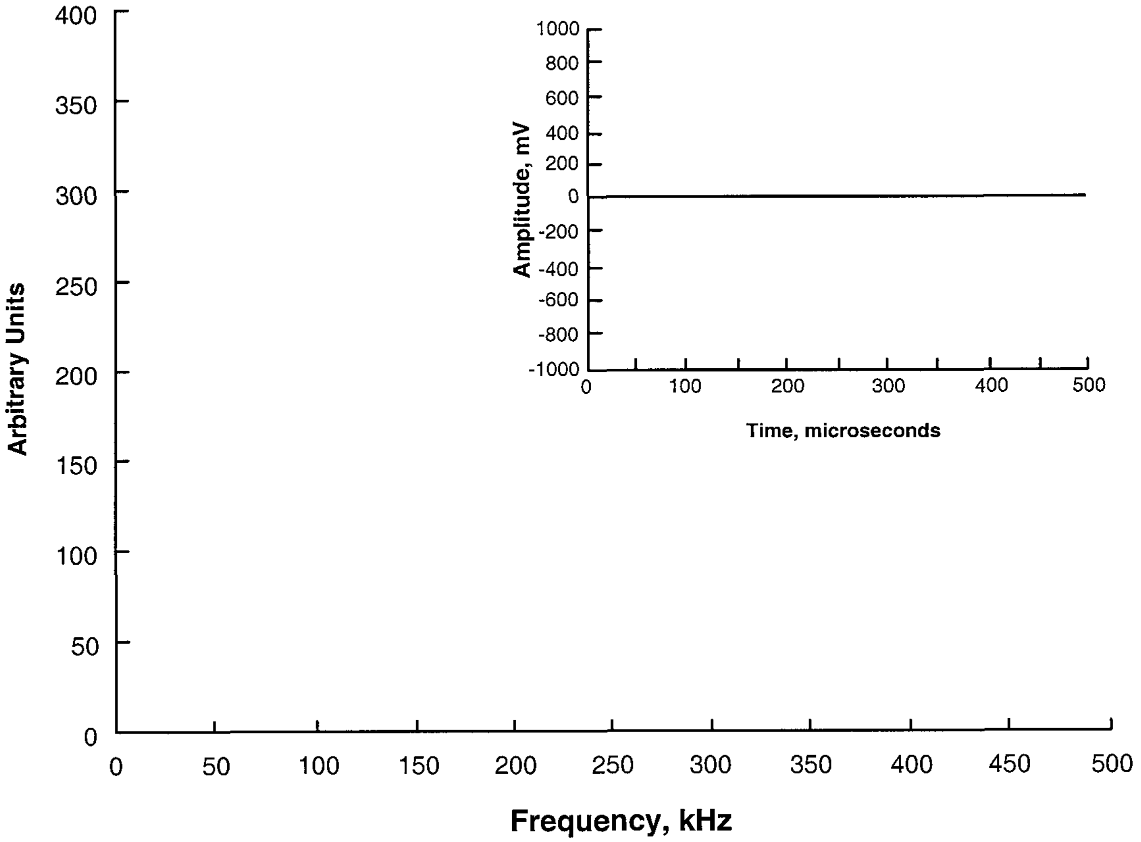


FIGURE 2 TYPICAL SIGNAL AND SPECTRUM FOR ROLLING TRANSDUCERS (from Duncan, et. al. ref. 11)

Overall, these related UMIST research studies, which commenced with the NCHRP 10-30 program, made several important contributions to the state of knowledge in various aspects of ultrasonic testing for prestressed concrete, including advanced signal processing techniques. For example, the developed grouted tendon NDT system was capable of identifying grout voids on the order of 30 mm at concrete depths on the order of 100 mm. Though the system was capable of detecting "major" cable breaks, it was not sensitive enough for detecting single wire breaks in multi-strand tendons.

Suzuki et al.(12) presented an ultrasonic method for detection of wire breaks in stay cable anchorage zones. An ultrasonic transducer is coupled to the exposed ends of individual wires. Wire breaks reflect the ultrasonic wave, thus providing a basis for wire break detection. The authors discussed wave propagation and dispersion inside and outside of wires in the anchorage socket. Attenuation levels due to the presence of different materials in contact with the wire are discussed. At higher frequencies, attenuation due to dispersion into the socket materials is reduced. However, at higher frequencies, the ultrasonic wave is divided into many wave packets and amplitudes become smaller as propagation distance increases. Detection of corrosion was found to be very difficult with this method. The authors report that attenuation in a wire constrained by cast material is much more pronounced than that in a free wire. The depth of wire break detection for a "Hi-Am" socket is limited to only a few meters. Degree of attenuation is demonstrated in Figure 3.

## Pulsed Eddy Current

Pulsed eddy current is a new NDT method for inspection and identification of hidden corrosion in layered structures such as aircraft lap-splices, as well as thickness and conductivity measurements of conductive coatings on metal plates. This method was developed at the Center for Nondestructive Evaluation of the Iowa State University in Ames, Iowa.(13) The major advantage of this method over conventional eddy current testing is the ability to cover a wide range of frequencies rapidly (i.e., greater information) due to pulsed excitation. It also uses simple, relatively inexpensive equipment. The eddy current method is based on the principle of electromagnetic induction. Flaws introduce changes in current induced by an induction coil. Eddy currents can penetrate into subsurface layers, even when those layers are not mechanically bonded. This is an advantage over ultrasonic methods where mechanical contact between layers is required. The pulsed eddy current method is reportedly capable of detecting metal loss in a 2-or 3-layer structure and can distinguish metal loss from metal separation.

Probe excitation is achieved with a 5-V, 1-kHz square wave. The probe is a two-part system consisting of two coaxial air-core coils. Two modes of operation exist. In the first mode (pitch-catch), the excitation is supplied to one coil, and the resulting electromagnetic field is detected in the inner coil. In the second mode (an absolute system), the excitation is again applied to the outer core, but the signal is obtained from this same coil (by recording voltage across a 1-ohm resistor in series with the coil). Tests reported by Moulder et al.(13) were performed using the absolute system. A signal from the defect-free area (reference signal) is subtracted from the test signals. Typically 100-500 signals are averaged to reduce noise.

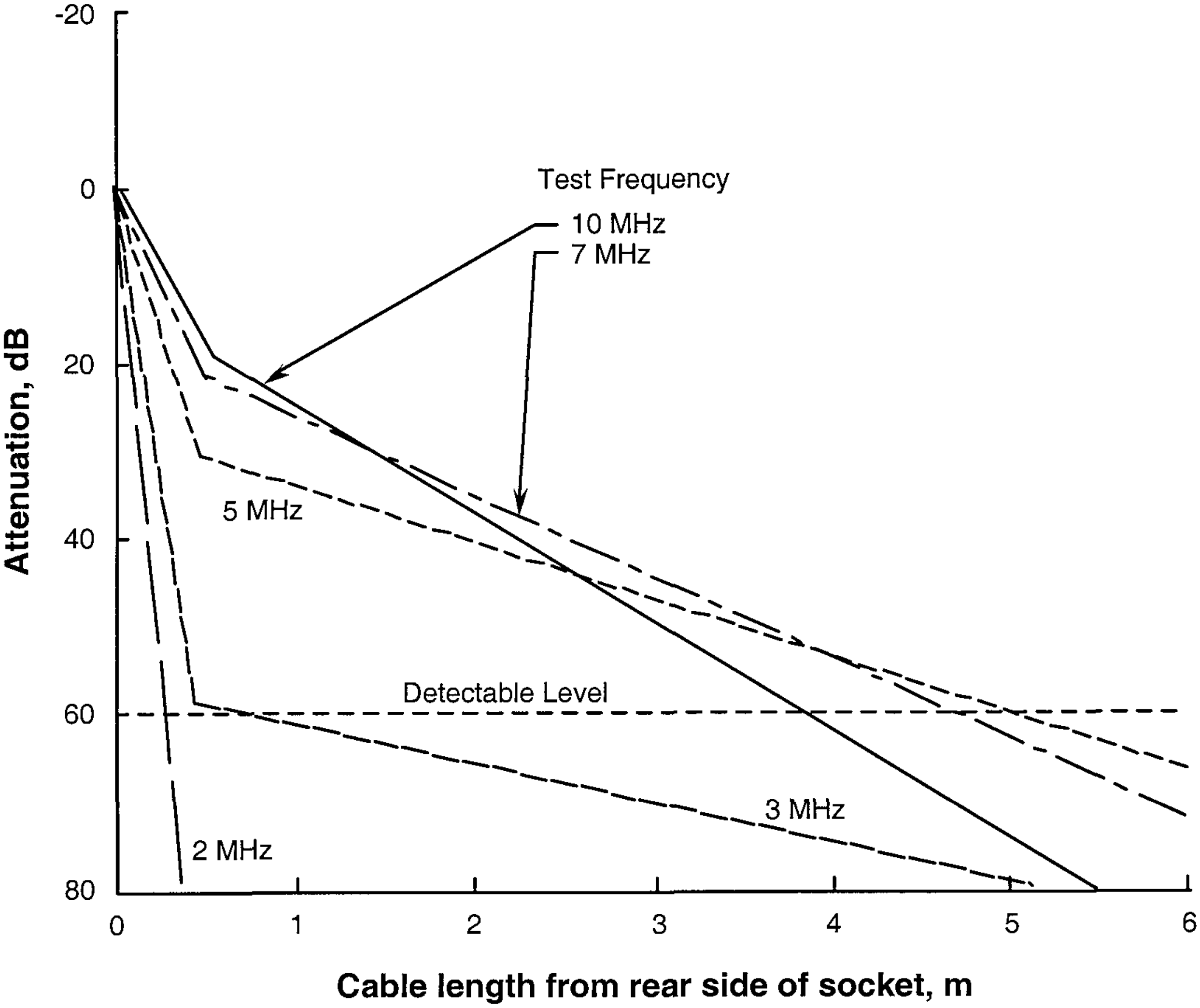


FIGURE 3 ATTENUATION OF ULTRASONIC WAVES IN STAY CABLE ANCHORAGE ZONES (from Suzuki et. al., ref. 12)

Tests were also performed on milled and unmilled 1-mm-thick 2024 aluminum coupons. Milling depths varied between 0.1 and 0.3 mm. In this study, three coupon configurations were studied: (1) milled area on the bottom of the top plate, (2) milled area on top of the bottom plate, and (3) two unmilled coupons separated by 1 to 3 plastic sheets (each 0.1 mm thick). In all cases, theoretical calculations agreed well with the experiments, as shown in Figure 4. The key features that uniquely characterize these signals are the initial peak height, the time of this peak, and the time of zero crossing (following the peak). The signal amplitudes from the test with plastic sheet spacers were comparable with the signal from metal loss. However, they occur on a much shorter time scale, which provides a possible means to discriminate between true corrosion and mere separation. When corrosion occurs in several locations at the same time, different diameter coils may be necessary to clearly distinguish the location of corrosion. The authors point to the possibility of using both probes for absolute measurements and then in pitch-catch type measurement to obtain additional information for quantitative characterization of corrosion.

The authors conclude that the pulsed eddy current technique is capable of detecting metal loss at any position in a 2-layer structure (either top or bottom plate). They also state that it appears possible to distinguish between metal loss and excessive separation of the two plates.

The pulsed eddy current method may have potential applications in prestressed concrete. However, experimental investigations on its application to concrete and prestressing steel are lacking. At this point, the effect of concrete medium is not clear. Further, ferromagnetic materials can only be evaluated by traditional eddy current techniques for defects over a depth of penetration of only fractions of a millimeter. The pulsed nature of the signal is believed to provide an opportunity to perform the test over a wide-frequency spectrum. Bigger probes may be needed in this application. Also, a separate sensor may need to be utilized (i.e., pitch-catch mode). In summary, the main questions on applicability of this technology to prestressed concrete relate to (a) whether probes that can tolerate higher power can be developed for interrogating at a distance through concrete, (b) whether the resulting spatial resolution is acceptable, and (c) whether distinct features of individual strands or wires in a group or tendon can be discerned. The aim of any such effort could only be directed at prestressing strands that are not encased in a metallic tendon duct.

### Acoustic Emission (Prestressing Wire Break Monitoring)

Acoustic emission testing is a "passive" monitoring method in which the detection system waits for the occurrence and capture of stress wave emissions associated with cracking, corrosion, or wire breaks. By contrast, classical flaw detection methods, such as ultrasonics, are considered "active" in that a stress wave is sent into the test object to identify the presence of defects.

In 1986, the Center for Civil Engineering Research, Codes and Specifications (CUR) issued a comprehensive report on the subject of acoustic monitoring of prestressing tendons and bars in concrete structures.(14) The report presents an excellent discussion of theoretical aspects as well as experimental results. The authors identified the leakage (attenuation) of acoustic signals through surrounding concrete as a major impediment to the application of this method to bonded prestressed concrete systems. The authors, however, foresaw potential application of this method to containment structures where tendons are typically unbonded.

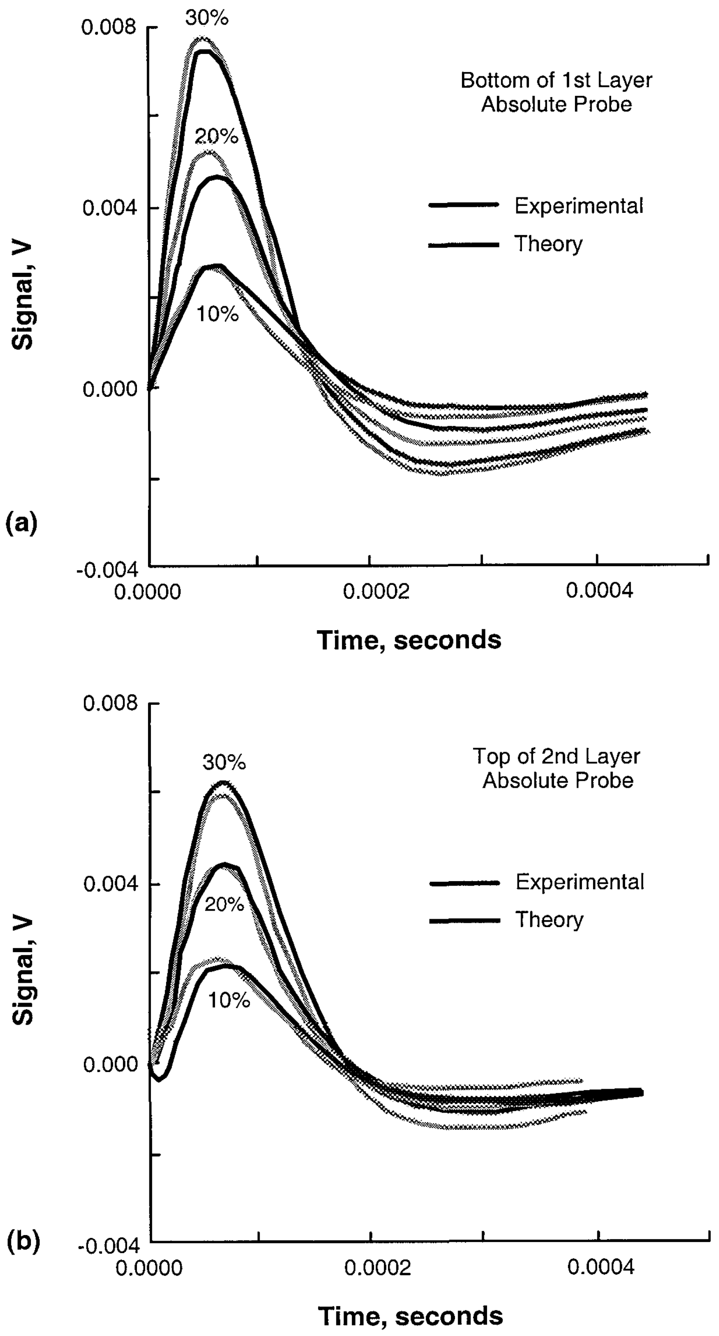


FIGURE 4 COMPARISONS OF THEORY AND EXPERIMENT FOR PULSED EDDY-CURRENT MEASUREMENTS OF FLAT-BOTTOMED HOLES IN SIMULATED LAP JOINTS COMPOSED OF 1-MM THICK 2024 ALUMINUM PLATES. (a) SHOWS THE RESULTS FOR 10-30% LOSS OF METAL AT THE BOTTOM OF THE FIRST LAYER. (b) SHOWS THE RESULTS FOR 10-30% LOSS OF METAL AT THE TOP OF THE SECOND LAYER. (from Moulder, et. al., ref. 13)

Tabatabai(15) verified the applicability of acoustic monitoring for the unbonded tendons of nuclear containment walls. A series of tests was performed on a one-tenth-scale model of a containment structure with greased and sheathed strands. The presence of grease in contact with the prestressing steel significantly reduced the signal attenuation that would otherwise be present in a bonded tendon. Simulated wire breaks were detected and break locations were identified using accelerometers placed at each end of the tendon. Travers(16) discusses acoustic monitoring of wire breaks in prestressed concrete pipes. In this case, geophones were placed in the pipe at different locations. Although wires in this case were bonded to the concrete pipe, the water in the pipe provided an excellent transmission path for the sound waves associated with wire breaks. Data capture and wire break detection software was developed in this effort.

