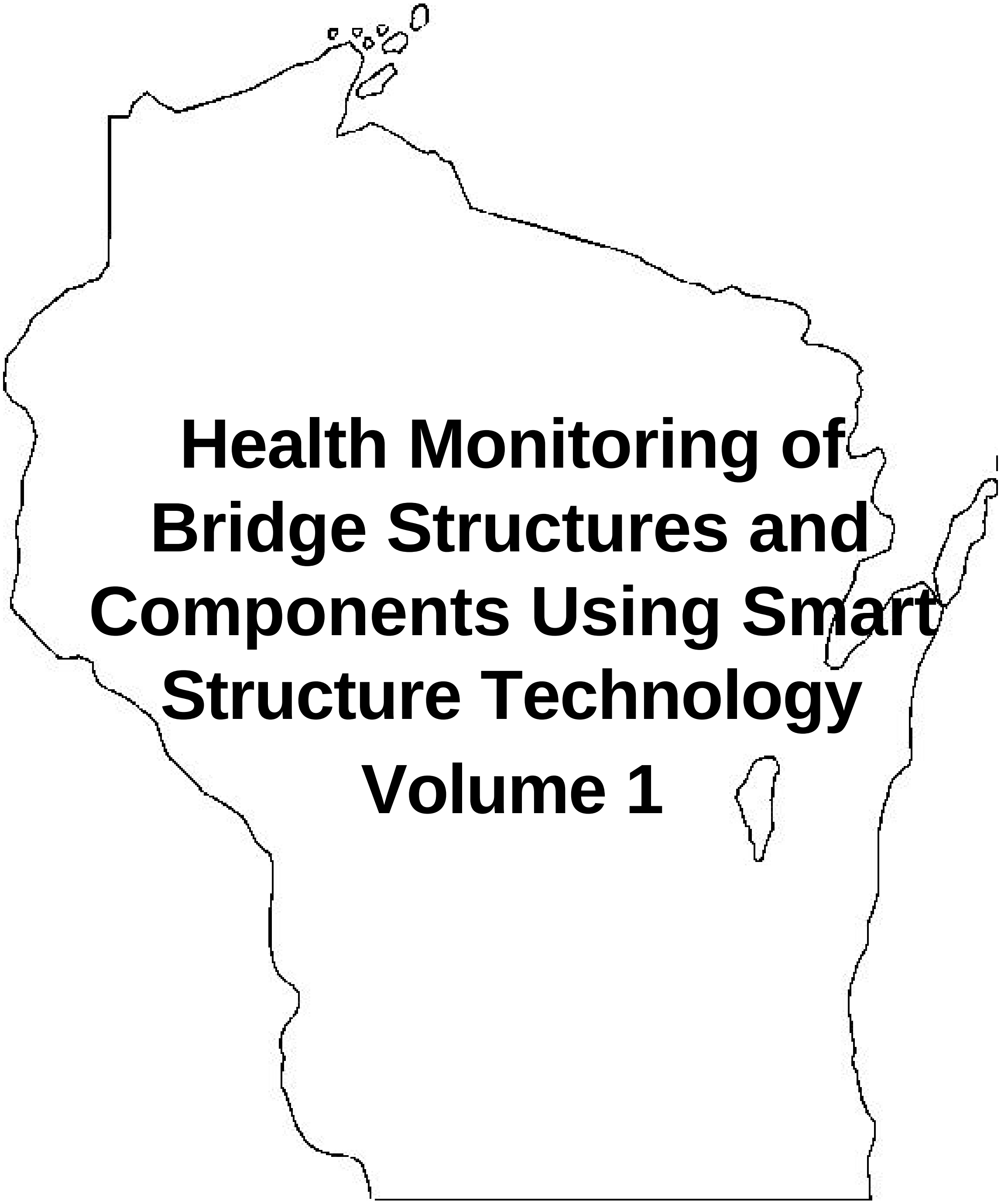
Wisconsin Highway Research Program



Health Monitoring of Bridge Structures and Components Using Smart Structure Technology Volume 1

Brent M. Phares, Terry J. Wipf, Lowell F. Greimann, and Yoon-Si Lee
Center for Transportation Research and Education
Iowa State University

January 2005

WHRP 05-03

DISCLAIMER

This research was funded through the Wisconsin Highway Research Program by the Wisconsin Department of Transportation and the Federal Highway Administration under Project # 0092-04-14. The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Wisconsin Department of Transportation or the Federal Highway Administration at the time of publication.

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof. This report does not constitute a standard, specification or regulation.

The United State Government does not endorse products or manufacturers. Trade and manufacturers' names appear in this report only because they are considered essential to the object of the document.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
0092-04-14			
4. Title and Subtitle Health Monitoring of Bridge Structures and Components Using Smart-Structure Technology Volume I		**5. Report Date** January 2005 **6. Performing Organization Code**	
7. Author(s) Brent M. Phares, Terry J. Wipf, Lowell F. Greimann, and Yoon-Si Lee		**8. Performing Organization Report No.**	
9. Performing Organization Name and Address Bridge Engineering Center Center for Transportation Research and Education Iowa State University 2901 South Loop Drive, Suite 3100 Ames, IA 50010-8634		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.**	
12. Sponsoring Organization Name and Address Wisconsin Department of Transportation 4802 Sheboygan Avenue Madison, Wisconsin 73707-7965		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**	
15. Supplementary Notes			
17. Key Words Structural health monitoring—Monitoring technologies—Sensors—Bridges		**18. Distribution Statement**	
19. Security Classification (of this report) Unclassified.	**20. Security Classification (of this page)** Unclassified.	**21. No. of Pages** 53	**22. Price** NA

16. Abstract

The objective of this research was to synthesize information on structural health monitoring technologies with a specific interest in those having smart-structure attributes. Following a comprehensive information collection campaign and a survey of State Departments of Transportation, the identified structural health monitoring technologies (both currently in use and emerging) were carefully reviewed and summarized. This final report includes a brief summary of the history of bridge evaluation in the United States of America, current and future trends of Structural Health Monitoring, and a series of completed *SHM Technology Evaluation Forms* for each of the identified technologies. In addition, a searchable database has been developed and is included with the final report that allows easy identification and review of structural health monitoring technologies. This volume (Volume I) summarizes the research approach and the key findings of the work. Volume II consists of completed *SHM Technology Evaluation Forms* for the 101 synthesized technologies.

EXECUTIVE SUMMARY

Project Summary

The objective of this research was to synthesize information on advanced structural health monitoring technologies with a specific interest in those having smart-structure attributes. Following a comprehensive information collection campaign and a survey of State Departments of Transportation, the identified SHM technologies (both currently in use and emerging) were carefully reviewed and summarized. The product of this work includes this report (Volumes I and II) and a searchable database of the individual technologies that have been synthesized.

Background

The ability to monitor the condition of a bridge structure to detect damage or changes in condition at early stages is of significant interest to many bridge owners. Currently, the most widely used damage detection methods rely on subjective, incremental visual assessments or localized testing techniques such as eddy current, ultrasonics, acoustic based sensing, strain monitoring, corrosion monitoring, and others. These methods require the location, or possible location, of damage to be known prior to the assessment. Often these locations can be estimated through appropriate engineering analysis. However, with the increasing complexity of many of the nation's bridges, potential damage locations may not be known or are too numerous to be economically tested using conventional techniques. Further complicating the issue is the fact that many conventional damage detection techniques do not allow for systematic comparison of the assessment results. Consequently, damage or deterioration cannot be easily monitored or tracked over time.

There are two primary approaches to health monitoring. First, install and monitor a relatively small number of sensors to monitor how the system is generally performing. Second, install and monitor a sufficient number of sensors with the application of advanced statistical analysis (or other methods) to detect and/or assess specific damage locations. Both approaches require various numbers of sensors and sensor types. The first provides specific behavior data, but may not reveal that important changes are taking place. This approach is well suited for an application where analysis indicates the possibility for a catastrophic failure is statistically low or in applications where the "cost" of a failure is acceptably low. For situations where specific damage or deficiencies are of significant importance or the "cost" of failure is high, one must follow the second approach, which requires the collection of significantly more performance information.