Paulson(17) discussed continuous acoustic monitoring of suspension bridges and stay cables. Limited tests were performed on a main cable of a suspension bridge in which a few wires were cut and the resulting stress waves were detected by accelerometers. However, the author did not present any test results on stay cables. Many stay cables in the United States are bonded systems (uncoated seven-wire strands with injected cement grout). Grout fills spaces between parallel strands within the cable pipe. The grout is expected to provide significant signal attenuation, thereby reducing the effectiveness of the acoustic emission monitoring substantially in bonded stay cables. It is expected, however, that acoustic emission methods would be effective in unbonded cable systems, such as cables with individually greased and sheathed strands. A sensor placed at the end of a cable would likely receive acoustic waves that are not significantly impeded by the grout. Acoustic monitoring has also been used on a number of parking structures, especially those with unbonded tendons.

Li et al.(18) presented discussions and laboratory test results on acoustic monitoring of reinforcing steel corrosion in concrete. The corrosion process and the resulting microcracks produce stress waves that can be detected by acoustic emission transducers. The authors reported successful correlation between acoustic emission events and corrosion activity. However, the largest concrete test specimen used was 102 x 127 x 406 mm (4 x 5 x 16 in.), which is very small compared with real structures. Therefore, the important issue of signal attenuation was not addressed in this study.

## Surface Spectral Resistivity Method

A method proposed by Monteiro, Morrison, and Frangos(19) from the University of California, Berkeley, was brought to the attention of the research team for consideration as a potential technology applicable to prestressed concrete. At the time of the writing of this report, no published papers were available. However, the developers of this method provided an unpublished paper on the subject for the research team's review.

This method uses a multi-electrode electrical resistivity array to determine reinforcing bar locations and the state of corrosion. The method is based on surface measurements of the frequency dependence of the complex impedance of reinforcing bars embedded in concrete. Complex impedance can be directly related to the corrosion rate of reinforcing steel in concrete. The advantage of this method is that it does not require removal of concrete cover to attach electrodes directly to the reinforcing steel. Also, resistivity of concrete can be determined in areas where reinforcing bars are away from the surface.

Experiments were performed on a single concrete block with four embedded bars with different surface preparations representing widely different surface impedances. These included a corroded bar, a clean bar, a bar coated with electrically insulating paint, and a gold-plated bar (complete chemical inertness). A four-electrode array (Wenner array) was used. An alternating current was applied to the outside two electrodes while voltage across the other two electrodes was measured.

## Nonlinear Vibro-acoustic Method

This method was originally developed in the 1980s at the Institute of Applied Physics of the Russian Academy of Sciences to control the quality of attachment of thermo-protective coatings on the Russian space shuttle. Two of the developers of this method, Dimitri M. Donskoy and Alexander Sutin, are working in the United States at the Stevens Institute of Technology in Hoboken, New Jersey. They have published two papers on the subject, including one on its applicability to detection of corrosion in reinforced concrete.

A paper by Sutin and Donskoy(20) presents the non-linear vibro-acoustic method. The conventional linear acoustic method includes effects of reflection, scattering, transmission, and absorption of acoustic energy. Presence of a defect changes the phase and/or amplitude of signal while the frequencies of the received signals are unchanged (same as emitted signal). The nonlinear technique correlates the presence and characteristics of a defect with acoustical signals whose frequencies differ from the frequencies of the emitted signal. This is due to the nonlinear transformation of the acoustic energy by a defect.

The method is based on the fact that materials containing cracks, fractures, disbondings, and so forth have a much larger nonlinear response. The advantages of the nonlinear methods include high sensitivity and applicability to highly nonhomogeneous structures such as composites and concrete. When a sinusoidal acoustic wave meets a defect, the wave changes the contact area (increase in compression, decrease in tension). This is somewhat analogous to closing a crack under compression and opening it under tension. This leads to generation of harmonics.

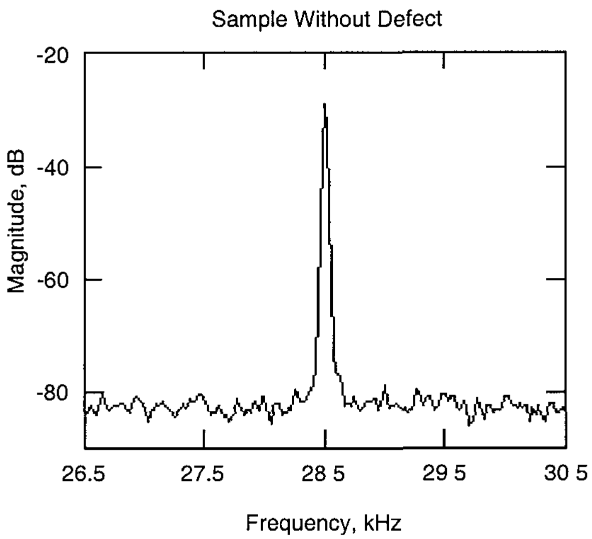
In the method of the "Second Harmonic," the amplitude of the second harmonic is measured. An increase indicates the presence and size of defect. The second harmonic method has a problem in that the signal generators, power amplifiers, and transducers all have their own non-linearities and generate the second harmonic at a certain level. To avoid this problem, a modulation method was developed that involves modulation of a higher frequency ultrasonic probe wave by a lower frequency vibration. By applying a low frequency ($\omega$) vibration to a material, the phase and the amplitude of the transmitted higher frequency ($\Omega$) ultrasonic wave vary accordingly, leading to the modulation of the signal. The result of this modulation will be sidebands (in the frequency domain) corresponding to $\Omega + \omega$ and $\Omega - \omega$ frequencies. The presence and amplitude of sidebands indicate the presence and degree of degradation. Two different modulation techniques are available. One uses sinusoidal vibration (vibro-modulation), and the other involves impact (impact-modulation method). According to the authors, both of these methods are reliable and sensitive to crack detection, even for structures where the conventional acoustic methods do not work. The authors conclude that a strong correlation between presence of contact-type defects and that of measured sideband spectral components was demonstrated.

Another paper by Donskoy et al.(21) addresses the application of this technology to concrete. A No. 8 reinforcing bar was embedded in a 15 x 15 x 36 cm concrete specimen. A dry-wet cycle involving placement of the specimen in a NaC1 solution up to just below the bar level was initiated. Linear Polarization and Electrochemical Impedance Spectroscopy was employed for measurement of corrosion activity. Two piezoelectric crystals were bonded to the concrete surface at opposite faces. One functioned as a 28.5-kHz transmitter, and the other was a receiver. A 250-Hz (low-frequency) vibration source was applied to the specimen. FFT analyses of the received signals were performed. As shown in Figure 5, the power spectrum for the uncorroded case showed a peak at 28.5 Hz only, while another test, after 37 exposure days, indicated sidebands at 28.5 ± 0.25 kHz. The nonlinear response of the material was characterized by the degree of modulation (the difference between the high-frequency and sideband intensities). The authors report that the excitation frequencies between 20 and 30 kHz and the low-frequency vibrations of 250 Hz had very low attenuation in the concrete specimen, resulting in the significant excitation of concrete. The degree of modulation did not depend on the amplitude of the high frequency. The authors conclude that there is dependence between the increase in the acoustical nonlinear response and the increase in corrosion. The extent of degradation area controls the degree of modulation. They also conclude that this technique is a potential early detection technique for the presence of corrosion of reinforcing steel in concrete. Nonlinear acoustics is easily applicable to heterogeneous materials such as concrete. The authors suggest further research on specimens with more accelerated corrosion to quantify the dependence between degradation area and degree of modulation.

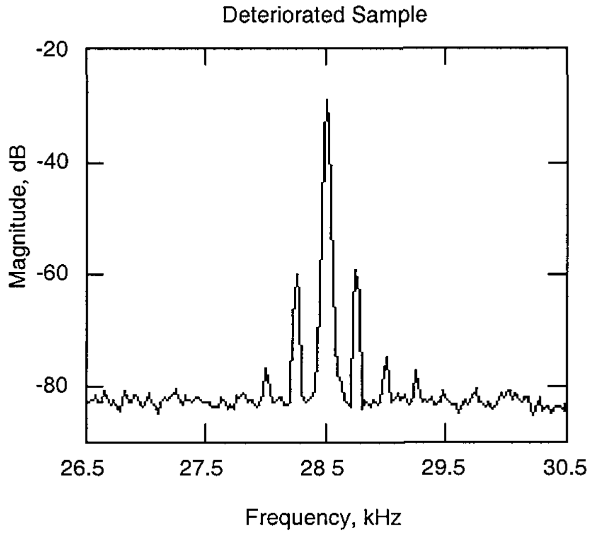
## Electrical Time Domain Reflectometry (ETDR)

ETDR has been defined as "closed-loop" radar. It has been extensively used for flaw detection in power transmission lines. The technology has also been used in sensing systems in geotechnical engineering applications. The method involves sending a high-frequency electrical pulse through the sensing cable. Impedance discontinuities (or mismatches) along the cable result in partial reflection of the pulse. These reflections are monitored using TDR cable test equipment. Impedance is mainly a function of the inductance *(L)* and capacitance *(C)* of the line. A typical TDR sensor is a coaxial cable for which the critical TDR parameter is the impedance between the center wire and the outside shield.

There are two distinct TDR concepts that have been suggested with regard to use in prestressed concrete. In the first concept, a TDR sensor (e.g., coaxial cable) can be developed for embedment in concrete for detection of concrete cracking or corrosion, or as a continuous strain gauge. Stastny, Roger, and Liang(22) proposed a structural health-monitoring sensing concept based on TDR for uses in composites, concrete structures, and so forth. Preliminary tests were performed on coaxial cables (not contained within concrete) and were used to study the feasibility of such a sensor. The authors concluded that ETDR has the potential to be a quantitative distributed NDT tool for real-time structural health monitoring. They also concluded that, compared with optical TDR (based on fiber-optic sensors), ETDR has higher spatial resolution and less expensive sensing cables. Their work has laid the foundation for distributed TDR gauges for concrete, even though they did not perform any tests on concrete specimens. Okanla et al.(23) performed an interesting simple test involving a single 3-m-long, 75 ?? coaxial cable in air. They progressively cut a notch into the cable until the wire was almost severed in two. However, the TDR equipment was not registering a change as the notch depth increased. The authors pointed out that impedance is basically a function of *L* and C and that the effect of resistance changes is small. The resistance change introduced by cutting a notch is negligible, and, therefore, the overall impedance does not change to an observable extent. However, if one



a) Before initiation of corrosion



b) After 37 testing days

FIGURE 5 SPECTRA OF ACOUSTIC SIGNAL (from Donskoy et al., ref. 21) were to press with the fingers on a coaxial cable or crimp it, there would be noticeable reflection because of the change in impedance. Therefore, a sensor designed on the basis of ETDR must produce appreciable impedance change as a result of changes in the parameter of interest. For example, Dowding and Pierce(24) discussed an ETDR sensor for groundwater level and pressure detection. This gauge is basically a small-diameter coaxial cable enclosed in a standpipe. The coaxial cable is hollow (i.e., the material between the center wire of the coaxial cable and its shield is removed to produce an air gap). Therefore, up to the level of the water table, the air gap will be filled with water resulting in a substantial change in impedance (compared with the cable area with air gaps). A similar method has been used to detect relative movements in rocks or dams. A borehole is drilled at measurement locations, a coaxial cable is placed in it, and the borehole is then grouted. The cable can also be pre-crimped at fixed intervals to help with rapid determination of the impedance change location. Any relative movement at any point along the length of cable introduces impedance changes and reflections that can be detected.

The second ETDR concept thought to possess potential for prestressed concrete condition assessment is based on using the strand itself as the sensing wire. However, with the strand as the main wire, a second wire (ground line) is still needed, so that the impedance between the two can be measured. Typically, an adjacent strand is used as the second wire or, in the case of PT tendons, the metal duct is used.

A proprietary system based on ETDR, Reflectometric Impulse Measurement Technique (RIMT)®, has been developed and is commercially available through a Canadian consulting firm. In a report submitted to the CTL research team by H. Keller of Cordec International(25), licensees of the RIMT® technology, an overview of this technology and a description of tests performed are presented. The report states that, in a laboratory environment, the sensitivity of the system is 7 percent to 15 percent loss of cross sectional area. However, in field conditions, energy losses to other tendons and unstable connections reduce the sensitivity dramatically. In tests performed on bonded and unbonded girders, the author reports "good" correlation between predicted corrosion defect areas and observed samples removed from the beams. However, in 23 cases, anomalies were predicted where no corrosion existed. Wire cuts in otherwise defect-free tendons could not be reliably identified. Subsequently, several improvements were made. Development of Frequency Domain Reflectometry (FDR) is suggested as a possible area of improvement. The author concludes that this technology is a "useful" tool for testing posttensioning tendons. Tests have been performed primarily on unbonded systems, but, in the view of the author, results of limited bonded tests have been "encouraging."

It was learned by the CTL research team that RIMT® technology was originally conceived and developed in Switzerland. An elaborate two-phased ETDR research effort was conducted by Elsener et al.(26,27) commencing in the late 1980s. This research was sponsored by the Swiss Federal Highway Agency. Although initial phases of the work showed promise, work completed between 1992 and 1996 (the recent results for grouted posttensioned systems) was discouraging. In grouted tendons, there was significant wave attenuation in addition to the problem of undefined geometry of wave propagation. Electrical conductance between the tendons and other reinforcing bars increased complications further. It was concluded that the recorded TDR signals from grouted PT tendons do not contain information regarding the condition of cable but are the artifacts of the measurement procedure itself. The following were suggested as necessary conditions for the successful application of RIMT: (1) a coaxial geometrical arrangement between cable and duct and (2) the use of a highly insulating, low-loss material between cable and duct. According to the authors, these conditions might be fulfilled for monostrand (unbonded systems).

Okanla et al.(23) of UMIST also performed some TDR-type assessments of strands or wires placed within a 3-m length of galvanized duct. Sand was used to represent grout. The duct was used as a ground conductor. Different lengths of dry void or wet sand were created inside ducts. The authors found a linear relationship between the root mean square of the waveforms and the water content or length of void. In another test series, a plastic duct was used. Adhesive aluminum tape was wrapped around the outer surface of the duct to serve as ground wire. A moist towel was wrapped over the tendon at one location. According to the authors, the towel area was not difficult to find, even though there was no direct electrical contact between the wet towel and the ground. The authors also point out that, over the length of the cable, the tendon must not make electrical contact with the ground (duct).

## X-Ray Diffraction for Direct Stress Measurements

Carfagno et al.(28) present the first use of X-ray diffraction technique to measure PT tendon stresses of prestressed deck slabs at La Guardia Airport in New York. The authors present a brief theory of X-ray diffraction. In this method, strains are estimated by measuring the elastic atomic lattice spacing (distance between atomic planes). The existing prestress was measured on these slabs to find the cause of longitudinal hairline crack over the negative moment region. Coring and drilling exposed the transverse PT tendons. The galvanized duct and grout were removed locally. An X-ray diffractometer designed specifically for field use was utilized. Strain measurements were performed at six locations. This method measures strain only at the surface of the sample. A 4-in.-long section of one exterior wire was removed to perform residual stress measurements without PT force. The measured strains for the stressed tendons were corrected for this residual effect. The authors conclude that this method is a relatively simple and effective technique for measurement of prestressing levels in wires.

Brauss et al.(29) present further tests on bridge suspender cables and wire ropes (in the laboratory and in the field) using the X-ray diffraction equipment. The authors conclude that this technique provides quantifiable results, is nondestructive, and provides a measure of total stresses (applied plus residual stresses).