In the recent past, there have been rapid advances in the development of technologies for the evaluation of bridges. Advanced structural health monitoring has fast become a growing field in which non-intrusive damage detection techniques are integrated into a structure to monitor the complete bridge or individual bridge members. If properly implemented, it is believed that these technologies extend the useful life of bridges by allowing deterioration/damage to be identified earlier and thereby allowing relatively minor corrective actions to be taken before the deterioration/damage grows to a state where major actions are required. In addition, structural health monitoring systems allow designers to learn from previous designs to improve the performance of future bridges. While a number of structural health monitoring technologies exist, a thorough compilation of these various technologies does not. Such a synthesis of available information would allow bridge owners to more effectively select and apply these technologies.

The Iowa State University Bridge Engineering Center, through the Wisconsin Highway Research Program, conducted the project. The Research Team included Brent M. Phares (Co-principle investigator), Terry J. Wipf (Co-principle investigator), Lowell F. Greimann (Co-principle investigator), and Yoon-Si Lee (Research Assistant). The Project Oversight Committee included Thomas Strock (Federal Highway Administration), Chris Foley (Marquette University), and Joel Alsum (Wisconsin Department of Transportation).

Process

The research consisted of four distinct work tasks. The first task, Task I, involved identifying the information that must be gathered to not only effectively monitor a bridge structure but to also be able to select an appropriate monitoring approach and technology. The product of Task I was a *SHM Technology Evaluation Form* that would be used in the synthesis of the identified structural health monitoring technologies. The intent was that the completed forms would provide a brief summary of the capability and applicability of each technology. Task II focused on collecting information on structural health monitoring technologies that are currently being used either successfully or with limited success. Similarly, Task III focused on identifying and evaluating technologies that are not currently being applied within the bridge engineering community but have potential applications. To collect information, a survey of State Bridge Engineers was performed and numerous technical reports and other literature were reviewed in addition to directly contacting numerous manufacturers. Task IV was accomplished by summarizing and synthesizing the collected information. The process for evaluating the applicability, capability, and viability of continuous or advanced health monitoring sensors and techniques, which is included in the completed *SHM Technology Evaluation Forms*, was based on unbiased, qualitative assessments of the ability of each technology to measure the metrics defined during Task I.

Findings and Conclusions

The product of this work includes a brief summary of bridge evaluation history, current and future trends of structural health monitoring technologies and a series of completed *SHM Technology Evaluation Forms* for each of the synthesized technologies. A comprehensive database was also developed to allow easy identification and review of structural health monitoring technologies and to facilitate the selection of technologies for a specific application. With this database, the user can prescribe a specific set of parameters (e.g., type of bridge, element type, etc.) for which they would like information on available monitoring technologies; applicable technologies are then automatically identified.

Although there are several technologies with "*Smart*" attributes, the research team was able to identify only one SHM system that satisfied the definition of "*Smart*" used in this work. This system, manufactured by Pure Technologies, utilizes sensed information to determine if a wire break has occurred in either a prestressed concrete structure or a cable-supported structure. Several SHM systems classified at "*Smart*" by the developers are currently in the development stages. However, it is unclear if these systems will, indeed, possess all of the characteristics to be considered truly "*Smart*."

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

1.1. GENERAL BACKGROUND

Bridges represent significant investments within the highway transportation network that supports commerce, economic vitality, and personal mobility. Almost 4 billion vehicles cross bridges every day in the United States. Unfortunately, these expensive assets must operate, for many years, in an environment that is not conducive to their durability and longevity. Predicting the life of an individual bridge is far from simple; its condition changes due to many internally and externally uncertain events. In many cases, the intensity and the type of parameters (e.g., loading, environmental conditions, etc.) are mostly unknown in both nature and magnitude and are very different from the ones generally taken into account during design. A great challenge is created for bridge owners when the uncertainties created during both construction and use are combined. Defining service levels and prioritizing maintenance budgets based only on theoretical computations and superficial observations can result in inaccurate diagnosis and inefficient use of resources. Traditionally, it has been assumed that biennial visual inspections would identify deterioration or damage sufficiently early to allow repairs to be made. Critical evaluations of visual inspection reliability, however, have found that this likely is not the case [1].

In the recent past, there have been rapid advances in the development of technologies for the evaluation of bridges. Advanced structural health monitoring (SHM) has fast become an important emerging field in which non-intrusive damage detection techniques are integrated into a structure to monitor the complete bridge or individual bridge members. If properly implemented, it is believed that these technologies extend the useful life of bridges by allowing deterioration/damage to be identified earlier and thereby allowing relatively minor corrective actions to be taken before the deterioration/damage grows to a state where major actions are required. In addition, SHM systems allow designers to learn from previous designs to improve the performance of future bridges.

While a number of SHM technologies exist, some with *"Smart"* attributes, a thorough compilation of these various technologies does not. Members of the research team have drawn upon their expertise in bridge engineering, remote monitoring, forensic engineering, bridge condition evaluation, and nondestructive evaluation as well as several national resources to develop this synthesis of currently available, as well as emerging, SHM technologies. This synthesis will allow bridge owners to more effectively select and apply these technologies.

1.2. RESEARCH OBJECTIVES

The objective of this work was to identify and compile the applicability, capability, and viability of advanced health monitoring technologies for the effective short- and long-term monitoring of both new and existing bridge structures. This objective was accomplished by implementing four distinct work tasks as follows:

- Task I – Definition of Important Monitoring Metrics
- Task II – Documentation of Existing Monitoring Technologies
- Task III – Documentation of Emerging Monitoring Technologies
- Task IV – Information Synthesis: Final Report

1.3. METHODOLOGY

1.3.1. Research Scope

The research program consisted of several tasks with the main emphasis on the identifying and evaluating various SHM technologies. The first task, Task I, involved identifying the information that must be gathered to not only effectively monitor a bridge structure but to also be able to select an appropriate monitoring approach. The product of the Task I was a *SHM Technology Evaluation Form* that would be used in the synthesis of the identified SHM technologies. The intent was that the completed forms would provide a brief summary of the capability and applicability of each technology. Task II focused on collecting information on SHM technologies that are currently being used either successfully or with limited success. Similarly, Task III focused on identifying and evaluating technologies that are not currently being applied within the bridge engineering community but have potential applications. To collect information, a survey of State Bridge Engineers was performed and numerous technical reports and other literature were reviewed in addition to directly contacting numerous manufacturers. Task IV was accomplished by summarizing and synthesizing the collected information. The process for evaluating the applicability, capability, and viability of continuous or advanced health monitoring sensors and techniques was based on unbiased, qualitative assessments of the ability of each technology to measure the metrics defined during Task I. This report and associated electronic files represent the product of Task IV.

1.3.2. Definitions

As SHM is a relatively new field within the bridge engineering community, some of the most important terms, Structural Health Monitoring, “Smart,” and State-of-the-Art, have been defined and discussed below. These definitions/explanations are the building blocks for the remainder of this report.

Structural Health Monitoring
SHM is the process of evaluating the condition or change in condition by the collection and evaluation of data. The process involves the observation of a system over time using either continuously monitored or periodically sampled response measurements completed with analysis of the results. In general, depending on the number and type of sensors and amount of statistical data processing completed, four different levels of damage detection can typically be achieved with an SHM system [2]:

- Level 1: Determination of damage that is present in the structure
- Level 2: Level 1 plus determination of the geometric location of the damage
- Level 3: Level 2 plus quantification of the severity of the damage
- Level 4: Level 3 plus prediction of the remaining service of life of the structure

“Smart”
A *“Smart”* technology is one in which *the system systematically reports on the condition of the structure by automatically making engineering-based judgments, records a history of past patterns and intensities, and provides early warning for excessive conditions or for impending failure without requiring human intervention*. These features make the system capable of

providing and facilitating *self-diagnostic, real-time continuous sensing, advanced remote sensing, self-organizing, self-identification, or self-adaptation (decision making and alarm triggering) functions.* Further, the user is not burdened with demanding operational and maintenance tasks.

State-of-the-Art
A State-of-the-Art SHM system incorporates what is considered to be the most advanced or newest technologies that may not have been widely used in bridge evaluation. It generally possesses some, but not all, of the attributes of "Smart" systems.

1.4. SIGNIFICANCE AND BENEFITS OF SYNTHESIS

The final product of this research is a synthesis of currently available and emerging monitoring technologies. Although practicing bridge engineers may not find all of the identified technologies immediately applicable to their needs, bridge owners will ultimately benefit from an increased knowledge base about available technologies. The synthesis provides a database of available monitoring technologies that can be used by engineers to more effectively manage a bridge inventory.