This is an interesting method for field application to structures. However, in case of enclosed elements such as PT tendons and stay cables, this method would be partially destructive. In any case, if one needs to subtract residual stresses from measured values, then a sample must be cut out from the cable. Also, in a multi-strand or multi-wire cable, there may be significant variations between absolute strain values in different elements. Therefore, a large number of tests may be required to obtain an average value as an estimate of total force.

Measurements on outer strand wires, which are bent spirally around a center wire, may pose additional complications. However, there maybe cases where this technology can be beneficial.

## Strain Relief for Prestress Measurements

Strain relief methods for concrete are similar to residual stress measurements in metals using hole-drilling concepts. While not comparable in principle to nondestructive flaw detection methods, they offer potential benefits as global evaluation techniques for evaluating and quantifying extent of time-dependent prestress losses. Strain relief methods have been extensively used for estimating stresses in rock and masonry structures. For masonry construction, ASTM Test Method C1196 has been developed based on the utilization of hydraulic flat jacks inserted in sawn horizontal slots in masonry joints.

Overman and Hanson(30) present the results of research sponsored by FHWA on utilization of strain relief methods for estimating stress levels in prestressed concrete. A set of flat jacks (less than 4-mm thick) is inserted into progressively deeper slots cut into concrete. Cutting is performed using a precision saw to predetermined depths corresponding to the dimensions of flat jacks. Progressive deformation between two reference points (on the two sides of the slot) is measured at different levels of fluid pressure. The pressure at which the distance between reference points is identical to the initial uncut distance is the canceling pressure. The prestress is then calculated using an equation developed in this study. The authors selected slitting rather than coring based on better sensitivity as determined from analytical investigations of the two methods. Experimental results identified a number of parameters that affected canceling pressures, including individual flat jack characteristics, time between cutting and pressurization, and the length of pressurization time. The authors concluded that, for stresses from zero to 1000 psi, stresses in laboratory specimens could be measured to within + 100 psi at a 90 percent confidence level. It was noted that shrinkage stresses were difficult to separate from applied stresses. Recommendations for further research included seeking reduction in measurement errors introduced by flat jack nonlinear characteristics and assessing the influence of site temperature and humidity on accuracy. Research activity into this technique for prestressed structure evaluation has not continued since the Overman study.

Ryall and Abdul-Rahman(31) present the results of an experimental study to develop methods for measuring existing stresses in concrete. In this method, a 42-mm-diameter hole was first drilled into concrete. Then a 42-mm cylindrical inclusion (made of epoxy grout) instrumented with strain gauges was inserted into the hole and bonded to concrete with epoxy. The concrete was then overcored with a 150-mm-diameter core containing the inclusion. Strain changes in the inclusion and on radially positioned concrete surface gauges were measured and subsequently related to stresses. Laboratory tests on concrete cubes and slabs were performed. Field tests were also performed on a concrete bridge. The authors attribute the "limited success" of their program to "environmental" and instrument design factors. Environmental factors listed include magnitude of in situ stresses, temperature changes, anisotropy, surface irregularities, and micro-cracks.

In summary, the major parameters affecting strain relief methods in concrete involve the effects of creep, creep recovery, shrinkage recovery due to moisture from coring, differential creep and shrinkage, and so forth. If these issues could be overcome, substantial benefit could be derived for structural evaluations of bridge components; however, the techniques are neither nondestructive nor rapid.

## Imaging and Tomographic Systems

Pla-Rucki and Eberhard(32) present a comprehensive summary of various imaging technologies for reinforced concrete. Different procedures are explained, and the advantages/disadvantages of each method are presented. Methods considered include radiography, radioactive computed tomography, infrared thermography, microwave imaging (including microwave tomography), and acoustical imaging (including acoustic tomography). The following is a summary of their paper.

In radiography, the radiation source is either X-rays or gamma rays. Radiography produces good 2-dimensional images of concrete because the attenuating characteristics of steel, concrete, and air differ greatly and are reproduced as variations in density on radiographic film. Limitations of conventional radiography include its relatively poor resolution of flaw details, expense, time-consuming nature, and radiation hazard. Field applications of radiography have included the detection of reinforcement location, voids, and cracks and the quality of grouted PT tendons. Radioscopy is a different form of radiography in which the transmitted radiation is converted into visible light and recorded by a video camera. Radioscopy has been used in France for detection of PT grouting problems.

In radioactive computed tomography, cross-sectional images of the 3-D object can be obtained instead of a 2-D image from conventional radiography. However, development of this method has been limited to the laboratory environment. Radioactive computed tomography is also hazardous and more expensive than radiography. Difficulties with portability of equipment and access to members also limit field applications.

Infrared (IR) thermography utilizes cameras that measure infrared radiation emitted from the surfaces of objects, which in turn can be related to surface temperatures. Information about the subsurface can be deduced from the surface temperature because the heat flow through the body is affected by the presence of internal anomalies. IR thermography is generally used to detect cracks, delaminations, and disintegration in bridge decks and pavements (ASTM D4788). The advantages of this method are the low danger involved in the use of equipment and the speed of inspection (including inspections at night). Because of the large coverage of the cameras, this method can identify the horizontal extent of large defects. The disadvantages of this method include the effects of the environment on the surface temperatures and the emmissivity factor. This method also does not provide information on the depth of a flaw.

Microwave imaging of concrete has several advantages over other methods. Microwaves can penetrate deep members without posing a hazard. Also, unlike acoustical waves, they scatter little and give an excellent contrast between concrete and steel. Their main disadvantage is that they diffract greatly because the wavelengths of microwaves are on the order of the member's dimensions (1 to 300 mm). Diffraction complicates the process of image reconstruction.

Ground-penetrating radars (GPR) send short microwave pulses into an object. The pulses are reflected at interfaces between media of differing dielectric properties, and a receiver monitors the echoes. Ground-penetrating radars are commonly used for inspecting concrete pavements (ASTM D4748), buildings, and bridge decks. There is no need to couple the GPR antennas to the concrete surface. On the other hand, GPR scans can be difficult to interpret, and the estimation of depth of reflectors (bars or voids) depends on an assumed velocity of wave propagation.

Holographic (wavefront) reconstruction of GPR measurements can make the task of data interpretation easier. Experiments have shown that many images are of good quality. However, there is a shadowing effect, and the reconstruction accuracy decreases when multiple reflectors are closely spaced.

Tomographic reconstruction for microwaves is a difficult problem because of the diffraction issue. Also, the scattered field is non-linearly related to the material's permittivity. Microwave tomography has been utilized to develop a "Microwave Camera" to detect reinforcing bars in concrete.

Acoustical imaging is safe and relatively inexpensive. However, high frequencies are quickly attenuated in concrete. Also, concrete is solid, and, therefore, it transmits shear and surface waves in addition to compression waves, whereas liquids and human tissue transmit compression waves only. This makes the task of image reconstruction more difficult. Therefore, no practical acoustic imaging system has yet been developed for reinforced concrete.

The use of acoustic tomography is also being researched. A key step in the practical development of acoustic tomography has been the development of an ultrasonic pulse velocity scanner with rolling transducers. Although the technique is promising and researchers were successful in detecting voids in concrete, the technique requires further development.

In a separate paper, Bligh et al.(33) discuss various NDT methods for assessment of grout conditions in bridge stay cables. Radiographic tomography methods were used in addition to ultrasonic methods. The authors report that both X-ray and gamma ray tomography methods easily detected small voids in grout. The authors further state that, although the technology for portable field units currently exists, the current energy output levels are not suitable. According to the authors, the limitations of computed tomography for this application include a scan time of 1 min per inch of thickness, data storage requirements of 6 to 7 MB per slice, and shielding requirements.

In summary, the radiographic tomography techniques, when developed, can provide far more useful information than the basic technologies because of the ability to observe cross-sectional images of the object. However, these methods currently pose safety and other limitations. With further advancements in portable radiography equipment for field applications, such devices could have widespread use. In particular, safety issue resolution, a high energy power source, and considerable imaging speed advances to permit practical scanning rates would be required.

### Magnetostrictive Sensors

Bartels, Kwun, and Hanley(34) and Kwun and Teller(35) report on research performed at the Southwest Research Institute on the use of Magnetostrictive Sensors (MsS) to characterize corrosion in prestressing strands and reinforcing bars and on the detection of fractures in steel cables, respectively.

Bartels, Kwun, and Hanley present MsS as a method to characterize the severity of corrosion in reinforcing bars and prestressing strands. The main focus of this work was on reinforcing bars and strands in air. However, brief reference is made to ongoing tests on concrete specimens. Each of the two MsS sensors consist of a coil that encircles the reinforcing bar or strand and a bias magnet that creates a biasing DC field, as shown in Figure 6. This technique is based on the principle that a magnetic material changes its shape when subjected to a changing magnetic field. This change in shape (deformation) results in an elastic wave that travels in both directions along the member (transmission sensor). Similarly, deformations of a magnetic material result in a change in magnetic induction of the material and in the coil's voltage (reception sensor). The MsS sensors used for transmission and reception of the elastic waves were identical.

Several 10-ft lengths of reinforcing bars and strands were corroded to two different levels. The transmitter and receiver sensors were located at the 1/4 and 1/2 points. Attenuation of the waves was obtained for various specimen conditions by measuring the ratios of the peak absolute values of the received signals. Wave attenuation increased significantly with corrosion, as shown by comparison of Figures 7 and 8, for which the researchers estimated attenuations of 0.62 dB/ft and 1.72 dB/ft, respectively.

Although not fully discussed in this paper, the authors also refer to tests to measure wave propagation properties of strands and reinforcing bars embedded in concrete. They note extremely high attenuation that is introduced by concrete. They suggest that lower frequencies

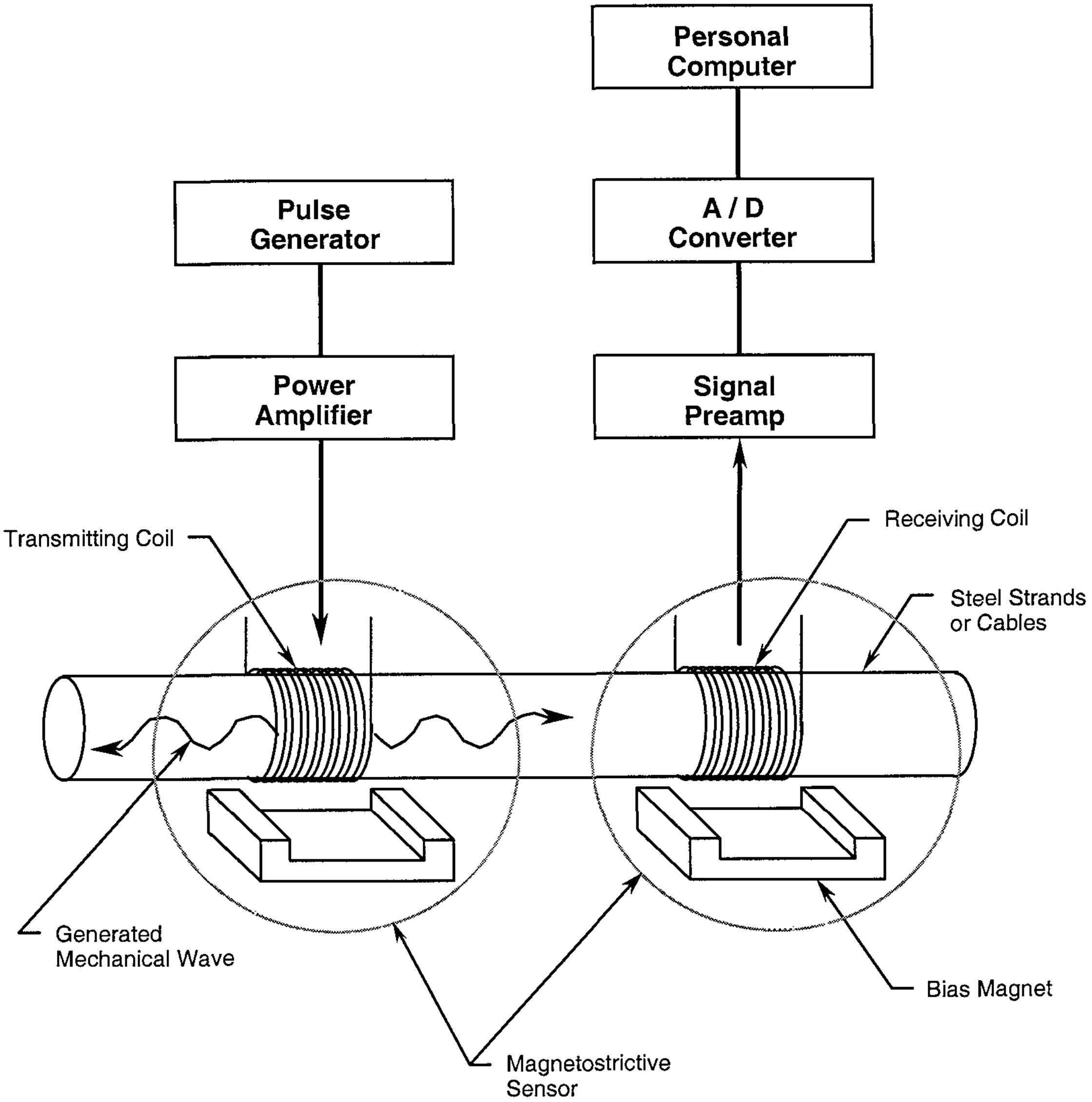


FIGURE 6 SCHEMATIC DIAGRAM OF MAGNETOSTRICTIVE SENSORS AND INSTRUMENTATION. (from Bartels, et. al., ref. 34)

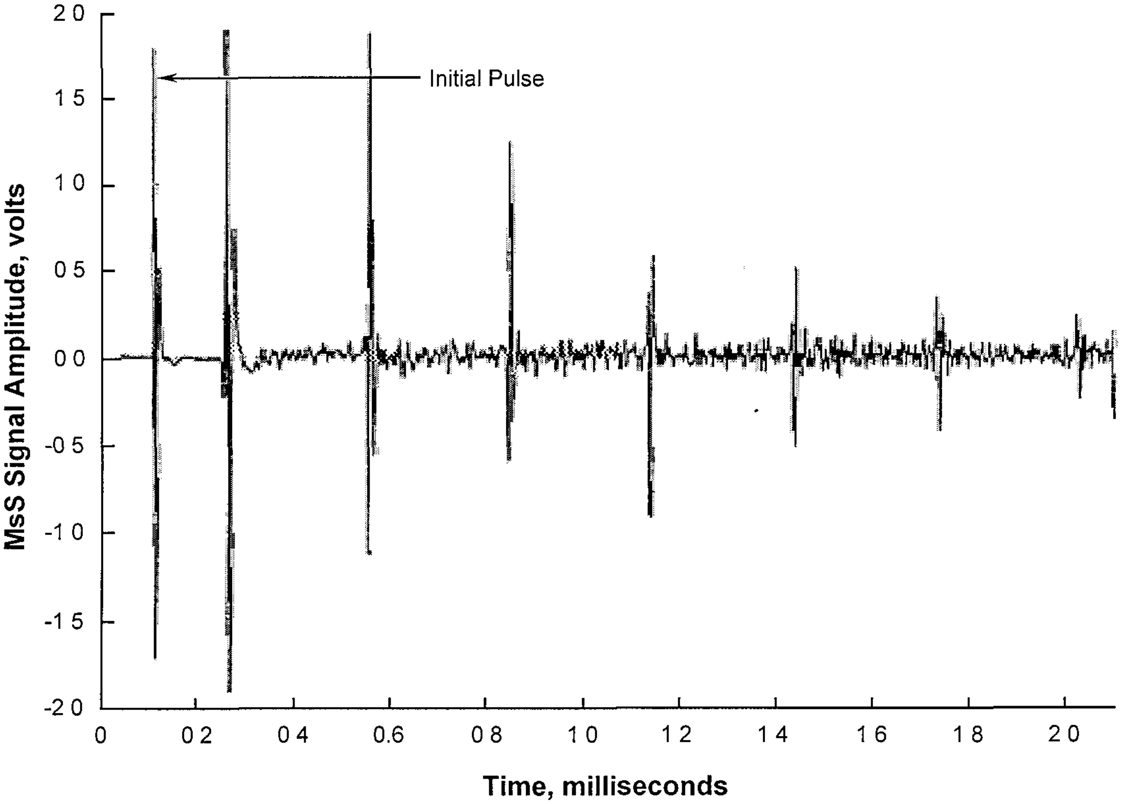


FIGURE 7 MsS DATA OBTAINED FROM UNCORRODED STRAND (from Bartels, et. al., ref. 34)