1.5. REPORT CONTENTS

This report consists of two volumes. The contents of each of the two volumes are briefly described below.

Volume I
Following a brief history of the development of bridge programs and inspection requirements, an overview on the use of bridge testing for bridge evaluation and current trends in bridge monitoring are given in Chapter 2. Chapter 3 provides an overview of the *SHM Technology Evaluation Form* and provides a brief summary of the use of a searchable database, followed by a brief description of selected SHM technologies in Chapter 4. Finally, a summary and discussion are presented in Chapter 5.

Volume II
Volume II of this report contains a series of completed *SHM Technology Evaluation Forms* for each of the synthesized technologies.

2. CHRONOLOGY OF BRIDGE EVALUATION

To provide a summary of bridge evaluation history, the development of the major programs that have been established and legislated to provide funding and to ensure bridge safety are summarized in this chapter. The current use of testing for bridge evaluation and other current trends in bridge evaluation are also summarized here.

2.1. BRIDGE PROGRAMS AND INSPECTION REQUIREMENTS

The first bridge construction boom started with the extensive road construction program mandated by the Federal Highway Act of 1956, which was initiated when President Eisenhower signed a bill creating the National System of Interstate and Defense Highways [3]. During this time, most emphasis was placed on the economical construction of new bridges. Consequently, little effort was given to safety inspection or preventative maintenance of bridges. The safety of the bridge network came into question in the late 1960's when the U.S. Highway 35 Silver Bridge, a 2,235 ft pin-connected link suspension bridge connecting Point Pleasant, West Virginia and Kanauga, Ohio, suddenly collapsed on December 17, 1967 [4]. This sudden catastrophic collapse, which was the first major failure of a structure since the wind-induced failure of the Tacoma Narrows Bridge in 1940, prompted the recognition of the deterioration of the national bridge network, and the need for periodic and consistent bridge evaluations and training of bridge inspectors. As a result, the Federal Highway Administration (FHWA) established the National Bridge Inspection Program (NBIP) in 1970 requiring State highway agencies to inspect their bridges every 2 years and to submit the inspection results to the FHWA, where they are maintained in the National Bridge Inventory (NBI) database. In the following year, the first National Bridge Inspection Standards (NBIS) were established in cooperation with the American Association of State Highway Officials (AASHO) under the Federal-Aid Highway Act of 1971. This landmark legislation was enacted on April 27, 1971 and, for the first time in the US, set uniform, national standards for bridge inspection and safety evaluation including a national policy related to frequency and qualifications of bridge inspectors, report formats, and inspection and rating procedures [4].

The collapse of the Silver Bridge was certainly a catastrophic disaster that resulted in the loss of 46 lives and disrupted commerce in the Midwestern US for several months. Nonetheless, it was the catalyst for what became a comprehensive bridge safety inspection program that was mandated by the NBIS. Engineers became more knowledgeable about bridge deterioration and, therefore, bridge structures were designed, and maintained for better quality and with at least some consideration for future evaluation and maintenance. Also, the Silver Bridge catastrophe highlighted the need to replace and/or rehabilitate bridges or members of bridges before they failed. The Special Bridge Replacement Program (SBRP) was also established under the Federal-Aid Highway Act of 1971 to provide funds to help States replace bridges. It was later expanded for rehabilitative activities and replaced with the Highway Bridge Replacement and Rehabilitation Program (HBRRP) in the Surface Transportation Assistance Act of 1978.

Despite the efforts of these bridge evaluation programs, other unforeseen events resulting in the collapse of bridges continued and periodically necessitated expansion of further effort. In June 1983, the collapse of the 100-foot section of the Mianus River Bridge on Interstate 95 in

Greenwich, Connecticut, killing three people and critically injuring three others, caused more concern regarding fatigue and fracture-critical bridges. The National Transportation Safety Board (NTSB) determined that the failure of the span was caused by an undetected lateral displacement of the hangers of the pin and hanger suspension assembly by corrosion-induced forces that were undetected due to deficiencies in the bridge safety inspection and maintenance program. Following this incident, and further investigation, significant research regarding fatigue of steel connections was conducted and special fracture-critical inspections were recommended to be mandated.

Scour-induced failures at the Schoharie Creek Bridge in New York in April 1987 and at the Hatchie River Bridge in Tennessee in April 1989 [4] illustrated the importance of designing bridge piers to resist scour and illustrated the need to better understand and design for scour effects. Consequently, guidance for scour assessment was provided and an underwater bridge inspection program for all structures at risk and susceptible to scour damage was initiated.

Over the decades, much has been learned in the field of bridge inspection, and many training and funding programs, including the NBIP and HBRRP, have been implemented. In some cases, the catastrophic problems had been foreseen and the possible dangers were identified by some engineers. However, potential solutions were sometimes delayed due to either excessive costs associated with existing technologies or by reluctance to adopt new technologies that had not been widely proven. In some of these cases, improved inspection technologies might have allowed the problems to be spotted even early and for the tragedies to have been avoided. As a result, it was recognized that research was often reactive, conducted in response to emergencies, and thus, a proactive research program that would provide solutions to prevent the catastrophic failure was needed.

Since the Federal-Aid Highway Act of 1971, the development of the NBIS and other associated bridge programs have incrementally enhanced bridged evaluation. Overall, approximately $55 billon in HBRRP funding and other sources of funding from Federal and State bridge programs have been allocated and used to improve the condition and safety of the nation’s bridges. The following summarizes the major bridge inspection and funding programs and the notable associated changes [5]:

- Federal-Aid Highway Act of 1971
    - Inventory requirements for all bridges on the Federal-aid system
    - Established minimum data collection requirements
    - Established minimum inspector qualifications and inspector training programs
    - Established SBRP
- Surface Transportation Assistance Act of 1978
    - Established HBRRP
    - Extended inventory requirements to all bridges on public roads in excess of 20 feet
    - Provided $4.2 billion for the HBRRP over 4 years
- Highway Improvement Act of 1982
    - Provided $7.1 billion for the HBRRP over 4 years
- Surface Transportation and Uniform Relocation Assistance Act of 1987

- Provided $8.2 billion for the HBRRP over 5 years
    - Added requirements for underwater inspections and fracture critical inspections
    - Allowed increased inspection intervals for certain types of bridges
- Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA-1991)
    - Provided $16.1 billion for the HBRRP over 6 years
    - Mandated State implementation of a quantitative computerized bridge management systems
- National Highway System Designation Act of 1995
    - Repealed mandate for management system implementation
- Transportation Equity Act for the 21st Century (TEA-21, 1998-2003)
    - Provided $20.4 billion in HBRRP funding over 6 years

In addition to the bridge programs, many standards, manuals, and technical advisories have been developed with respect to bridge inspection. Most of these were developed by the FHWA or the American Association of State Highway and Transportation Officials (AASHTO), formally known as the AASHO. A list of the major publications related to bridge inspection and their issued dates follow [4]:

- AASHO Manual for Maintenance Inspection of Bridges (1970)
- AASHTO Manual for Maintenance Inspection of Bridges (1974, 1978, 1983, and 1993)
- AASHTO Manual for Condition Evaluation of Bridges (1994)
- FHWA National Bridge Inspection Standards (1971, 1979, and 1988)
- FHWA Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation 's Bridges (1972, 1979, 1988, 1991, and 1995)
- FHWA The Bridge Inspector 's Manual for Movable Bridges (1977)
- FHWA Bridge Inspector 's Training Manual 70 (1979)
- FHWA Culvert Inspection Manual (about 1979)
- FHWA Inspection of Fracture Critical Bridge Members (1986)
- FHWA Scour at Bridges, a technical advisory (1988)
- FHWA Hydraulic Engineering Circular No. 18 (about 1988)
- FHWA Bridge Inspector 's Training Manual 90 (1991)
- FHWA Engineering Concepts for Bridge Inspectors (1994)

Areas of concern and emphasis related to bridge safety issue are changing and expanding as new problems become apparent and newer bridge types and materials become more common. Yet, one factor remains constant: the ability to effectively evaluate bridge components and materials and to make sound evaluations with accurate ratings is critical to maintaining the safety and efficiency of the transportation system.

Current bridge inspection protocol calls for a biannual inspection. The NBIS requires that inspectors periodically perform inspections on the Nation’s bridges and report their conditions in a standardized format with the condition ratings ranging from zero to nine for each of three bridge components: the superstructure, substructure, and bridge deck. The FHWA also recommends that the bridge inspection be supplemented with a program that identifies the needs for preventive maintenance on an annual basis.

2.2. CURRENT USE OF BRIDGE TESTING

The need to facilitate a more accurate and rapid determination of the safe load carrying capacity of bridges was recognized in the 1980's and the National Cooperative Highway Research Program (NCHRP) launched a project, 'Nondestructive Load Testing for Bridge Evaluation and Rating', in an effort to develop guidelines for load testing of highway bridges to augment the codified rating process [6]. The product of this research was a report that provided a comprehensive review of literature related to bridge load testing and a summary of the current status of load-test technologies. Since that time, the use of bridge testing for bridge evaluation has become more available, thereby allowing a limited level of funds to be targeted to bridges that are most in need. Today, the use of the load rating procedure that incorporates diagnostic load testing results has become an accepted practice for addressing bridge conditions by many public agencies.

The basic approach for using testing and analysis in load rating is very similar to that used in both standard highway and railroad bridge design codes. The only exception is that instead of relying on estimated distribution factors and assumed member behavior, actual measured field data are used to develop an accurate analytical model of the structure which is used for the subsequent evaluation.

Academia has been using bridge testing for decades as a valuable tool to assess the performance of new bridge systems, new bridge repairs, and retrofit schemes. Early references cite the use of manual dial gages and/or surveying instruments to collect behavior information. The electronic collection of behavior data began as early as the 1970s. Advancements in available sensors have ensured that bridge testing remained an economical and useful tool for in-depth study of structural systems.

Today, a few academic institutions, including the one preparing this report, have extensive in-house expertise on the application and use of bridge testing equipment [7, 8, 9, 10]. In many cases, this expertise requires personnel familiar with sensor installation, data acquisition system operation, and interpretation of test results. Institutions with staff and faculty with these skills can frequently provide innovative testing solutions to bridge owners nationwide.

2.3. SURVEY OF STATE DOTS ON SMART SHM TECHNOLOGIES

To collect information on how State bridge owners are currently using *"Smart"* SHM technologies to manage their inventory, a survey was conducted. A short questionnaire was developed and published on the Iowa State University Bridge Engineering Center website so that respondents could fill out the questionnaire on-line. A copy of the survey questionnaire is presented in the Appendix. The survey consisted of six sections. In the first section, the respondent was asked to provide contact information. This allowed the research team to collect information needed to contact them in the event that further information was needed. The second section asked if the specific DOT had used SHM technologies with smart-structure concepts. If the answer was "No", no further information was needed. If the answer was "Yes", the next four sections asked for information on the specific application, information on current uses, and a place for the respondent to provide additional pertinent information.

A request to complete the survey was sent out by the Wisconsin DOT using email lists maintained in-house. The request was sent to the State Bridge Engineer in all 50 States plus the District of Columbia and Puerto Rico.

The results of the survey showed that most of respondents did not have experience with *"Smart"* SHM technologies. Among the twenty survey respondents, only five States responded that they have some experiences with *"Smart"* technologies, and fifteen states responded with 'No' experiences. From this survey, three companies were identified: Pure Technologies, Ltd., Applied Geomechanics, Inc., and Virginia Technologies, Inc.

From the survey results, it appears that the *"Smart"* SHM technologies have not yet been widely implemented by State DOTs. As will be evident from the results of the complete synthesis, this may be due to a lack of SHM system with truly "Smart" attributes.

3. STRUCTURAL HEALTH MONITORING TECHNOLOGY DATA COLLECTION PROTOCOL

The applicability of any SHM technology depends on many parameters. To provide a mechanism for consistently summarizing the applicability of the synthesized SHM technologies, the research team has drawn upon their expertise in bridge engineering, bridge condition evaluation, nondestructive evaluation, and several national resources to develop a *SHM Technology Evaluation Form* that was used to collect and summarize pertinent information about the identified SHM systems. The discussion presented in the following sections describes the various portions of the form, and why each portion was deemed important. Each *SHM Technology Evaluation Form*, given in Volume II of this report, has been completed with the information collected during this work. The completed forms provide a brief summary of the capability and applicability of the identified technologies and should provide enough information to make preliminary assessments of the individual systems. In all cases, information is also provided on how to get additional information. Note that some fields on the forms may not be completed. Typically this is because the research team was unable to locate a specific piece of information. A comprehensive database with the information in the *SHM Technology Evaluation Form* in a tabular and searchable format was also created to facilitate the selection of technologies and is described in this Chapter.

3.1. DEVELOPMENT OF SHM TECHNOLOGY EVALUATION FORM

The *SHM Technology Evaluation Form* was created as a convenient and concise format for collecting the information that would be of interest to a bridge owner. The form was developed based on four key considerations, given below, to effectively evaluate technologies:

- Definition of the monitoring interest.
- Operational and environmental conditions under which the system can be used.
- Economic considerations.
- System limitations.

To this end, the collected information has been grouped into 8 primary sections: (1) General Information, (2) Applicability, (3) Cost, (4) Limitations, (5) Implementation Needs, (6) Availability, (7) On-going or Completed Bridge Related Projects and References, and (8) Notes.

The *SHM Technology Evaluation Form* consists of both “check-box” type entries as well as areas for textual descriptions. After completing the review of a specific SHM technology, the research team completed the form by “checking” boxes next to items which the SHM technology is applicable. The textual areas were also completed with a concise description of pertinent information. The following briefly summarizes the information contained in each of the eight sections:

Section 1 – General Information

The first section aims to collect basic information on the individual technologies. This includes a description of the technology, name and address of manufacturer/developer of the technology and contact information including website information and phone number (s). A brief description of the notable features of the technology is given, including:

- Sensor type: available sensors and/or their functions are described.
- Data acquisition, processing, and archiving: available devices and their functions are described.
- Smart attributes: *"Smart"* or other unique features of the system are described (note that *"Smart"* attributes, as applied in this work, have been previously defined in Chapter 1).
- Other: additional useful information about the system is provided.

With this information, a quick overview of the technology can be obtained. Additionally, this section provides the information on where to go to obtain further information.

Section 2 – Applicability
The second section is, by far, the longest and contains some very critical information on the applicability of the technology. To effectively examine the applicability of different technologies, some key information related to SHM application was identified. The Applicability section is divided into four sub-categories thought to best meet the owner's needs: Bridge Type, Bridge Component, Monitoring Interest, and Measurement Metric. Each of these is briefly described below.

The first sub-category in Section 2 is Bridge Type. In most cases, bridges are designed and built for different objectives and come in different shapes and sizes. Therefore, it is important to understand if there are limits on the types of bridges that can be monitored. A total of 10 types of common bridges, as given in the bullet list below, have been identified to which the applicability of each technology was evaluated.

- Slab
- Girder/Deck
- Truss
- Arch
- Rigid Frame
- Suspension
- Cable-stayed
- Vertical lift
- Swing
- Bascule

Since bridge components for specific bridges may differ from that of others, it was necessary to first clearly identify what can specifically be monitored. The second sub-category of applicability is related to the three major components of most bridges: deck, superstructure, and substructure. The following summarizes the information collected for each of these components

The structural deck is the major bridge components that transfers the live load to the superstructure while, at the same time, providing the traffic with a safe and smooth riding surface. Depending on the type or function of the bridge, deck components may include surface protection (i.e., asphalt concrete overlay), bridge joints, expansion devices, curbs, sidewalks, parapets, fascias, railing, and scuppers. Possible interesting damage features within the structural deck can vary from heavy traffic exposure (e.g., wear, abrasion, impact damage, etc.) to environmental effects (e.g., freeze-thaw cycles, use of de-icing agent, moisture, etc.). Because the behavior and deterioration of different deck materials can be quite different, the deck section was divided into four materials (Timber, Concrete, Steel, and FRP with associated further sub-division as shown below) for which the applicability of the SHM technologies was reviewed.