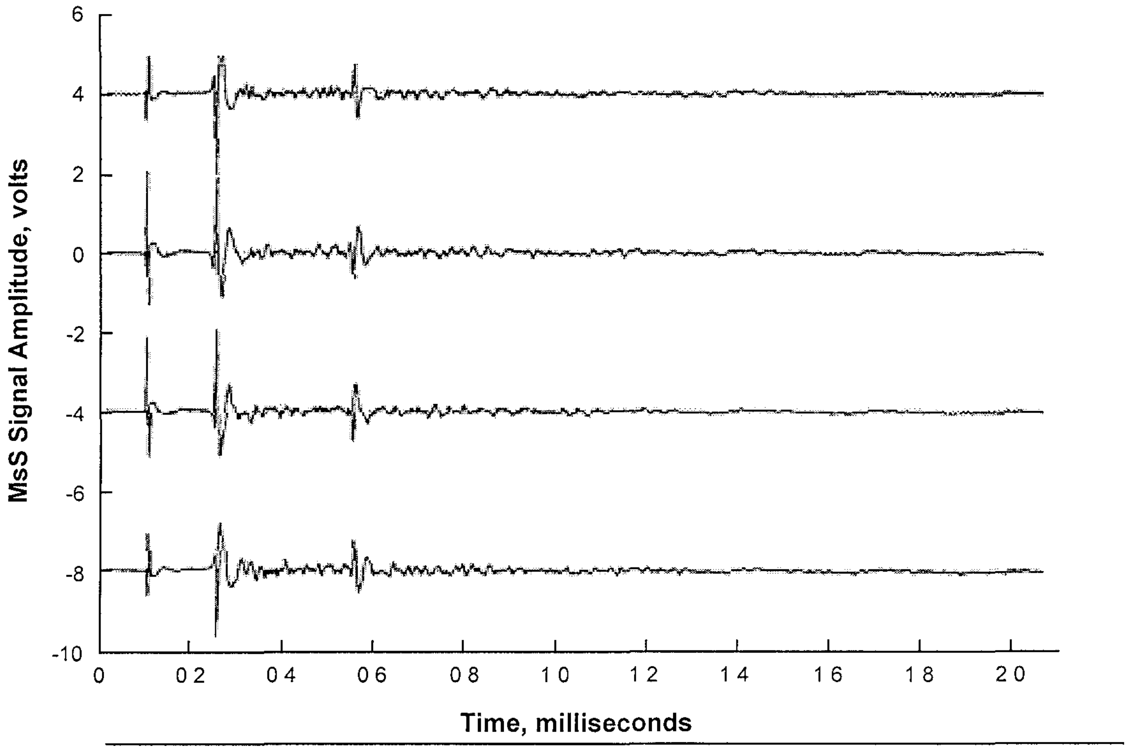


FIGURE 8 MsS DATA OBTAINED FROM THE FOUR SEVERELY CORRODED STRANDS (from Bartels, et. al., ref. 34)

(less than 10 kHz) may be effective in concrete. At 50 kHz, no signals were detected at the receiver over a 2.5-ft distance.

The authors conclude that the MsS technique provides an effective, non-contact way of inspecting strands and reinforcing bars over long distances based on attenuation measurements. However, it is not clear how the significant attenuation in concrete will affect results. Also, in existing prestressed concrete bridge members, it may not be possible to place encircling MsS sensors around the target strands.

Kwun and Teller(35) discuss the results of a feasibility study on the use of MsS for detection of fractured wires in steel cables. The authors point out that, despite the successful use of magnetic flux leakage technique to wire rope inspection, its application to inspection of bridge cables or prestressing tendons has been very limited because of lack of direct accessibility to the steel elements.

The experimental program consisted of testing three 6-m-long steel cables (7-, 21-, and 49-wire strands) suspended in air. Two MsS sensors (one transmitter and one receiver) were used. Each sensor consisted of a DC magnet and a 6-mm-long inductive coil that encircled the cable. A DC bias field was applied in the longitudinal direction of the cable for a primarily longitudinal wave mode. A square voltage pulse with an amplitude of about 10 volts and a duration of 20 to 50 ??'s was applied at a rate of one per second. The produced elastic wave propagates along the cable in both directions and is detected when it passes through the receiving coil. The authors state that, as far as the wire break detection is concerned, using a lower frequency wave gives a better inspection range and depth, with lower spatial resolution. The sensors in this study operated in a low 10-kHz frequency range.

The authors conclude that fractured wires in a steel cable can be detected using noncontact MsS. An inspection depth of more than 15 mm, a range of more than 100 m, and a detectability of about 2 percent loss of section was achieved with the 10-kHz frequency. The sensors reportedly showed good tolerance to the gap between the sensor and the steel cable. However, problems were noted in detecting breaks near cable ends.

## Magnetic Flux Leakage

Magnetic methods have been extensively used in concrete structures to detect the locations of reinforcing bars. Such methods have also been used routinely for inspections of wire ropes and other cables in air.

Burdekin et al.(39) reported on the work performed in the 1970s and 1980s by the Southwest Research Institute on detection of corrosion or fracture of prestressing steel in pretensioned and posttensioned concrete beams. The prototype system consisted of a large DC excited electro-magnet and a magnetic field sensor. Preliminary results were promising.
However, difficulties arose during field testing when signals from other steel elements in the beams made the data interpretation difficult.

Burdekin et al.(39) stated that the possibility of successful development of such systems for pretensioned members exists (except at anchorage areas), provided that detailed information on all steel elements within the beam is available. However, they state that "it is difficult to see how such systems could be successful for posttensioning cables in metal ducts."

A magnetic perturbation system for detection of corrosion and loss of steel cross section in stay cables has also been developed through research sponsored by FHWA. However, this system has not been routinely or widely used because of its size and weight.

Ghorbanpoor(38) prepared an interim (unpublished) university report on a research study sponsored by FHWA on a magnetic-based system for non-destructive evaluation of prestressing steel in pretensioned and posttensioned concrete bridges. In this research, a prototype system was developed that can travel along the bottom of the prestressed beam and scan the entire span (for one beam) in a matter of minutes. The system is essentially a robot that contains permanent magnets and multiple Hall effect sensors, remote-controlled support and drive mechanisms, an on-board data acquisition system with telemetering capability, a battery to provide power, and other operational accessories. Special attention was paid to reducing the weight of the system. Typical diaphragm obstructions in bridges have been taken into account by supporting the system on the two vertical faces of the bottom flange of the beams being surveyed. Initial mounting of the device near one end of the beam requires two people. Data from the robot is sent to a laptop computer through wireless communications. The computer can control the operations of the robot as well as receiving and displaying sensor outputs in real time using a graphical program.

Preliminary tests have been performed on strands (in air) contained within a wooden box to represent the beam geometry. The research team at the University of Wisconsin-Milwaukee has also performed some sensitivity analyses using finite element modelling. A CTL researcher for the NCHRP 10-53 project witnessed the field application of this robot on a pretensioned girder of a bridge in Milwaukee, Wisconsin, in August 1998.

## Power Focusing Ground Penetrating Radar

The Power Focusing Ground Penetrating Radar (PFGPR) technology was developed recently for use in real-time detection of buried metallic and non-metallic land mines.(36) It has been adapted for rapid inspection of pavements and bridge decks with the goal of allowing deck/pavement evaluations at higher vehicle speeds.

This technology involves the use of ultra-wideband, task-specific antenna arrays that conform to the particular media (i.e., concrete member). The permittivity contrast between the output of the antenna and the media must be low to ensure an efficient transfer of power into the media. A focused array is an assemblage of antennas that are used to focus sequentially at specific locations within its field of view permitting development of 2- and 3-dimensional tomographic cross sections of the structure. Advanced, high-speed signal processing, together with adaptation of artificial intelligence-based learning systems, greatly reduce the amount of effort needed for data interpretation, approaching real-time recognition of imaging features.

Electromagnetic fields generated by radar cannot penetrate and propagate through steel strands or metallic ducts, thus preventing direct evaluation of the reinforcement's internal condition. However, the system developers postulate that if a correlated relationship between the condition of the concrete surrounding corroded or cracked prestressing strand or tendons and its electromagnetic signature can be derived, the technology would possess merit. To accomplish this, previously untried laboratory and analytical derivations of multivariate physical, geometric, and deterioration parameters of strand and concrete cover on electromagnetic response of concrete surrounding strand would be required.

# CHAPTER 5

# EVALUATION OF NDT TECHNOLOGIES

## Synopsis of Need

For the prestressed concrete bridge inventory, the desire to bring into use systems that permit evaluation of the condition of individual embedded prestressing strands (or wires) responds to a "flaw detection-based" condition evaluation philosophy. Specifically, this rationale is predicated on studying and integrating, via structural computation and engineering judgment, the quantitative strength and serviceability impacts of reduced cross-sectional area, individual ruptured wires or strand, and other impairments. Implementing this methodology is one means for advancing the bridge engineering community's diagnostic tools beyond the realm of subjectivity associated with visual inspection.

## Characterization and Evaluation

To permit concise characterization and evaluation of the NDT techniques identified and received in the prior task, a list of relevant factors was compiled. These factors were chosen to permit comparative evaluation of candidate systems for use in inspection and maintenance of the concrete bridge inventory, taking into consideration scientific principles of operation, projected utility, operational characteristics, functional support requirements, accuracy, efficiency, research risk factors, safety parameters, training requirements, and cost considerations.

Completed detailed evaluations for each technique reviewed are included in Appendix B of this report. Condensed versions of the evaluation data are presented in Tables 1 and 2. Table 1 describes each technique's operational principles and logistical requirements, while Table 2 presents an evaluation of each technique's respective effectiveness.

## Summation of Comparative Evaluation Results

Summarized below is a discussion of the candidate techniques that, following comparative evaluation and based on progress in technological development in the last decade, were deemed to possess some measure of future potential for satisfying project objectives.

### *Ultrasonic*

The research team's technology review has indicated that recent advances have been made in the area of ultrasonic inspection of prestressed concrete members. Use of these techniques for concrete structures and their components has been exhaustively pursued for nearly three decades. Regardless of some progress in their use for concrete flaw detection and documented capabilities for strand/wire flaw detection near posttensioning and stay cable anchorages, the largest impediment to utilization of ultrasonic waves for strand condition evaluation has been and will remain the significant signal attenuation problem posed by concrete. This factor currently limits the length over which a strand embedded in grout can be evaluated for presence of defects and deterioration to a few meters from the transducer location at its end. The development of new sensors, advanced signal processing, deconvolution analyses, as reported in the recent scientific literature, are encouraging. However, as the degree of

# TABLE 1 - NDT METHOD CHARACTERISTICS AND LOGISTICAL REQUIREMENTS

| Candidate Method | Sensor Type | Sensor Position | | | Sensor | | Self Propelled Sensor | Type of Readings | | Data Acquisition | | | Impairing Environ. Effects? | Support Vehicle Req'd.? | Weight | | Traffic Control | | | Drilling/ Patching Req'd.? | Auxiliary Power Req'd.? | Crew Size |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | End | Side | Deck | Contacting | Noncontacting | | Continuous | Discrete | Manual | Semiauto | Auto | | | Eqpt. | Sensor | Lane | Bridge | None | | | |
| Direct Ultrasonic Detection | Piezoelectric | ✓ | | | ✓ | | N | | ✓ | ✓ | | | N | N | L | L | | | ✓ | N | N | 2 |
| Nonlinear Vibro-Acoustics | Acoustic Ultrasonic | | ✓ | | ✓ | | N | | ✓ | ✓ | | | N | N | L | L | | | ✓ | N | N | 2 |
| Acoustic Emission Monitoring(1) | Accelerometer | ✓ | ✓ | | ✓ | | N | ✓ | | | | ✓ | N | N | L | L | | | ✓ | N | N | None |
| Pulsed Eddy Current | Electromagnetic Inductance Probe | | ✓ | | ✓ | ✓ | N | | ✓ | UNK | UNK | UNK | N | N | UNK | L | | | ✓ | UNK | N | 2 |
| ETDR Instrumentation(2) | Coaxial Cable | (3) | | | (3) | | (3) | ✓ | | | | ✓ | N | N | L | L | | | ✓ | N | N | None |
| Surface Spectral Resistivity | Resistivity Probe | | ✓ | | ✓ | | N | | ✓ | ✓ | | | N | N | L | L | | | ✓ | Y | N | 2 |
| Automated Magnetic Flux Leakage | Hall Sensor | | ✓ | | | ✓ | Y | ✓ | | | | ✓ | N | Y | M | M | | | ✓ | N | Y | 3 |
| Power Focusing Ground Penetrating Radar | Electromagnetic Antenna | | ✓ | | | ✓ | N | ✓ | | | ✓ | | N | Y | M | M | | | ✓ | N | N | 3 |
| Radiographic Imaging | Radiographic Source/Film | | ✓ | | | ✓ | N | | ✓ | ✓ | | | Y | Y | H | H | | ✓ | | N | Y | 3+ |
| Reflectometric Impulse Measurement (RIMT®) | Strand Itself | ✓ | | | ✓ | | N | ✓ | | M | | | N | N | L | L | | | ✓ | Y | N | 2 |
| X-Ray Diffraction Based Tendon Stress Measurement | X-Ray Diffractometer | | ✓ | | ✓ | | N | | ✓ | ✓ | | | Y | Y | M | M | | ✓ | ✓ | Y | Y | 3 |
| Strain Relief-Based Prestress Measurements | Displacement/Strain | | ✓ | | ✓ | | N | | ✓ | ✓ | | | Y | Y | H | L | | | ✓ | Y | N | 4 |

(1) Will not establish existing condition and extent of deterioration in concrete bridge inventory.
(2) Valid for future new construction only.
(3) Sensor preplaced alongside strand during fabrication.

Key to Abbreviations: Y = yes; N = no; L = low; M = medium; H = high, UNK = unknown

## TABLE 2 - SUMMARIZED POTENTIAL EFFECTIVENESS EVALUATION OF NDT METHODS

| Candidate Method | Projected Utility | | | Readings Req'd per 100 ft of Strand | Live Load Effects on Data | Multiple Reinforcement Layer Shadowing | Potential Sensitivity to Loss of Section | Prior Use for Concrete Reinf. | Prior Use in Other Industry | Level of Scientific Maturity | Time and Cost of Development | User Safe? | Passersby Safe? | User Physiological Monitoring Req'd.? | State Multiunit Affordability | Multistate Sharing of Common Resource | Training Complexity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | P/C | Steel Duct P/T | Plastic Duct P/T | | | | | | | | | | | | | | |
| Direct Ultrasonic Detection | Y | Y | Y | L | N | Y | H | Y | Y | H | H | Y | Y | N | Y | Y | M |
| Nonlinear Vibro-Acoustics | Y | N | N | H | N | UNK | UNK | Y | Y | M | H | Y | Y | N | Y | Y | M |
| Acoustic Emission Monitoring(1) | N | N | N | NA | N | NA | NONE | Y | N | M | NA | Y | Y | N | NA | NA | M |
| Pulsed Eddy Current | Y | N | UNK | L | UNK | Y | UNK | N | Y | M | H | Y | Y | N | Y | Y | UNK |
| ETDR Instrumentation(2) | Y | Y | Y | NA | UNK | N | UNK | N | Y | L | M | Y | Y | N | Y | Y | UNK |
| Surface Spectral Resistivity | Y | NA | NA | H | N | Y | NONE | Y | Y | M | NA | Y | Y | N | Y | Y | NA |
| Automated Magnetic Flux Leakage | Y | UNK | Y | M | N | Y | M to H | Y | Y | M | L | Y | Y | N | Y | Y | M |
| Power Focusing Ground Penetrating Radar | Y | N | Y | L | N | Y | UNK | N | Y | L | M | Y | Y | N | Y | Y | M |
| Radiographic Imaging | Y | Y | Y | H | Y | Y | L to M | Y | Y | H | M | N | N | Y | N | Y | M |
| Reflectometric Impulse Measurement (RIMT®) | N | N | N | L | N | Y | NONE | Y | Y | M | NA | Y | Y | N | NA | NA | M |
| X-Ray Diffraction Based Tendon Stress Measurement | Y | Y | Y | H | Y | N | NONE | Y | N | L | M | N | N | Y | Y | Y | M |
| Strain Relief-Based Prestress Measurements | Y | Y | Y | H | Y | N | NONE | Y | Y | M | M | Y | Y | N | Y | Y | M |

(1) Will not establish existing condition and extent of deterioration in concrete bridge inventory.
(2) Valid for future new construction only.

Key to Abbreviations: Y = yes; N = no; L = low; M = medium; H = high, UNK = unknown sophistication of attempts to detect corrosion on individual strands embedded in concrete increases, the practicality of short- and medium-term widespread use of the technology (as envisioned by the NCHRP research goals) decreases. In the opinion of the writers of this report, there is merit to seeking improved methodology within the area of automated, refined data analysis and sensor improvements. This, however, would be considered a long-term, high-risk research effort requiring resources far beyond those of a single NCHRP research project, rather than a technology that could be implemented practically soon on actual structures.

### *Nonlinear Vibro-Acoustic Method*

The nonlinear vibro-acoustic method is based on the theory that materials containing cracks, fractures, disbondings, and so forth have a much larger nonlinear response due to nonlinear transformation of acoustic energy by a defect. The advantages of the nonlinear methods include high sensitivity and applicability to highly non-homogeneous structures such as concrete. The method involves modulation of a higher frequency ultrasonic probe wave by a lower frequency vibration. Modulation will produce sidebands in the frequency domain if there is degradation. This method is readily adaptable to field applications and does not appear to involve very sophisticated tools for data interpretation and analysis. Wave attenuation in concrete is a limiting condition. Overall, this method is believed to have potential for long-term success in providing information regarding condition and soundness of the concrete-steel interface, not direct measure of loss of cross-sectional area or presence of cracking/fracture in the strand.

### *Acoustic Emission*

Passive monitoring of prestressed concrete structures using acoustic emission techniques is a useful method for passive monitoring of deterioration in unbonded tendons only. Severe attenuation of elastic waves in strands bonded with concrete substantially reduces the method's effectiveness. Acoustic emission techniques require continuous monitoring for detection and capturing of waveforms. The recorded signal then has to be analyzed (either manually or through artificial intelligence algorithms) to distinguish real events from false triggers. The locations of events can be determined using differences in arrival times of waveforms at different sensors. Based on the above and given that it will not permit definition of the presence and quantified extent of corrosion on embedded bonded prestressing strand, further development of this method was not warranted within the scope of this NCHRP study.

### *Pulsed Eddy Current*

This technology was developed at the Iowa State University for application to thin aircraft skins. It could have applications in prestressed concrete; however, so far there have been no attempts to test this concept on prestressed concrete. This method has an advantage over the ultrasonic methods in that coupling to the concrete surface is not required. However, higher power probes may be required for use in a pitch-catch mode. The spiral nature of 7-wire strands and the potential ineffectiveness of the method for discriminating flaw characteristics of an individual strand in their customary groupings (shadowing effects) will likely introduce other complications. Prestressing strands are ferromagnetic. Therefore, the depth of inspection would be limited to the wire surface. Any development of this method for prestressed concrete should be viewed as high-risk basic research (i.e., long-term development is needed, with a strong possibility of no success) and is deemed by the research team to offer little potential for successful development within the limitations of this NCHRP study.

### *Electrical Time Domain Reflectometry*

Two distinct approaches were evaluated for applying the ETDR technology to prestressing reinforcement. The first is development of ETDR sensors for embedment in concrete (in new structures), and the other involves utilizing the strand itself as the NDT sensor. Although the latter offers little promise for the prestressed infrastructure since its effectiveness is limited to unbonded systems, the development of a low-cost ETDR strain sensor for embedment in concrete is believed to have strong merit and potential for near-term development and implementation. This device presents the potential for incorporation of a very-low-cost sensor on a systemic basis in new construction for the purpose of structural health monitoring. The ETDR sensor is expected to be a variation of the basic coaxial cable. The cable (or a connector) can exit concrete at a convenient location. TDR monitoring systems are commercially available (for applications in power lines and geotechnical applications). Sensor development could focus on two areas: (1) the beam ends, where a low-cost sensor would be beneficial for estimating transfer lengths of strands immediately after prestress transfer (for quality control) and throughout the service life of the member and (2) the entire length of the prestressed member, in which a continuous sensor could provide continuous indications of strain. The key is to make the sensor sensitive to an acceptable level for prestressed concrete. If successful, this sensor could also be used to perform continuous modal analyses for more detailed damage detection. This sensor must also be resistant to the concrete environment. Therefore, special coatings may be required for the sensor. The disadvantage of this technology, which eliminated it from consideration in this study, was its lack of adaptability to existing bridge structures.

### *Surface Spectral Resistivity Method*

This method is based on surface measurements of the frequency dependence of the complex impedance of reinforcing bar embedded in concrete. Complex impedance can be directly related to the corrosion rate of reinforcing steel in concrete. The advantage of this method is that it does not require removal of concrete cover to attach electrodes directly to the reinforcing steel. This method is believed to be similar to existing methods for detecting corrosion in underground steel pipes. There may be a way to improve on this method by providing a pulsed current that covers a wide range of frequencies (in lieu of a single frequency) and by looking at the resulting voltage in the frequency domain. In any case, although this method offers new concepts, the basic methodology has in fact been in use in the form of half-cell potential and linear polarization measurements of the electrochemical state of concrete. This method shares the same advantages and limitations of the half-cell potential method and is not recommended for further research within this NCHRP study, because it cannot directly or indirectly measure the degree of loss of cross-sectional area in strand embedded in an existing structure.

### *Magnetostrictive Sensors*

This technique is based on the principle that a magnetic material changes its shape (elastic wave) when subjected to a changing magnetic field and vice versa. There are no published test data on the effectiveness of this method for prestressed concrete. It is currently not clear how the significant attenuation in concrete will affect results. Also, in real prestressed concrete members, it may not be possible to place encircling MsS sensors around the target strands (at least not for existing structures). Overall, it is believed that the application of this technology would be limited in bonded prestressed concrete because of the significant attenuation of waves propagating along the steel when embedded in concrete. Therefore, further research within the scope of this NCHRP project was not recommended.

### *Magnetic Flux Leakage*

The recent work performed by Ghorbanpoor et al. (1996)(38) has substantially advanced the process of obtaining data on prestressed beams and has improved the speed of data collection. The system was deemed to have the potential to achieve the desired goals of the study for pretensioned beams. The existing hardware are at an essentially complete state of development. However, practical, rapid interpretation of data obtained in the field is known to require further development. Correlation of interpreted test data with observed corrosion in prestressed beams in the field is also not currently available. This method (and hardware) were believed to offer the best potential to achieve the stated goals of this study within its budgetary and time constraints. In its automated form, this method is believed to be applicable to pretensioned members in general and to AASHTO beams in particular. Applications to posttensioned beams with parabolic tendons (with plastic ducts) would be a manual (not automated) effort. Applications to PT tendons with steel ducts may be more complicated because of the shadowing effect of the duct itself. The anchorage areas in all cases (pretensioned or posttensioned) would require manual operation. The areas directly above the bearings may not be easy to inspect.

### *Power Focusing Ground Penetrating Radar*

This technology involves the use of an ultra-wideband antenna array that would conform to the particular media (i.e., concrete member). This technology promises high-speed tomographic evaluation of prestressed members. However, the electromagnetic field generated by radar cannot penetrate and propagate through steel strands. Therefore, any inspection abilities would rely exclusively on developing strong correlations between the state of the corroded steel surface of the strand and its resulting induced changes in the dielectric properties and characteristics of the surrounding concrete cover. A great deal of high-risk developmental work would be required to arrive at workable prototype for field application. Further development of this concept within the scope of this program was not warranted.

## CHAPTER 6

## CONCLUSIONS AND RECOMMENDATIONS

This technology review and evaluation of nondestructive flaw detection and imaging technologies sought a single methodology which, in the near term, would quantitatively and precisely define loss of cross-sectional area in bonded prestressing strand embedded in existing pretensioned and posttensioned concrete bridge structures. This and prior searches for an appropriate NDT system capable of successfully attaining these goals have encompassed methods which

- Directly measure specific material properties or characteristics indicative of its condition,
- Indirectly (i.e., through inference based on experimental correlation) establish the boundary conditions of a material, or
- Provide graphic images of physical conditions existing within the body of a component.

It is the CTL research team's conclusion that the state of the art and the complex material constituents of a prestressed concrete bridge component will not permit existing NDT technologies or advances on the technological horizon to examine the individual strand's condition as precisely and accurately as sought in this study's goals (and with its constraints). Referring to Table 2, this conclusion can be noted by comparing system characteristics for evaluation parameters, such as the widespread utility for all prestressed systems, sensitivity to loss of section, scientific maturity, and time and cost of needed development.

Ultrasonic techniques, which fundamentally possess the strongest scientific basis for the high degree of defect resolution required to discern a 5-percent loss of cross-sectional area, are attenuated so strongly by the concrete medium that complete signal loss occurs within less than 2 m of the tested strand's end. Thus, utilization of this method of strand evaluation is limited exclusively to prestressed member anchorage zones. The vibro-acoustic method of evaluation of the corrosion-affected interface between concrete and strand poses an interesting and challenging long-term research topic; however, its practical limitations related to the need for extensive empirical correlations between waveforms and degree of corrosion offered the program low potential as a successful and practical technique within the context and resources of this NCHRP project.

Magnetic techniques for reinforced/prestressed concrete have been extensively researched for two decades. Operational systems for use in prestressed structures and bridge cables have been developed since the mid-1970s under the sponsorship of the FHWA. To date, and despite the method's demonstrated ability to detect wire fracture due to corrosion of bridge cables, this technology has not been used for prestressed construction because of complexities in signal interpretation. The data analysis difficulties are related to signal clutter produced by mild reinforcement and metallic construction accessories. Additionally, the size, weight, and unwieldy nature of sensor arrays has produced reluctance on the part of potential users. The most recent phase of improvement of the magnetic flux leakage systems concentrated on developing a modular design and self-propelled sensor array carriages to allow tests on I-beams, flanges of box beams, and pier elements. Development goals still remain in the areas of simplification of data analysis and interpretative post-processing techniques. If these can be overcome, the systems may be capable of reliably quantifying extent of deterioration in prestressed reinforcement.

Recently developed passive acoustic monitoring systems have been adopted for evaluating the progress of deterioration in prestressed structures such as parking garages and prestressed concrete pipelines. These offer limited benefit for bridges-the concept will not function well for bonded system, because it cannot be used to discern the existing condition of strand in the bridge inventory, nor does it possess the sensitivity necessary to quantify the condition of the strand as impaired by corrosion. Other reviewed newer technologies, including pulsed eddy current, reflectometric impulse measurement (RIMT)®, surface spectral resistivity, and power focusing radar methods, present similar and even more significant drawbacks, as noted in Chapter 5.

Although none of the reviewed candidate techniques offered the precise quantitative strand integrity and loss of cross-sectional area evaluation features sought by this NCHRP study for both pretensioned and posttensioned construction, some promise exists with the magnetic flux leakage method. The research team noted that, throughout its development, progressive, successful improvements in the practicality and mobility of this technology's hardware have been made. Although the technique has been demonstrated to effectively sense and locate wire and strand fractures, little rigorous development work has been carried out attempting to (1) correlate and grade signals from corroding strand in concrete and (2) discriminate signals produced by mild steel stirrup reinforcement and metallic construction accessories from indications of flaws and defects. The research team concluded that execution of an analytical and experimental program to define the relationship between magnetic field disturbances and the degree and extent of strand corrosion ranging from incipient to severe in pretensioned beams would successfully fulfill a sizeable proportion of this NCHRP project's goals. It was recommended that this development program be instituted in the second phase of the NCHRP 10-53 research program. The Phase II research plan included in Appendix D (not included) was developed. This research plan addressed specific damage identification improvements needed in the MFL technology so that objective identification and classification of damage could be made in pretensioned bridge girders. The plan proposed use of finite element model-based training of neural net systems for flaw and defect recognition, integrated with full-scale laboratory testing on large deteriorated prestressed concrete specimens at the CTL facilities, and field testing at nationwide bridge sites. (NCHRP note: Phase II not pursued.)

Technology review efforts of this research study also identified another concept that, although falling outside the realm of the specific NDT goals of this 10-53 project, could be of some advantage in fulfilling the future need for evaluating the condition of the prestressed infrastructure. Specifically, a low-cost preplaced sensor for quantitative condition evaluation of prestressed structures was identified. The feasibility of using low-cost distributed coaxial cables (ETDR sensors) for structural monitoring was suggested by Stastny, Roger, and Laing(22). This sensor system, which offers the potential for periodically interrogating the strain state in concrete with a simple data acquisition device, could be promising as a quantitative structural evaluation tool for prestressed structures to be constructed in the future. The concept has positive characteristics, including inherent cost-effectiveness and simplicity, and may be suitable for widespread, direct quantitative structural condition assessment and load rating of bridges and other structures. Its relevance is particularly strong if one believes that the variety and complexity of prestressed concrete may not allow reliable and precise inspection of strand condition in not only existing structures, but also for structures to be designed and constructed in the near- to mid-term future. The research team recommends that this concept be studied for applicability in new structures through a future research effort separate from this NCHRP 10-53 study.

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# APPENDIX A

## PROJECT CONSULTANT REPORT

## "ASSESSMENT OF THE POTENTIAL FOR USING EMERGING NONDESTRUCTIVE EVALUATION TECHNIQUES TO DETECT CORROSION AND CRACKING IN PRESTRESSING STEEL STRANDS", SRI INTERNATIONAL

SRI International

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Task 1 Report • July 1997

# ASSESSMENT OF THE POTENTIAL FOR USING EMERGING NONDESTRUCTIVE EVALUATION TECHNIQUES TO DETECT CORROSION AND CRACKING IN PRESTRESSING STEEL STRANDS

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NCHRP Project 10-53

SRI Project 1883

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This report documents the results of a brief study carried out to assess the potential for using emerging nondestructive evaluation techniques to detect and characterize corrosion and cracking in steel prestressing strands embedded in concrete bridge members. The conclusions reported here are based on information obtained from a literature search. attendance at a recent conference on the nondestructive characterization of materials. and personal experience.

We have discovered nothing new in the areas of conventional ultrasound, acoustic emission, magnetics, radar, or X rays that would suggest that the performance of these techniques for detecting corrosion and cracking in prestressing steel strands can be improved. Each approach still has its problems in the difficult environment associated with inspecting bridges.

There are, however, some results in three different nondestructive evaluation (NDE) technology areas related to corrosion detection that have been reported recently and are worth mentioning. The first technique uses pulsed eddy currents. This work was carried out by John Moulder and coworkers at the Center for Nondestructive Evaluation at Iowa State University [l-2]. Their aim was to detect and characterize corrosion in aircraft lap splices. This technique uses more-or-less standard eddy-current probes, but the excitation is pulsed. This approach has the advantage of being able to interrogate a wide range of frequencies very rapidly, thereby quickly acquiring a great deal of information about the flawed electrically conducting object. The disadvantage for the application at hand is, of course, the need for a conventional eddy-current probe to be in close proximity to the test piece (strand) in order to achieve sufficient sensitivity and high spatial resolution. However, the technique may be worth considering if probes that tolerate higher power could be developed for interrogating at a distance through the cement, and if the resulting spatial resolution is acceptable.

The second technique is a nonlinear vibro-acoustic technique that I heard described at a recent meeting on the nondestructive characterization of materials. This technique was developed about 10 years ago at the Institute of Applied Physics in the Russian Academy of Sciences to control the quality attachment of thermo-protective coatings on the Russian space shuttle. In this method, a low-frequency vibration is applied to the area of interest, and then a frequency product associated with modulation by the low-frequency sound wave of a second applied, higher-frequency sound wave is detected. The assumption is that a corroded or cracked material is required for this modulation to take place, and this correspondence is claimed to have been verified by experiment. In particular, tests have been conducted demonstrating crack and corrosion detection in steel-reinforced concrete. This technique has the advantage of high sensitivity because it discriminates against the multitude of linear scattering mechanisms present in the material, such as structural inhomogeneities. Furthermore, the spatial resolution is determined by the higher-frequency interrogating sound wave. I do not have any literature references on this technique. but one its inventors, Dimitri Donskoy, is now working in this country at the Stevens Institute of Technology in Hoboken, NJ. and no doubt could supply more information if the technique is of interest to you.

The third technique takes a different tack and requires embedding fiber-optic sensors in new concrete structures along side and in close proximity to the prestressing strands. These sensors are currently under development for applications such as "smart" structures [3-41]. Since they are accessible at the ends of the concrete structure, these sensors would be used with optical time-domain reflectometry to locate and assess areas of corrosion or other damage along the steel strands. It remains to be seen, however, how robust and reliable these sensors might be.