- Timber
    - Plank deck
    - Nailed laminated deck
    - Glue laminated deck panels
    - Pre-stressed laminated deck/stressed timber deck
- Concrete
    - Reinforced cast-in-place (CIP)
    - Pre-cast (Reinforced concrete deck or pre-stressed concrete deck)
- Steel
    - Corrugated steel flooring
    - Orthotropic deck
    - Grid deck
    - Buckle plate deck
- FRP

The superstructure is the portion of a bridge that receives and supports loads transmitted through the bridge deck. Its components are usually characterized by how it transmits loads to the substructure (i.e., through tension, compression, bending, or a combination), whether it is a primary or secondary bridge element, or if it is part of the bearing system. The following system was used to determine the system applicability to the various superstructure types and components:

- Primary elements
    - Beam/stringer/girder
        - Multi-beam/girder system
        - Girder floor beam/diaphragm system
        - Tee beam
        - Box girder
        - Channel beam
    - Slab
    - Truss
    - Arch
- Secondary elements
    - Connectors and fasteners
        - Riveted/bolted/welded
        - Pin & hanger
        - Splice
    - Bracing
        - Cross
        - Lateral

        - Sway
    - Diaphragm
    - Cover plate
    - Stiffener
- Bearing
    - Fixed
    - Expansion bearing
        - Sliding plate
        - Roller
        - Rocker
        - Pin and link
        - Elastomeric
        - Pot
        - Restraining

In this study, the substructure was considered to consist of those components that are below the bridge bearings. The substructure supports the superstructure and transmits loads to the supporting ground through piles and/or other foundation elements. The substructure can generally be divided into two general groups: abutments and piers/bents as summarized and further sub-divided in the following:

- Abutment
    - Footing
    - Bridge seat
    - Piles
    - Wall
- Piers/bents/extended pile
    - Pier cap
    - Shaft
    - Column/stem
    - Submerged pile/pile cap/footing

For some unique types of bridges, such as cable-supported bridges and movable bridges, there are components that are used exclusively within those structures. A list of the specialized components of these types of bridges is given below. The identified SHM technologies were evaluated on their ability to evaluate these specialized bridge types and components.

- Cable-supported bridge
    - Tower
    - Main/secondary cable
    - Cable anchorage
    - Anchor rod
    - Damping system
    - Strand shoes
    - Cable bands
    - Cable enclosures

- Movable bridge
    - Electric brakes
    - Motors and power
    - Operating machinery and equipment

The third sub-category under Applicability is Monitoring Interest. This sub-category was developed to define the common types of structural changes that are either abnormalities or indicate potential problems within a structure. A total of 18 monitoring interests were identified and used to classify technologies as given below:

- Crack/fracture
- Section loss
- Deformation
- Debonding
- Corrosion
- Expansion/contraction
- Settlement
- Wire breakage
- Erosion/scour
- Environmental
- Rotation/torsion
- Misalignment
- Mechanical/electrical malfunction
- Looseness and pounding
- Wear/spalling/scaling/delamination
- Connection failure or deficiencies
- Impact damage
- Excessive joint closing/opening

Measurement metrics is the fourth and final sub-category under Applicability. In this section, the type of measurement that is made by the SHM technology is summarized. This information is important as it gives the engineer a fundamental basis for the physics behind the monitoring system. Fourteen common types of measurements were utilized:

- Strain
- Deflection/displacement
- Acceleration/vibration
- Moisture/humidity level
- Temperature
- Magnetic field/flux
- Electrical voltage/current
- Chemical composition
- Radar waves
- Acoustic waves
- Magnetic waves
- Electromagnetic waves

- Thermal waves
- Wind speed/direction

Section 3 – Cost
Since a requirement of any SHM technology is that it be cost-effective, cost information obtained by the research team is provided. In general, the three most common cost considerations for SHM technologies are the hardware, software, and labor related costs for implementing and using the technology.

Section 4 – Limitations
To ensure that a particular system meets all expectations of a potential installation, potential limitations and constraints were identified and summarized in this section. By providing limitations on Life expectancy, Power, Environmental conditions, and Data storage/transfer/processing, the general usability of each technology can be assessed.

Section 5 – Implementation Needs
In some instances the actual implementation of an SHM system may require special preparation. Section 5 summarizes features needed to successfully implement each technology. The most common needs associated with implementation are: Power source, Accessibility, and Technical expertise.

Section 6 – Availability
Section 6 discusses the availability of the technology. This includes a concise description of how quickly, following placing an order, the technology could be received from the manufacturer. If applicable, the "in-stock volume" of the technology is also given in this section.

Section 7 – On-going or Completed Bridge Related Projects and References
To give an indication of how widely the technology has been used, information obtained by the research team on on-going or completed projects using the technology is given. Specific emphasis was placed on identifying bridge related applications.

Section 8 – Notes
Other important information not well contained in the previous seven sections is provided in Section 8. Where applicable, this section also contains research team's global assessment of the technology.

Note that the synthesis of each identified technologies in the SHM Technology Evaluation Form, provided in Volume II of this report, was completed based on information collected from conversations with manufacturers/developers, Internet searches, and reviewing available technical literature. Because some information were treated as 'confidential' by the manufacturers/developers and in some cases simply could not be found, some portions are left blank or marked as 'Information not available.' Also note that some information regarding cost and specification of products or technologies are subjected to change. Therefore, it is recommended that one make contact to manufactures for more information when selecting any technology.

3.2. DATABASE

To facilitate the review of the technologies identified and synthesized in this project, and to aid in the selection of a technology for a specific need, an electronic database was created. This searchable database contains all of the information summarized and synthesized in the previously mentioned *SHM Technology Evaluation Form* and, where possible, has been formatted similarly. The following sections describe the use of the database. In general, there are two types of search functions that can be completed; first, a "word" search can be completed and, second, a "checkbox" search can be completed. It must, however, be pointed out that in all cases the search algorithm used in the database is an "AND" search. For example, if the user completes a "word" search for "remotely powered", both words "remotely" AND "powered" must be found. Similarly, if the user performs a "checkbox" search where "Slab", "Crack/Fracture", and "Strain" are all checked, then ALL three must be attributes of a technology for it to be identified.

3.2.1. System Requirements

Software:

- Windows XP or Windows 2000
- Internet Explorer
- Adobe Reader
- Microsoft Jet 4.0

Hardware:

- CD-ROM

Administrative rights may be needed the first time the application is run to ensure proper functionality and/or installation of the previously stated requirements.

3.2.2. Database Use

To use the database, insert the provided CD into the computer's CD-ROM (note a CD/DVD drive may also be used). The database should automatically start. The user will know that the database has started when the "splash screen" shown in Fig. 1 is observed. If the database does not automatically start, double click the file *SHM.exe* on the CD-ROM disk. The screen shown in Fig. 1 should then appear indicating that the database is loading.

Figure 1. Structural health monitoring technology database splash screen.

After the database has completely loaded, the screen shown in Fig. 2 will automatically open. At this time, the user has the option of completing either a “word” search or a “checkbox” search. Each of these will be described in greater detail in the following two sections. It should also be pointed out that although the two types of searches (i.e., “word” and “checkbox”) are described separately below, they can also be used together.

3.2.2.1. “WORD” SEARCH FUNCTION

Using the “word” search function involves entering a word, or a string of words, into the box to the right of the words “Document Word Search” that is located near the top of the screen shown in Fig. 2. As described previously, the search is an AND search so all words listed must be found for a technology to be identified. For example to search for technologies with “Remote Power” the user simply types the words “Remote” and “Power” as shown in Fig. 3 into the Document Word Search box. After typing the words, press the “Search” button located near the bottom of the screen. The database will then search through all of the technologies and list those matching the search criteria as shown in Fig. 4. To view specific details about an identified technology, select the technology as shown in Fig. 5 followed by pressing the “Open” button. The completed *SHM Technology Evaluation Form* (in pdf format) will then open automatically. The user may review the completed form electronically or print it. Once completed, the user should close the Internet Explorer window. If desired, another technology can be selected (from the list like the one shown in Fig. 4) for viewing. When all technologies of interest have been reviewed, press the “close” button and the window will close. The user may then either conduct another “word” search or conduct a “textbox” search as described below.

3.2.2.2. “CHECKBOX” SEARCH FUNCTION

For convenience, the “checkbox” search options have been divided into categories matching those on the *SHM Technology Evaluation Form*: Bridge Type, Bridge Component, Monitoring Interest, and Measurement Metric. Each of these categories has a series of checkboxes located on the respective “pages” indicated by the selection tabs with the category names (see Figs. 6-9). To move about the different categories, the user simply clicks on the category name tabs. The Bridge Component category is further subdivided into the subcategories Deck, Superstructure, Substructure, and Miscellaneous as shown in Figs. 10-13.