Finally, in regard to your own suggestion of using electromagnetic time-domain reflectometry (ETDR), I agree that it sounds promising. However, other than the references that you cite, I have not found anyone doing anything with this technique that is directly related to the application of interest. I see three main issues involved with making an ETDR work in the prestressed-concrete environment. The first issue is how to efficiently couple the voltage pulse onto the steel strand(s). The guided wave on the strand will have a high impedance and an extended field distribution, and so the coupler should match these characteristics. The second issue is the amount of attenuation suffered by the guided wave and how much of its energy is reflected by corrosion or other defects. and. therefore, how sensitive we need to make the instrument (in the presence of other benign reflections and transmitter feedthrough). Finally, the third issue is getting sufficient spatial resolution along the strand and learning how to interpret the data.

One approach to getting enough signal onto the strand is to use very-high-voltage pulses, such as those being used by SRI in our ultra-wideband ground-penetrating radars (GPR). Pulsers are available commercially, for example, from POWERSPECTRA in Sunnyvale, CA. Sub-nanosecond pulses with peak voltages of several kilovolts are typical. Using such a large short pulse increases the dynamic range (ability to see small returns) and provides spatial resolution of less than a foot, provided you can keep the leakage of this pulse into the receiver from masking the returns. To illustrate this point numerically, consider the following fictitious case: Let the peak voltage of the exciting pulse be 1 kV (60 dBV), and let the coupler loss and flaw reflectivity be -10 dB and -20 dB, respectively. Furthermore, assume that the detection threshold (determined by leakage and coherent clutter) is 0 dBV. This means that we can tolerate 30 dB (60 - 10 - 20) of round-trip loss along the prestressing strand. Hence, if the propagation loss along the strand is.

0.5 dB per meter, we could expect to detect flaws with this magnitude of reflectivity over a strand length of up to 30 meters.

Over the years, SRI has conducted several projects aimed at detecting fault, in electromagnetic cables using time-domain reflectometry. One notable example is our development of an instrument for use with power cables in mines where we used a stepped-frequency signal to obtain wide bandwidth (high spatial resolution) while maintaining a low peak voltage (a safety issue). However, because the propagation environment is so different between electromagnetic cables and steel strands in concrete, I do not believe it would be very accurate to extrapolate quantitative cable results to the steel-strand case.

Another potential advantage of using such high-voltage pulses is that you may be able to detect harmonic frequencies that, say, are only generated by corrosion and not by voids in the grout or cement around the strand (for this to happen requires that the defect of interest possess a nonlinear voltage-current characteristic). If successful. this technique would discriminate between signals from the defect and those from other scatterers that have only a linear response (such as voids). It may also allow you to distinguish between different types of defects, etc. A variation on this theme might be to combine the electromagnetic interrogating pulse with a low-frequency sound wave as in the vibro-acoustic technique described above. In this case, the hope is that the electromagnetic pulse would be modulated by the sound wave in areas of corrosion damage.

For your information, SRI is presently embarking on an internally funded study of using nonlinear techniques to detect and characterize faults in underground power cables. We are also planning to conduct research to improve our understanding of the physical mechanisms that produce nonlinear responses. No results are available yet.

Since all our work at SRI to date with such high-voltage pulses has been for use in GPR, it is not possible for me to comment knowledgeably on possible thermal effects or interactions with secondary steel reinforcements that might occur in the prestressed-concrete application.

In conclusion, we have identified four NDE techniques that bear watching for possible application to prestressed-concrete bridge members: (1) pulsed eddy currents, (2) nonlinear vibro acoustics, (3) fiber-optic sensing, and (4) electromagnetic time-domain reflectometry (possibly using high-voltage pulses).

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# APPENDIX B

# CANDIDATE NDT SYSTEM EVALUATION DATA

# CANDIDATE SYSTEM CHARACTERIZATION & EVALUATION DATA

Physical Principle of Operation: **DIRECT ULTRASONIC DEFECT DETECTION**

Sensor Type: Piezoelectric

| | |
|---|---|
| **Projected Utility** | |
| Applicable to Pretensioned AASHTO/Bulb T Category? Y/N/UNK | Y |
| Applicable to Steel Ducted P/T Category? Y/N/UNK | Y |
| Applicable to Plastic Ducted P/T Category? Y/N/UNK | Y |
| Applicable to Multi-cell Pretensioned Box Girder Category? Y/N/UNK | Y |
| **Operational Characteristics (Existing Technology)** | |
| Required or Anticipated Sensor Position - i.e., Beam End, Side, Deck Surface? | End |
| Contact/Surface Coupling Necessary? Y/N/UNK | Y |
| Self-Propelled Sensor? Y/N/UNK | N |
| Discrete Readings? Y/N/UNK | Y |
| Continuous Scan? Y/N/UNK | Y |
| Means of Data Acquisition - Manual, Semiautomated, Automated | Semiautomated |
| Environmental Effects on Measurement - Day/Night, Rain/Dry, Sun/Shade, Seasonal? | None |
| **Functional Support Requirements** | |
| Instrumentation Vehicle Required? Y/N | N |
| Access Vehicle or Equipment Required? Y/N | Y |
| Equipment Weight? L/M/H | L |
| Sensor Weight? L/M/H | L (minimal) |
| Traffic Control Requirements - Y/N and Degree (Bridge Closure or Lane Closures?) | N |
| Drilling/Electrical Connection/Patching Required? Y/N | Y |
| Auxiliary Electrical Power Requirements? Y/N | N |
| **Potential Accuracy & Efficiency** | |
| Number of Readings (tests) Required per 100 ft of Strand? L/M/H | N/A |
| Time Expended Using Single Hardware Unit for Data Gathering for 100 ft of Strand? L/M/H | N/A |
| Time Expended Using Single Unit for Data Interpretation for 100 ft of Strand? L/M/H | N/A |
| Interfering Effects of Live Load Passage? Y/N/UNK | N/A |

| | |
|---|---|
| Interfering Effects of Multiple Steel Layers (shadowing)? Y/N/UNK | N |
| Minimum Sensitivity to LOCSA? L/M/H | H |

### Developmental Risk Factors

| | |
|---|---|
| Successful Basis and History of Utilization for Strand or Reinforcement? Y/N/UNK | N |
| Successful History of Utilization in Other Industries? Y/N | Y |
| Established Level of Scientific Maturity as Test Method? L/M/H | H |
| Perceived Degree of Research Risk? L/M/H | H |
| Time to Development? L/M/H | H |
| Newly Adapted Technique/Existing Hardware? Y/N | Y |
| New Technique/New Hardware? Y/N | N |

### Safety Parameters

| | |
|---|---|
| User Safe? Y/N/UNK | Y |
| Passersby Safe? Y/N/UNK | Y |
| User Physiological Monitoring Required? Y/N/UNK | N |

### Projected Staffing/Training Efforts

| | |
|---|---|
| Total Crew Size (including functional support)? | 2 |
| Leader Training Time Required - first year? L/M/H | M |
| Technician Training Time Required - first year? L/M/H | M |

### Cost Considerations

| | |
|---|---|
| Relative Cost of Development/Implementation? L/M/H | N/A |
| Affordable as Multiunit Inventory for Individual State? Y/N/UNK | Y |
| Affordable as Specialized Unit w/ Operators Shared by Multistate Regions? Y/N/UNK | Y |

### Other Factors - Disadvantages

Lacks penetrating range beyond 2 m into strand. Severe attenuation of signal strength by concrete is too severe to permit present implementation

## CANDIDATE SYSTEM CHARACTERIZATION & EVALUATION DATA

Physical Principle of Operation: **NONLINEAR VIBROACOUSTICS**

Sensor Type: Accelerometer/Acoustic Ultrasonic

### Projected Utility

| | |
|---|---|
| Applicable to Pretensioned AASHTO/Bulb T Category? Y/N/UNK | Y |
| Applicable to Steel Ducted P/T Category? Y/N/UNK | N |
| Applicable to Plastic Ducted P/T Category? Y/N/UNK | N |
| Applicable to Multi-cell Pretensioned Box Girder Category? Y/N/UNK | Y |

### Operational Characteristics (Existing Technology)

| | |
|---|---|
| Required Sensor Position - i.e., Beam End, Side, Deck Surface? | Side |
| Contact/Surface Coupling Necessary? Y/N/UNK | Y |
| Self-Propelled Sensor? Y/N/UNK | N |
| Discrete Readings? Y/N/UNK | Y |
| Continuous Scan? Y/N/UNK | N |
| Means of Data Acquisition - Manual, Semiautomated, Automated | Manual |
| Environmental Effects on Measurement - Day/Night, Rain/Dry, Sun/Shade, Seasonal? | UNK |

### Functional Support Requirements

| | |
|---|---|
| Instrumentation Vehicle Required? Y/N | N |
| Access Vehicle or Equipment Required? Y/N | Y |
| Equipment Weight? L/M/H | L |
| Sensor Weight? L/M/H | L |
| Traffic Control Requirements - Y/N and Degree (Bridge Closure or Lane Closures?) | N |
| Drilling/Electrical Connection/Patching Required? Y/N | N |
| Auxiliary Electrical Power Requirements? Y/N | N |

### Potential Accuracy & Efficiency

| | |
|---|---|
| Number of Readings (tests) Required per 100 ft of Strand? L/M/H | H |
| Time Expended Using Single Hardware Unit for Data Gathering for 100 ft of Strand? L/M/H | H |
| Time Expended Using Single Unit for Data Interpretation for 100 ft of Strand? L/M/H | M |
| Interfering Effects of Live Load Passage? Y/N/UNK | N |

| | |
|---|---|
| Interfering Effects of Multiple Steel Layers (shadowing)? Y/N/UNK | Y |
| Minimum Sensitivity to LOCSA? L/M/H | UNK |

**Developmental Risk Factors**

| | |
|---|---|
| Basis and Successful History of Utilization for Strand or Reinforcement? Y/N/UNK | N |
| Successful History of Utilization in Other Industries? Y/N | Y |
| Established Level of Scientific Maturity as Test Method? L/M/H | L |
| Perceived Degree of Research Risk? L/M/H | H |
| Time to Development? L/M/H | M |
| Newly Adapted Technique/Existing Hardware? Y/N | Y |
| New Technique/New Hardware? Y/N | N |

**Safety Parameters**

| | |
|---|---|
| User Safe? Y/N/UNK | Y |
| Passersby Safe? Y/N/UNK | Y |
| User Physiological Monitoring Required? Y/N/UNK | N |

**Projected Staffing/Training Efforts**

| | |
|---|---|
| Total Crew Size (including functional support)? | 2 |
| Leader Training Time Required - first year? L/M/H | UNK |
| Technician Training Time Required - first year? L/M/H | UNK |

**Cost Considerations**

| | |
|---|---|
| Relative Cost of Development/Implementation? L/M/H | M |
| Affordable as Multiunit Inventory for Individual State? Y/N/UNK | Y |
| Affordable as Specialized Unit w/ Operators Shared by Multistate Regions? Y/N/UNK | Y |

# CANDIDATE SYSTEM CHARACTERIZATION & EVALUATION DATA

Physical Principle of Operation: **PULSED EDDY CURRENT**

Sensor Type: Electromagnetic Inductance Probe

| | |
|---|---|
| **Projected Utility** | |
| Applicable to Pretensioned AASHTO/Bulb T Category? Y/N/UNK | Y |
| Applicable to Steel Ducted P/T Category? Y/N/UNK | N |
| Applicable to Plastic Ducted P/T Category? Y/N/UNK | UNK |
| Applicable to Pretensioned Box Girder Category? Y/N/UNK | Y |
| **Operational Characteristics (Existing Technology)** | |
| Required Sensor Position - i.e., Beam End, Side, Deck Surface? | Side |
| Contact/Surface Coupling Necessary? Y/N/UNK | Y |
| Self-Propelled Sensor? Y/N/UNK | N |
| Discrete Readings? Y/N/UNK | N |
| Continuous Scan? Y/N/UNK | Y |
| Means of Data Acquisition - Manual, Semiautomated, Automated | UNK |
| Environmental Effects on Measurement - Day/Night, Rain/Dry, Sun/Shade, Seasonal? | None |
| **Functional Support Requirements** | |
| Instrumentation Vehicle Required? Y/N | N |
| Access Vehicle or Equipment Required? Y/N | Y |
| Equipment Weight? L/M/H | UNK |
| Sensor Weight? L/M/H | UNK |
| Traffic Control Requirements - Y/N and Degree (Bridge Closure or Lane Closures?) | N |
| Drilling/Electrical Connection/Patching Required? Y/N | UNK |
| Auxiliary Electrical Power Requirements? Y/N | N |
| **Potential Accuracy & Efficiency** | |
| Number of Readings (tests) Required per 100 ft of Strand? L/M/H | L |
| Time Expended Using Single Hardware Unit for Data Gathering for 100 ft of Strand? L/M/H | L |
| Time Expended Using Single Unit for Data Interpretation for 100 ft of Strand? L/M/H | UNK |
| Interfering Effects of Live Load Passage? Y/N/UNK | UNK |

| | |
|---|---|
| Interfering Effects of Multiple Steel Layers (shadowing)? Y/N/UNK | Y |
| Minimum Sensitivity to LOCSA? L/M/H | UNK |

### Developmental Risk Factors

| | |
|---|---|
| Prior Basis and History of Utilization for Reinforcement or Strand? Y/N/UNK | N |
| Successful History of Utilization in Other Industries? Y/N | Y |
| Established Level of Scientific Maturity as Test Method? L/M/H | M |
| Perceived Degree of Research Risk? L/M/H | H |
| Time to Development? L/M/H | H |
| Newly Adapted Technique/Existing Hardware? Y/N | N |
| New Technique/New Hardware? Y/N | Y |

### Safety Parameters

| | |
|---|---|
| User Safe? Y/N/UNK | Y |
| Passersby Safe? Y/N/UNK | Y |
| User Physiological Monitoring Required? Y/N/UNK | N |

### Projected Staffing/Training Efforts

| | |
|---|---|
| Total Crew Size (including functional support)? | 2 |
| Leader Training Time Required - first year? L/M/H | UNK |
| Technician Training Time Required - first year? L/M/H | UNK |

### Cost Considerations

| | |
|---|---|
| Relative Cost of Development/Implementation? L/M/H | H |
| Affordable as Multiunit Inventory for Individual State? Y/N/UNK | Y |
| Affordable as Specialized Unit w/ Operators Shared by Multistate Regions? Y/N/UNK | Y |

# CANDIDATE SYSTEM CHARACTERIZATION & EVALUATION DATA

Physical Principle of Operation: **RADIOGRAPHIC IMAGING**

Sensor Type: Radiographic Hardware

| **Projected Utility** | |
|---|---|
| Applicable to Pretensioned AASHTO/Bulb T Category? Y/N/UNK | Y |
| Applicable to Steel Ducted P/T Category? Y/N/UNK | Y |
| Applicable to Plastic Ducted P/T Category? Y/N/UNK | Y |
| Applicable to Multi-cell Pretensioned Box Girder Category? Y/N/UNK | Y |

| **Operational Characteristics** | |
|---|---|
| Required Sensor Position - i.e., Beam End, Side, Deck Surface? | Side |
| Contact/Surface Coupling Necessary? Y/N/UNK | N |
| Self-Propelled Sensor? Y/N/UNK | Various |
| Discrete Readings? Y/N/UNK | Y |
| Continuous Scan? Y/N/UNK | N |
| Means of Data Acquisition - Manual, Semiautomated, Automated | Various/Manual |
| Environmental Effects on Measurement - Day/Night, Rain/Dry, Sun/Shade, Seasonal? | None |

| **Functional Support Requirements** | |
|---|---|
| Instrumentation Vehicle Required? Y/N | Y |
| Access Vehicle or Equipment Required? Y/N | Y |
| Equipment Weight? L/M/H | H |
| Sensor Weight? L/M/H | H |
| Traffic Control Requirements - Y/N and Degree (Bridge Closure or Lane Closures?) | Y |
| Drilling/Electrical Connection/Patching Required? Y/N | N |
| Auxiliary Electrical Power Requirements? Y/N | Y |

| **Potential Accuracy & Efficiency** | |
|---|---|
| Number of Readings (tests) Required per 100 ft of Strand? L/M/H | H |
| Time Expended Using Single Hardware Unit for Data Gathering for 100 ft of Strand? L/M/H | H |
| Time Expended Using Single Unit for Data Interpretation for 100 ft of Strand? L/M/H | H |
| Interfering Effects of Live Load Passage? Y/N/UNK | Y |

| | |
|---|---|
| Interfering Effects of Multiple Steel Layers (shadowing)? Y/N/UNK | Y |
| Minimum Sensitivity to LOCSA? L/M/H | M |

**Developmental Risk Factors**

| | |
|---|---|
| Successful Basis and History of Utilization for Strand or Reinforcement? Y/N/UNK | Y |
| Successful History of Utilization in Other Industries? Y/N | Y |
| Established Level of Scientific Maturity as Test Method? L/M/H | H |
| Perceived Degree of Research Risk? L/M/H | M |
| Time to Development? L/M/H | M |
| Newly Adapted Technique/Existing Hardware? Y/N | N |
| New Technique/New Hardware? Y/N | N |

**Safety Parameters**

| | |
|---|---|
| User Safe? Y/N/UNK | N |
| Passersby Safe? Y/N/UNK | N |
| User Physiological Monitoring Required? Y/N/UNK | Y |

**Projected Staffing/Training Efforts**

| | |
|---|---|
| Total Crew Size (including functional support)? | 3/More |
| Leader Training Time Required - first year? L/M/H | M |
| Technician Training Time Required - first year? L/M/H | M |

**Cost Considerations**

| | |
|---|---|
| Relative Cost of Development/Implementation? L/M/H | H |
| Affordable as Multiunit Inventory for Individual State? Y/N/UNK | N |
| Affordable as Specialized Unit w/ Operators Shared by Multistate Regions? Y/N/UNK | Y |

**Other Factors-Advantages**

Provides direct image of internal conditions. Readily detects wire breakage.