To initiate a search using the “checkbox” function, the user simply checks the applicable attributes of the desired technology by clicking in the white space to the left of the attribute of interest. As before, after the user presses the “Search” button, the database initiates a search for technologies with ALL of the desired attributes. For example, if the user wanted to find technologies for using on a “Girder/Deck” bridge type, with a “Girder Floor Beam/Diaphragm System” superstructure, using “Strain”, the user would simply check the appropriate boxes as shown in Figs. 14-16. This results in the identification of the technologies shown in Fig. 17. As before, the user can view the completed *SHM Technology Evaluation Form* by selecting the technology and pressing the “Open” button.

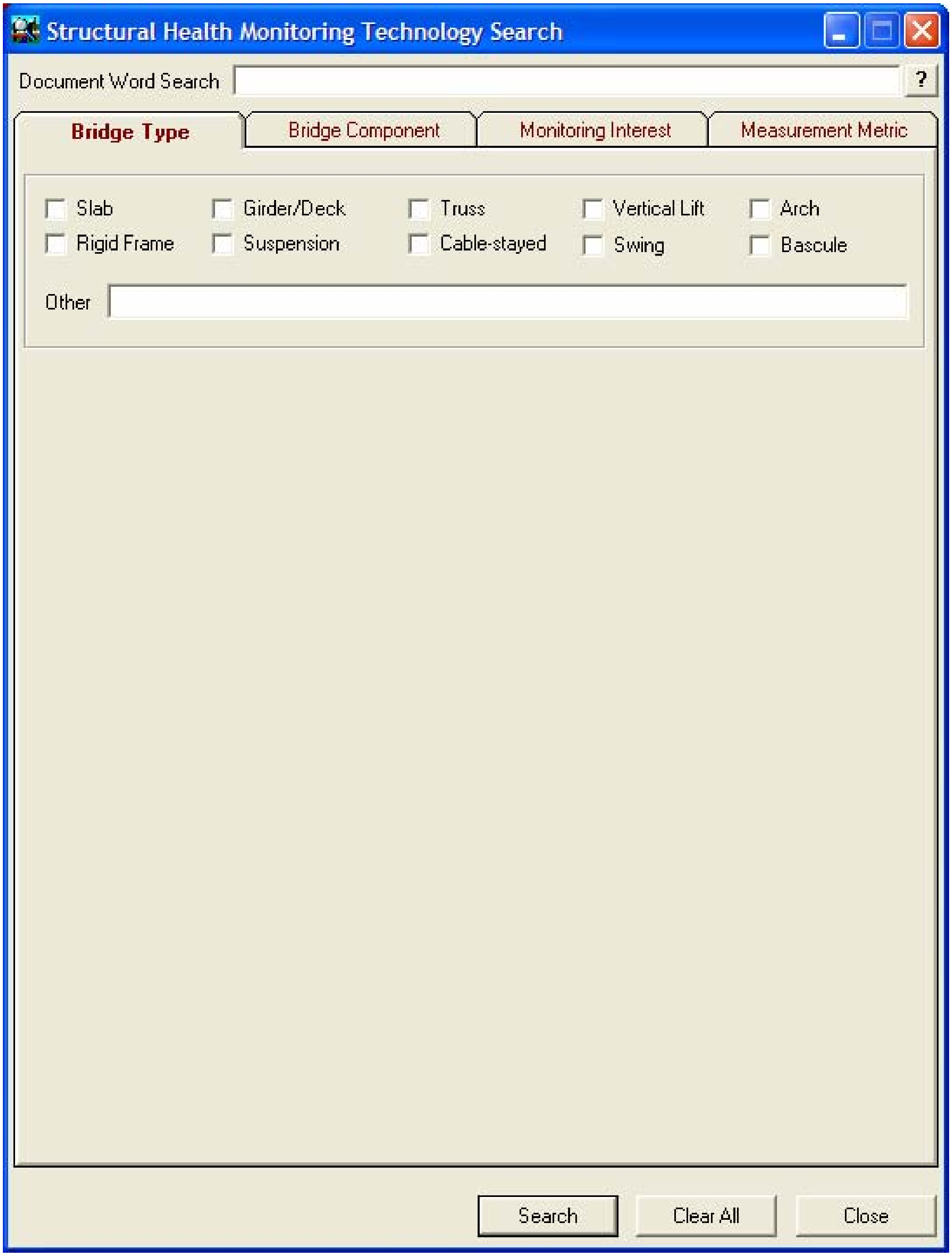


Figure 2. Initial database screen showing areas for "word" and "checkbox" searches.

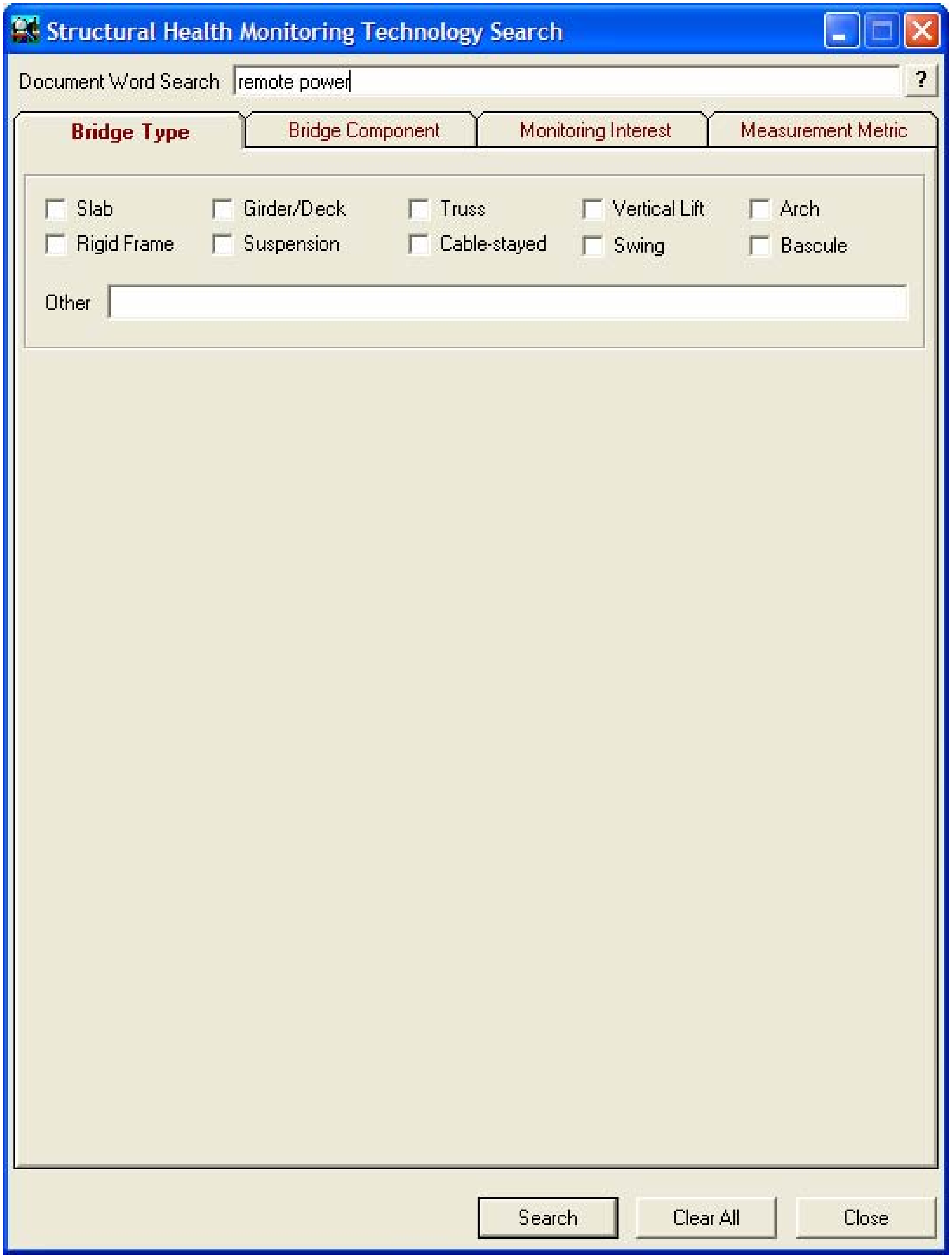


Figure 3. Example use of the database to search for technologies with "Remote Power"