**Other Factors - Disadvantages**

Costly, hazardous, time-consuming process which is not practical for systematic strand condition evaluation based on periodic condition inspection methodologies utilized by highway agencies.

## CANDIDATE SYSTEM CHARACTERIZATION & EVALUATION DATA

Physical Principle of Operation: **AUTOMATED MAGNETIC FLUX LEAKAGE**

Sensor Type: Hall Sensor

| | |
|---|---|
| **Projected Utility** | |
| Applicable to Pretensioned AASHTO/Bulb T Category? Y/N/UNK | Y |
| Applicable to Steel Ducted P/T Category? Y/N/UNK | UNK |
| Applicable to Plastic Ducted P/T Category? Y/N/UNK | Y |
| Applicable to Multi-cell Pretensioned Box Girder Category? Y/N/UNK | Y |
| **Operational Characteristics** | |
| Required Sensor Position - i.e., Beam End, Side, Deck Surface? | Side/Bottom |
| Contact/Surface Coupling Necessary? Y/N/UNK | N |
| Self-Propelled Sensor? Y/N/UNK | Y |
| Discrete Readings? Y/N/UNK | N |
| Continuous Scan? Y/N/UNK | Y |
| Means of Data Acquisition - Manual, Semiautomated, Automated | Automated |
| Environmental Effects on Measurement - Day/Night, Rain/Dry, Sun/Shade, Seasonal? | None |
| **Functional Support Requirements** | |
| Instrumentation Vehicle Required? Y/N | N |
| Access Vehicle or Equipment Required? Y/N | Y |
| Equipment Weight? L/M/H | M |
| Sensor Weight? L/M/H | M |
| Traffic Control Requirements - Y/N and Degree (Bridge Closure or Lane Closures?) | N |
| Drilling/Electrical Connection/Patching Required? Y/N | N |
| Auxiliary Electrical Power Requirements? Y/N | Y |
| **Potential Accuracy & Efficiency** | |
| Number of Readings (tests) Required per 100 ft of Strand? L/M/H | M |
| Time Expended Using Single Hardware Unit for Data Gathering for 100 ft of Strand? L/M/H | L |
| Time Expended Using Single Unit for Data Interpretation for 100 ft of Strand? L/M/H | M |
| Interfering Effects of Live Load Passage? Y/N/UNK | N |

| | |
|---|---|
| Interfering Effects of Multiple Steel Layers (shadowing)? Y/N/UNK | Y |
| Minimum Sensitivity to LOCSA? L/M/H | L to M |

## Developmental Risk Factors

| | |
|---|---|
| Successful Basis and History of Utilization for Strand or Reinforcement? Y/N/UNK | Y |
| Successful History of Utilization in Other Industries? Y/N | Y |
| Established Level of Scientific Maturity as Test Method? L/M/H | M |
| Perceived Degree of Research Risk? L/M/H | L |
| Time to Development? L/M/H | L |
| Newly Adapted Technique/Existing Hardware? Y/N | Y |
| New Technique/New Hardware? Y/N | N |

## Safety Parameters

| | |
|---|---|
| User Safe? Y/N/UNK | Y |
| Passersby Safe? Y/N/UNK | Y |
| User Physiological Monitoring Required? Y/N/UNK | N |

## Projected Staffing/Training Efforts

| | |
|---|---|
| Total Crew Size (including functional support)? | 3 |
| Leader Training Time Required - first year? L/M/H | M |
| Technician Training Time Required - first year? L/M/H | M |

## Cost Considerations

| | |
|---|---|
| Relative Cost of Development/Implementation? L/M/H | M |
| Affordable as Multiunit Inventory for Individual State? Y/N/UNK | Y |
| Affordable as Specialized Unit w/ Operators Shared by Multistate Regions? Y/N/UNK | Y |

## Other Factors-Advantages

Possesses significant, moderately successful history of development for strand and cables. Extensive hardware development work already completed.

## Other Factors - Disadvantages

Correlation data for relating loss of area defect to signal features presently lacking requires considerable effort to develop reliable means for rapidly interpreting data through advanced signal analysis.

## CANDIDATE SYSTEM CHARACTERIZATION & EVALUATION DATA

Physical Principle of Operation: **SURFACE SPECTRAL RESISTIVITY**

Sensor Type: Resistivity Probe

| | |
|---|---|
| **Projected Utility** | |
| Applicable to Pretensioned AASHTO/Bulb T Category? Y/N/UNK | Y |
| Applicable to Steel Ducted P/T Category? Y/N/UNK | N |
| Applicable to Plastic Ducted P/T Category? Y/N/UNK | N |
| Applicable to Pretensioned Box Girder Category? Y/N/UNK | Y |
| **Operational Characteristics (Existing Technology)** | |
| Required or Anticipated Sensor Position - i.e., Beam End, Side, Deck Surface? | Side |
| Contact/Surface Coupling Necessary? Y/N/UNK | Y |
| Self-Propelled Sensor? Y/N/UNK | N |
| Discrete Readings? Y/N/UNK | Y |
| Continuous Scan? Y/N/UNK | N |
| Means of Data Acquisition - Manual, Semiautomated, Automated | Manual |
| Environmental Effects on Measurement - Day/Night, Rain/Dry, Sun/Shade, Seasonal? | None |
| **Functional Support Requirements** | |
| Instrumentation Vehicle Required? Y/N | N |
| Access Vehicle or Equipment Required? Y/N | Y |
| Equipment Weight? L/M/H | M |
| Sensor Weight? L/M/H | L |
| Traffic Control Requirements - Y/N and Degree (Bridge Closure or Lane Closures?) | N |
| Drilling/Electrical Connection/Patching Required? Y/N | Y |
| Auxiliary Electrical Power Requirements? Y/N | N |
| **Potential Accuracy & Efficiency** | |
| Number of Readings (tests) Required per 100 ft of Strand? L/M/H | H |
| Time Expended Using Single Hardware Unit for Data Gathering for 100 ft of Strand? L/M/H | H |
| Time Expended Using Single Unit for Data Interpretation for 100 ft of Strand? L/M/H | H |
| Interfering Effects of Live Load Passage? Y/N/UNK | N |

| | |
|---|---|
| Interfering Effects of Multiple Steel Layers (shadowing)? Y/N/UNK | Y |
| Minimum Sensitivity to LOCSA? L/M/H | UNK |

### Developmental Risk Factors

| | |
|---|---|
| Basis and Successful History of Utilization for Strand or Reinforcement? Y/N/UNK | N |
| Successful History of Utilization in Other Industries? Y/N | Y |
| Established Level of Scientific Maturity as Test Method? L/M/H | L |
| Perceived Degree of Research Risk? L/M/H | H |
| Time to Development? L/M/H | H |
| Newly Adapted Technique/Existing Hardware? Y/N | Y |
| New Technique/New Hardware? Y/N | N |

### Safety Parameters

| | |
|---|---|
| User Safe? Y/N/UNK | Y |
| Passersby Safe? Y/N/UNK | Y |
| User Physiological Monitoring Required? Y/N/UNK | N |

### Projected Staffing/Training Efforts

| | |
|---|---|
| Total Crew Size (including functional support)? | 2 |
| Leader Training Time Required - first year? L/M/H | UNK |
| Technician Training Time Required - first year? L/M/H | UNK |

### Cost Considerations

| | |
|---|---|
| Relative Cost of Development/Implementation? L/M/H | M |
| Affordable as Multiunit Inventory for Individual State? Y/N/UNK | Y |
| Affordable as Specialized Unit w/ Operators Shared by Multistate Regions? Y/N/UNK | Y |

### Other Factors - Disadvantages

Technique shares measurement principles with electrical potential, linear polarization and other corrosion state measurements and, as such, will not function as quantitative measure of strand deterioration.

## CANDIDATE SYSTEM CHARACTERIZATION & EVALUATION DATA

Physical Principle of Operation: **PASSIVE ACOUSTIC EMISSION WIRE BREAKAGE MONITORING**

Sensor Type: Accelerometer/Acoustic Emission Transducer

### Projected Utility

| | |
|---|---|
| Applicable to Pretensioned AASHTO/Bulb T Category? Y/N/UNK | N |
| Applicable to Steel Ducted P/T Category? Y/N/UNK | N |
| Applicable to Plastic Ducted P/T Category? Y/N/UNK | N |
| Applicable to Multi-cell Pretensioned Box Girder Category? Y/N/UNK | N |

### Operational Characteristics

| | |
|---|---|
| Required Sensor Position - i.e., Beam End, Side, Deck Surface? | End, Side |
| Contact/Surface Coupling Necessary? Y/N/UNK | Y |
| Self-Propelled Sensor? Y/N/UNK | N |
| Discrete Readings? Y/N/UNK | N |
| Continuous Scan? Y/N/UNK | Y |
| Means of Data Acquisition - Manual, Semiautomated, Automated | Automated |
| Environmental Effects on Measurement - Day/Night, Rain/Dry, Sun/Shade, Seasonal? | None |

### Functional Support Requirements

| | |
|---|---|
| Instrumentation Vehicle Required? Y/N | N |
| Access Vehicle or Equipment Required? Y/N | Y |
| Equipment Weight? L/M/H | L |
| Sensor Weight? L/M/H | L |
| Traffic Control Requirements - Y/N and Degree (Bridge Closure or Lane Closures?) | N |
| Drilling/Electrical Connection/Patching Required? Y/N | Y |
| Auxiliary Electrical Power Requirements? Y/N | Y |

### Potential Accuracy & Efficiency

| | |
|---|---|
| Number of Readings (tests) Required per 100 ft of Strand? L/M/H | N/A |
| Time Expended Using Single Hardware Unit for Data Gathering for 100 ft of Strand? L/M/H | N/A |
| Time Expended Using Single Unit for Data Interpretation for 100 ft of Strand? L/M/H | N/A |
| Interfering Effects of Live Load Passage? Y/N/UNK | N/A |

| | |
|---|---|
| Interfering Effects of Multiple Steel Layers (shadowing)? Y/N/UNK | N/A |
| Minimum Sensitivity to LOCSA? L/M/H | N/A |

**Developmental Risk Factors**

| | |
|---|---|
| Prior Basis and History for Utilization for Strand or Reinforcement? Y/N/UNK | Y |
| Successful History of Utilization in Other Industries? Y/N | N |
| Established Level of Scientific Maturity as Test Method? L/M/H | M |
| Perceived Degree of Research Risk? L/M/H | M |
| Time to Development? L/M/H | N/A |
| Newly Adapted Technique/Existing Hardware? Y/N | Y |
| New Technique/New Hardware? Y/N | N |

**Safety Parameters**

| | |
|---|---|
| User Safe? Y/N/UNK | Y |
| Passersby Safe? Y/N/UNK | Y |
| User Physiological Monitoring Required? Y/N/UNK | N |

**Projected Staffing/Training Efforts**

| | |
|---|---|
| Total Crew Size (including functional support)? | 2 |
| Leader Training Time Required - first year? L/M/H | L |
| Technician Training Time Required - first year? L/M/H | L |

**Cost Considerations**

| | |
|---|---|
| Relative Cost of Development/Implementation? L/M/H | L |
| Affordable as Multiunit Inventory for Individual State? Y/N/UNK | N/A |
| Affordable as Specialized Unit w/ Operators Shared by Multistate Regions? Y/N/UNK | N/A |

**Other Factors - Disadvantages**

Not feasible for utilization as active flaw detection method.

| | |
|---|---|
| Interfering Effects of Multiple Steel Layers (shadowing)? Y/N/UNK | N/A |
| Minimum Sensitivity to LOCSA? L/M/H | N/A |

### Developmental Risk Factors

| | |
|---|---|
| Prior Basis and History for Utilization for Strand or Reinforcement? Y/N/UNK | Y |
| Successful History of Utilization in Other Industries? Y/N | N |
| Established Level of Scientific Maturity as Test Method? L/M/H | M |
| Perceived Degree of Research Risk? L/M/H | M |
| Time to Development? L/M/H | N/A |
| Newly Adapted Technique/Existing Hardware? Y/N | Y |
| New Technique/New Hardware? Y/N | N |

### Safety Parameters

| | |
|---|---|
| User Safe? Y/N/UNK | Y |
| Passersby Safe? Y/N/UNK | Y |
| User Physiological Monitoring Required? Y/N/UNK | N |

### Projected Staffing/Training Efforts

| | |
|---|---|
| Total Crew Size (including functional support)? | 2 |
| Leader Training Time Required - first year? L/M/H | L |
| Technician Training Time Required - first year? L/M/H | L |

### Cost Considerations

| | |
|---|---|
| Relative Cost of Development/Implementation? L/M/H | L |
| Affordable as Multiunit Inventory for Individual State? Y/N/UNK | N/A |
| Affordable as Specialized Unit w/ Operators Shared by Multistate Regions? Y/N/UNK | N/A |

### Other Factors - Disadvantages

Not feasible for utilization as active flaw detection method.

## CANDIDATE SYSTEM CHARACTERIZATION & EVALUATION DATA

Physical Principle of Operation: **TIME DOMAIN REFLECTROMETRY INSTRUMENTATION**

Sensor Type: Coaxial Cable Placed Along Strand Inside Concrete

| **Projected Utility** | |
|---|---|
| Applicable to Pretensioned AASHTO/Bulb T Category? Y/N/UNK | Y |
| Applicable to Steel Ducted P/T Category? Y/N/UNK | Y |
| Applicable to Plastic Ducted P/T Category? Y/N/UNK | Y |
| Applicable to Multi-cell Pretensioned Box Girder Category? Y/N/UNK | Y |

| **Operational Characteristics** | |
|---|---|
| Required Sensor Position - i.e., Beam End, Side, Deck Surface? | Alongside Strand |
| Contact/Surface Coupling Necessary? Y/N/UNK | N |
| Self-Propelled Sensor? Y/N/UNK | N/A |
| Discrete Readings? Y/N/UNK | N |
| Continuous Scan? Y/N/UNK | Y |
| Means of Data Acquisition - Manual, Semiautomated, Automated | Automated |
| Environmental Effects on Measurement - Day/Night, Rain/Dry, Sun/Shade, Seasonal? | None |

| **Functional Support Requirements** | |
|---|---|
| Instrumentation Vehicle Required? Y/N | N |
| Access Vehicle or Equipment Required? Y/N | N |
| Equipment Weight? L/M/H | L |
| Sensor Weight? L/M/H | L |
| Traffic Control Requirements - Y/N and Degree (Bridge Closure or Lane Closures?) | N |
| Drilling/Electrical Connection/Patching Required? Y/N | N |
| Auxiliary Electrical Power Requirements? Y/N | N |

| **Potential Accuracy & Efficiency** | |
|---|---|
| Number of Readings (tests) Required per 100 ft of Strand? L/M/H | N/A |
| Time Expended Using Single Hardware Unit for Data Gathering for 100 ft of Strand? L/M/H | L |
| Time Expended Using Single Unit for Data Interpretation for 100 ft of Strand? L/M/H | L |
| Interfering Effects of Live Load Passage? Y/N/UNK | UNK |

| | |
|---|---|
| Interfering Effects of Multiple Steel Layers (shadowing)? Y/N/UNK | N |
| Minimum Sensitivity to LOCSA? L/M/H | UNK |

### Developmental Risk Factors

| | |
|---|---|
| Prior History and Basis for Utilization for Strand or Reinforcement? Y/N/UNK | N |
| Successful History of Utilization in Other Industries? Y/N | Y |
| Established Level of Scientific Maturity as Test Method? L/M/H | M |
| Perceived Degree of Research Risk? L/M/H | M |
| Time to Development? L/M/H | M |
| Newly Adapted Technique/Existing Hardware? Y/N | Y |
| New Technique/New Hardware? Y/N | N |

### Safety Parameters

| | |
|---|---|
| User Safe? Y/N/UNK | Y |
| Passersby Safe? Y/N/UNK | Y |
| User Physiological Monitoring Required? Y/N/UNK | N |

### Proiected Staffing/Training Efforts

| | |
|---|---|
| Leader Training Time Required - first year? L/M/H | UNK |
| Technician Training Time Required - first year? L/M/H | UNK |

### Cost Considerations

| | |
|---|---|
| Relative Cost of Development/Implementation? L/M/H | M |
| Affordable as Multiunit Inventory for Individual State? Y/N/UNK | Y |
| Affordable as Specialized Unit w/ Operators Shared by Multistate Regions? Y/N/UNK | Y |

### Other Factors-Advantages

Offers promise as low-cost sensor for systematic monitoring of structural condition.