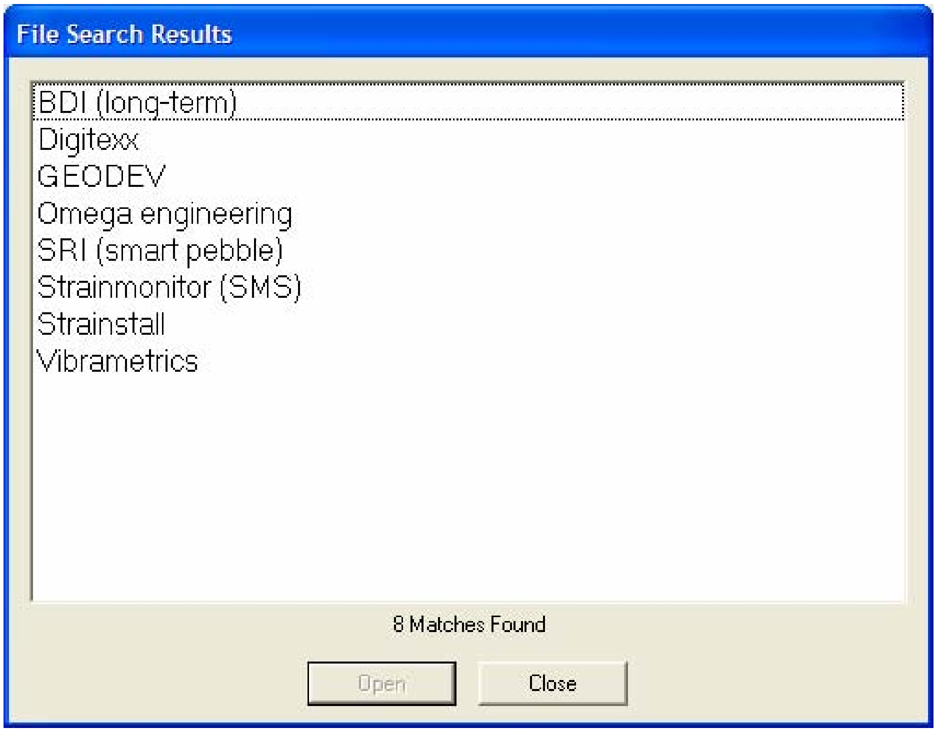


Figure 4. Technologies found to include the words “Remote Power” in the completed *SHM Technology Evaluation Form.*

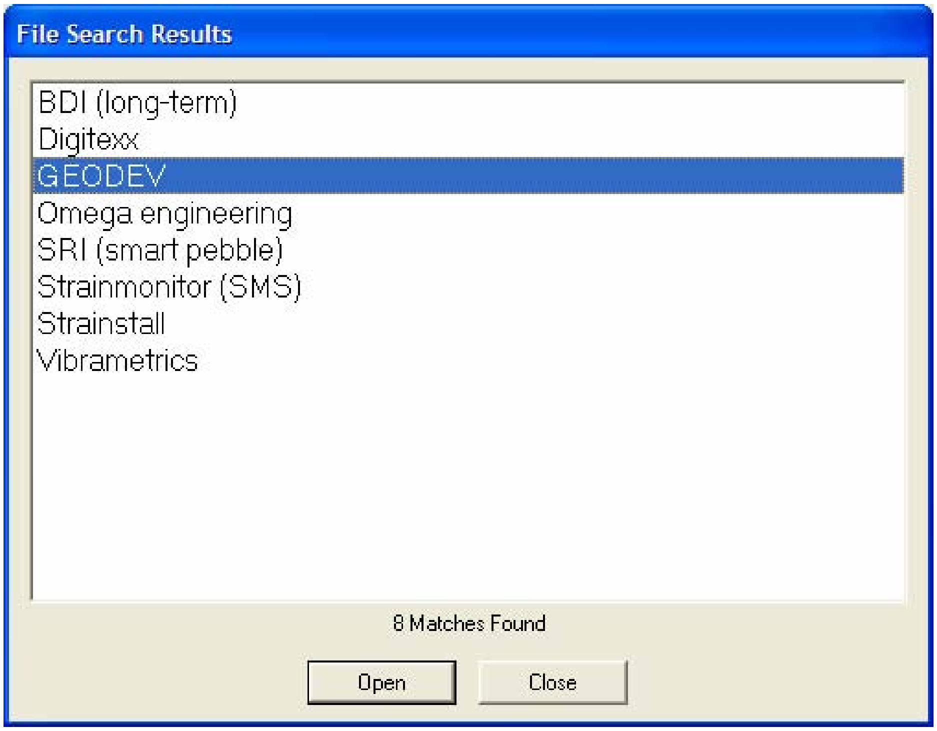


Figure 5. Selection of a specific technology for viewing of the completed *SHM Technology Evaluation Form.*

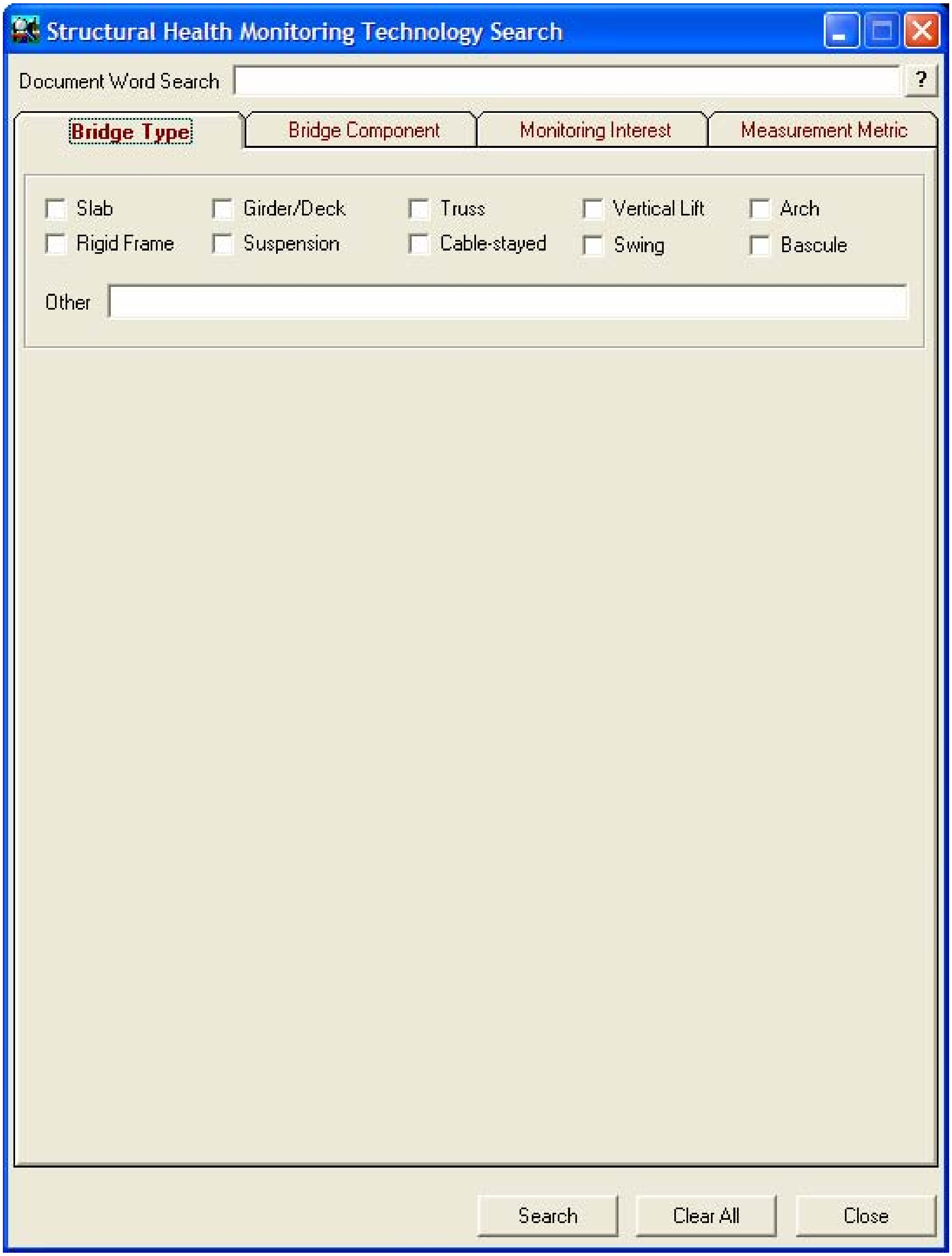


Figure 6. Bridge Type category for conducting a "checkbox" search.