### Other Factors- Disadvantages

Not feasible for utilization as a flaw detection method in existing structures. Only applicable in new structures.

## CANDIDATE SYSTEM CHARACTERIZATION & EVALUATION DATA

Physical Principle of Operation: **REFLECTOMETRIC IMPULSE MEASUREMENT TECHNIQUE (RIMT®)**

Sensor Type: Strand Itself

### Projected Utility

| | |
|---|---|
| Applicable to Pretensioned AASHTO/Bulb T Category? Y/N/UNK | N |
| Applicable to Steel Ducted P/T Category? Y/N/UNK | N |
| Applicable to Plastic Ducted P/T Category? Y/N/UNK | N |
| Applicable to Multi-cell Pretensioned Box Girder Category? Y/N/UNK | N |

### Operational Characteristics (Existing)

| | |
|---|---|
| Required Sensor Position - i.e., Beam End, Side, Deck Surface? | End |
| Contact/Surface Coupling Necessary? Y/N/UNK | Y |
| Self-Propelled Sensor? Y/N/UNK | N |
| Discrete Readings? Y/N/UNK | N |
| Continuous Scan? Y/N/UNK | N |
| Means of Data Acquisition - Manual, Semiautomated, Automated | Manual |
| Environmental Effects on Measurement - Day/Night, Rain/Dry, Sun/Shade, Seasonal? | None |

### Functional Support Requirements

| | |
|---|---|
| Instrumentation Vehicle Required? Y/N | N |
| Access Vehicle or Equipment Required? Y/N | Y |
| Equipment Weight? L/M/H | L |
| Sensor Weight? L/M/H | N/A |
| Traffic Control Requirements - Y/N and Degree (Bridge Closure or Lane Closures?) | N |
| Drilling/Electrical Connection/Patching Required? Y/N | Y |
| Auxiliary Electrical Power Requirements? Y/N | N |

### Potential Accuracy & Efficiency

| | |
|---|---|
| Number of Readings (tests) Required per 100 ft of Strand? L/M/H | L |
| Time Expended Using Single Hardware Unit for Data Gathering for 100 ft of Strand? L/M/H | L |
| Time Expended Using Single Unit for Data Interpretation for 100 ft of Strand? L/M/H | M |
| Interfering Effects of Live Load Passage? Y/N/UNK | N |

| | |
|---|---|
| Interfering Effects of Multiple Steel Layers (shadowing)? Y/N/UNK | Y |
| Minimum Sensitivity to LOCSA? L/M/H | L |

**Developmental Risk Factors**

| | |
|---|---|
| Successful Basis and History of Utilization for Strand or Reinforcement? Y/N/UNK | N |
| Successful History of Utilization in Other Industries? Y/N | Y |
| Established Level of Scientific Maturity as Test Method? L/M/H | M |
| Perceived Degree of Research Risk? L/M/H | H |
| Time to Development? L/M/H | H |
| Newly Adapted Technique/Existing Hardware? Y/N | Y |
| New Technique/New Hardware? Y/N | N |

**Safety Parameters**

| | |
|---|---|
| User Safe? Y/N/UNK | Y |
| Passersby Safe? Y/N/UNK | Y |
| User Physiological Monitoring Required? Y/N/UNK | N |

**Projected Staffing/Training Efforts**

| | |
|---|---|
| Total Crew Size (including functional support)? | 2 |
| Leader Training Time Required - first year? L/M/H | M |
| Technician Training Time Required - first year? L/M/H | M |

**Cost Considerations**

| | |
|---|---|
| Relative Cost of Development/Implementation? L/M/H | L |
| Affordable as Multiunit Inventory for Individual State? Y/N/UNK | Y |
| Affordable as Specialized Unit w/ Operators Shared by Multistate Regions? Y/N/UNK | Y |

**Other Factors - Disadvantages**

Does not provide meaningful and reliable results for bonded prestressing systems. No applicability for bridges.

## CANDIDATE SYSTEM CHARACTERIZATION & EVALUATION DATA

Physical Principle of Operation: **POWER FOCUSING GROUND PENETRATING RADAR**

Sensor Type: High Frequency Electromagnetic Antenna

| | |
|---|---|
| **Projected Utility** | |
| Applicable to Pretensioned AASHTO/Bulb T Category? Y/N/UNK | Y |
| Applicable to Steel Ducted P/T Category? Y/N/UNK | N |
| Applicable to Plastic Ducted P/T Category? Y/N/UNK | Y |
| Applicable to Multi-cell Pretensioned Box Girder Category? Y/N/UNK | Y |
| **Operational Characteristics** | |
| Required Sensor Position - i.e., Beam End, Side, Deck Surface? | Side |
| Contact/Surface Coupling Necessary? Y/N/UNK | N |
| Self-Propelled Sensor? Y/N/UNK | N |
| Discrete Readings? Y/N/UNK | N |
| Continuous Scan? Y/N/UNK | Y |
| Means of Data Acquisition - Manual, Semiautomated, Automated | Automated |
| Environmental Effects on Measurement - Day/Night, Rain/Dry, Sun/Shade, Seasonal? | None |
| **Functional Support Requirements** | |
| Instrumentation Vehicle Required? Y/N | Y |
| Access Vehicle or Equipment Required? Y/N | Y |
| Equipment Weight? L/M/H | M |
| Sensor Weight? L/M/H | M |
| Traffic Control Requirements - Y/N and Degree (Bridge Closure or Lane Closures?) | N |
| Drilling/Electrical Connection/Patching Required? Y/N | N |
| Auxiliary Electrical Power Requirements? Y/N | N |
| **Potential Accuracy & Efficiency** | |
| Number of Readings (tests) Required per 100 ft of Strand? L/M/H | L |
| Time Expended Using Single Hardware Unit for Data Gathering for 100 ft of Strand? L/M/H | L |
| Time Expended Using Single Unit for Data Interpretation for 100 ft of Strand? L/M/H | M |
| Interfering Effects of Live Load Passage? Y/N/UNK | N |

| | |
|---|---|
| Interfering Effects of Multiple Steel Layers (shadowing)? Y/N/UNK | Y |
| Minimum Sensitivity to LOCSA? L/M/H | UNK |

### Developmental Risk Factors

| | |
|---|---|
| Successful Basis and History of Utilization for Strand/Reinforcement? Y/N/UNK | N |
| Successful History of Utilization in Other Industries? Y/N | Y |
| Established Level of Scientific Maturity as Test Method? L/M/H | L |
| Perceived Degree of Research Risk? L/M/H | H |
| Time to Development? L/M/H | M |
| Newly Adapted Technique/Existing Hardware? Y/N | Y |
| New Technique/New Hardware? Y/N | N |

### Safety Parameters

| | |
|---|---|
| User Safe? Y/N/UNK | Y |
| Passersby Safe? Y/N/UNK | Y |
| User Physiological Monitoring Required? Y/N/UNK | N |

### Projected Staffing/Training Efforts

| | |
|---|---|
| Total Crew Size (including functional support)? | 3 |
| Leader Training Time Required - first year? L/M/H | H |
| Technician Training Time Required - first year? L/M/H | M |

### Cost Considerations

| | |
|---|---|
| Relative Cost of Development/Implementation? L/M/H | H |
| Affordable as Multiunit Inventory for Individual State? Y/N/UNK | Y |
| Affordable as Specialized Unit w/ Operators Shared by Multistate Regions? Y/N/UNK | Y |

### Other Factors - Disadvantages

Proposed physical principal of operation unproven, and likelihood of successful development low since impulse radar signal does not penetrate steel elements.

## CANDIDATE SYSTEM CHARACTERIZATION & EVALUATION DATA

Physical Principle of Operation: **X-RAY-DIFFRACTION-BASED TENDON STRESS MEASUREMENT**

Sensor Type: X-Ray Diffractometer

| | |
|---|---|
| **Projected Utility** | |
| Applicable to Pretensioned AASHTO/Bulb T Category? Y/N/UNK | Y |
| Applicable to Steel Ducted P/T Category? Y/N/UNK | Y |
| Applicable to Plastic Ducted P/T Category? Y/N/UNK | Y |
| Applicable to Multi-cell Pretensioned Box Girder Category? Y/N/UNK | Y |
| **Operational Characteristics** | |
| Required Sensor Position - i.e., Beam End, Side, Deck Surface? | Side |
| Contact/Surface Coupling Necessary? Y/N/UNK | Y |
| Self-Propelled Sensor? Y/N/UNK | N |
| Discrete Readings? Y/N/UNK | Y |
| Continuous Scan? Y/N/UNK | N |
| Means of Data Acquisition - Manual, Semiautomated, Automated | Manual |
| Environmental Effects on Measurement - Day/Night, Rain/Dry, Sun/Shade, Seasonal? | None |
| **Functional Support Requirements** | |
| Instrumentation Vehicle Required? Y/N | N |
| Access Vehicle or Equipment Required? Y/N | Y |
| Equipment Weight? L/M/H | M |
| Sensor Weight? L/M/H | M |
| Traffic Control Requirements - Y/N and Degree (Bridge Closure or Lane Closures?) | N |
| Drilling/Electrical Connection/Patching Required? Y/N | Y |
| Auxiliary Electrical Power Requirements? Y/N | N |
| **Potential Accuracy & Efficiency** | |
| Number of Readings (tests) Required per 100 ft of Strand? L/M/H | H |
| Time Expended Using Single Hardware Unit for Data Gathering for 100 ft of Strand? L/M/H | H |
| Time Expended Using Single Unit for Data Interpretation for 100 ft of Strand? L/M/H | H |
| Interfering Effects of Live Load Passage? Y/N/UNK | Y |

| | |
|---|---|
| Interfering Effects of Multiple Steel Layers (shadowing)? Y/N/UNK | N |
| Minimum Sensitivity to LOCSA? L/M/H | L |

### Developmental Risk Factors

| | |
|---|---|
| Successful Basis and History of Utilization for Strand or Reinforcement? Y/N/UNK | Y |
| Successful History of Utilization in Other Industries? Y/N | N |
| Established Level of Scientific Maturity as Test Method? L/M/H | L |
| Perceived Degree of Research Risk? L/M/H | M |
| Time to Development? L/M/H | M |
| Newly Adapted Technique/Existing Hardware? Y/N | Y |
| New Technique/New Hardware? Y/N | N |

### Safety Parameters

| | |
|---|---|
| User Safe? Y/N/UNK | N |
| Passersby Safe? Y/N/UNK | N |
| User Physiological Monitoring Required? Y/N/UNK | Y |

### Projected Staffing/Training Efforts

| | |
|---|---|
| Total Crew Size (including functional support)? | 3 |
| Leader Training Time Required - first year? L/M/H | M |
| Technician Training Time Required - first year? L/M/H | M |

### Cost Considerations

| | |
|---|---|
| Relative Cost of Development/Implementation? L/M/H | M |
| Affordable as Multiunit Inventory for Individual State? Y/N/UNK | Y |
| Affordable as Specialized Unit w/ Operators Shared by Multistate Regions? Y/N/UNK | Y |

### Other Factors-Advantages

Measured existing stress in individual wires.

### Other Factors - Disadvantages

Not applicable for strand flaw detection.

# CANDIDATE SYSTEM CHARACTERIZATION & EVALUATION DATA

Physical Principle of Operation: **CORING AND SLITTING - ACTIVATED STRAIN RELIEF-BASED PRESTRESS MEASUREMENTS**

Sensor Type: Displacement (Strain) Measurement

| **Projected Utility** | |
|---|---|
| Applicable to Pretensioned AASHTO/Bulb T Category? Y/N/UNK | Y |
| Applicable to Steel Ducted P/T Category? Y/N/UNK | Y |
| Applicable to Plastic Ducted P/T Category? Y/N/UNK | Y |
| Applicable to Multi-cell Pretensioned Box Girder Category? Y/N/UNK | Y |

| **Operational Characteristics (Existing)** | |
|---|---|
| Required Sensor Position - i.e., Beam End, Side, Deck Surface? | Side |
| Contact/Surface Coupling Necessary? Y/N/UNK | Y |
| Self-Propelled Sensor? Y/N/UNK | N |
| Discrete Readings? Y/N/UNK | Y |
| Continuous Scan? Y/N/UNK | N |
| Means of Data Acquisition - Manual, Semiautomated, Automated | Manual |
| Environmental Effects on Measurement - Day/Night, Rain/Dry, Sun/Shade, Seasonal? | Y |

| **Functional Support Requirements** | |
|---|---|
| Instrumentation Vehicle Required? Y/N | N |
| Access Vehicle or Equipment Required? Y/N | Y |
| Equipment Weight? L/M/H | H |
| Sensor Weight? L/M/H | L |
| Traffic Control Requirements - Y/N and Degree (Bridge Closure or Lane Closures?) | N |
| Drilling/Electrical Connection/Patching Required? Y/N | Y |
| Auxiliary Electrical Power Requirements? Y/N | N |

| **Potential Accuracy & Efficiency** | |
|---|---|
| Number of Readings (tests) Required per 100 ft of Strand? L/M/H | H |
| Time Expended Using Single Hardware Unit for Data Gathering for 100 ft of Strand? L/M/H | N/A |
| Time Expended Using Single Unit for Data Interpretation for 100 ft of Strand? L/M/H | N/A |
| Interfering Effects of Live Load Passage? Y/N/UNK | Y |

| | |
|---|---|
| Interfering Effects of Multiple Steel Layers (shadowing)? Y/N/UNK | N |
| Minimum Sensitivity to LOCSA? L/M/H | L |

### Developmental Risk Factors

| | |
|---|---|
| Successful Basis and History of Utilization for Strand or Reinforcement? Y/N/UNK | Y |
| Successful History of Utilization in Other Industries? Y/N | Y |
| Established Level of Scientific Maturity as Test Method? L/M/H | M |
| Perceived Degree of Research Risk? L/M/H | L |
| Time to Development? L/M/H | L |
| Newly Adapted Technique/Existing Hardware? Y/N | N |
| New Technique/New Hardware? Y/N | N |

### Safety Parameters

| | |
|---|---|
| User Safe? Y/N/UNK | Y |
| Passersby Safe? Y/N/UNK | Y |
| User Physiological Monitoring Required? Y/N/UNK | N |

### Projected Staffing/Training Efforts

| | |
|---|---|
| Total Crew Size (including functional support)? | 4 |
| Leader Training Time Required - first year? L/M/H | M |
| Technician Training Time Required - first year? L/M/H | M |

### Cost Considerations

| | |
|---|---|
| Relative Cost of Development/Implementation? L/M/H | M |
| Affordable as Multiunit Inventory for Individual State? Y/N/UNK | Y |
| Affordable as Specialized Unit w/ Operators Shared by Multistate Regions? Y/N/UNK | Y |

### Other Factors - Disadvantages

Not applicable for strand flaw detection.