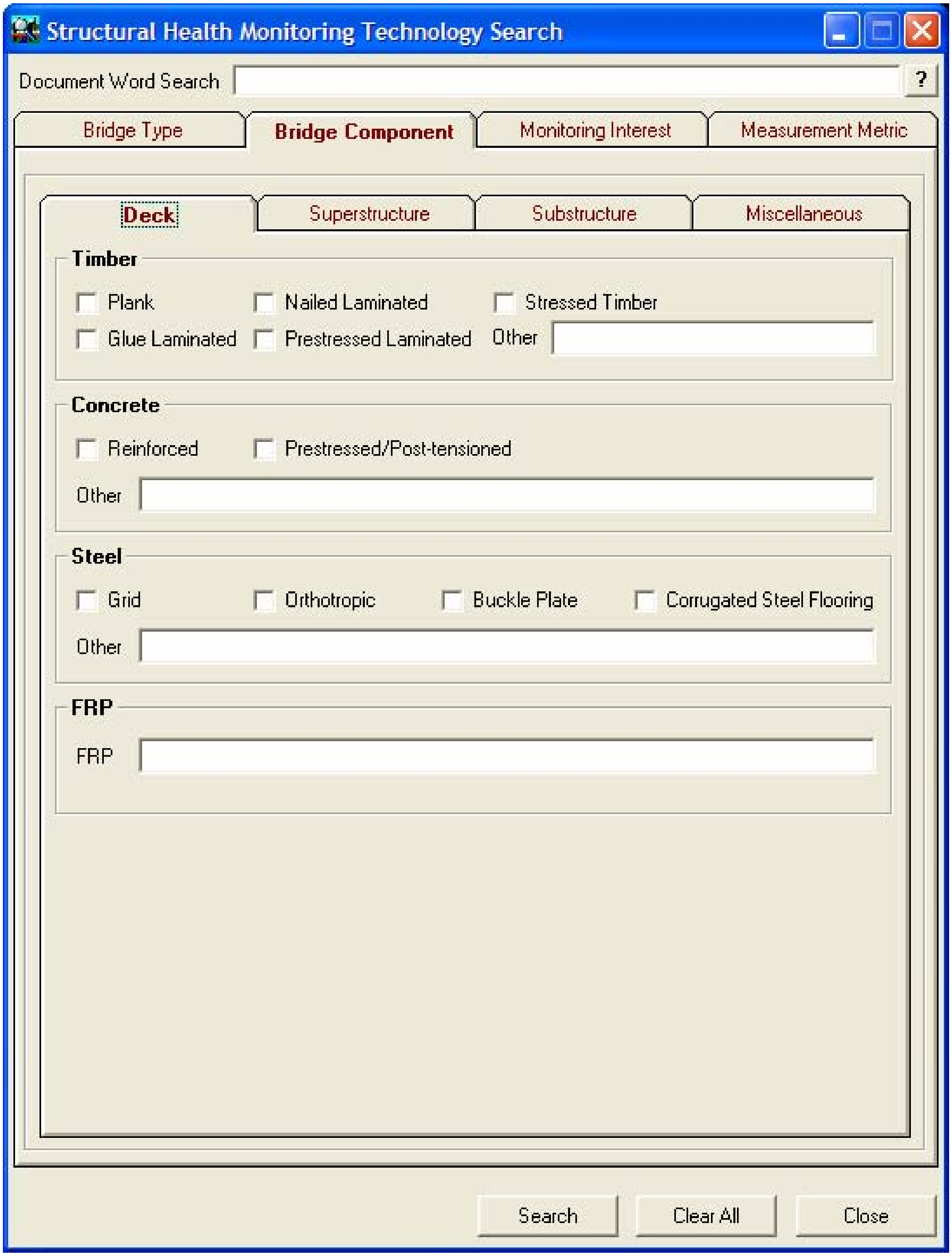


Figure 7. Bridge Component category for conducting a “checkbox” search.

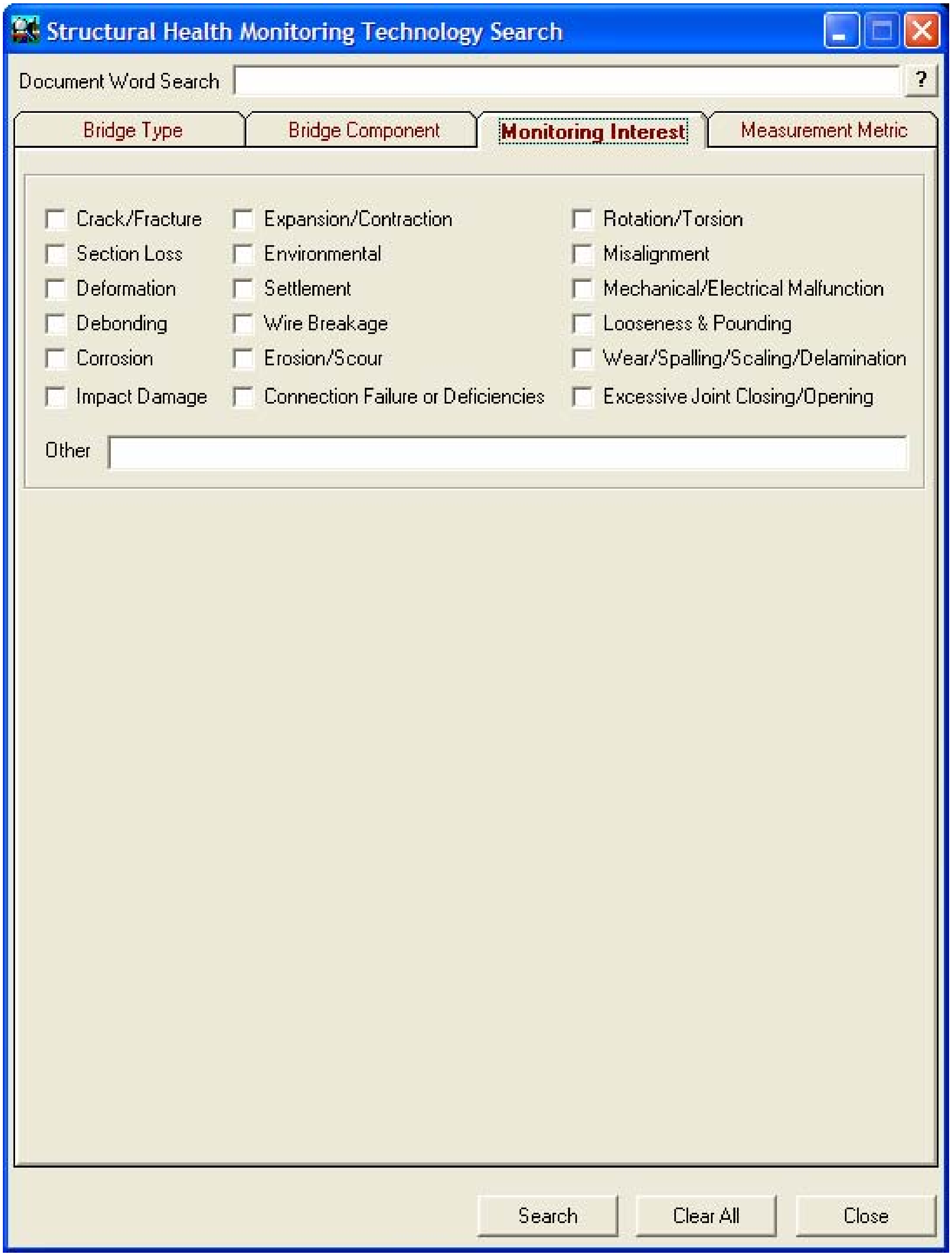


Figure 8. Monitoring Interest category for conducting a “checkbox” search.

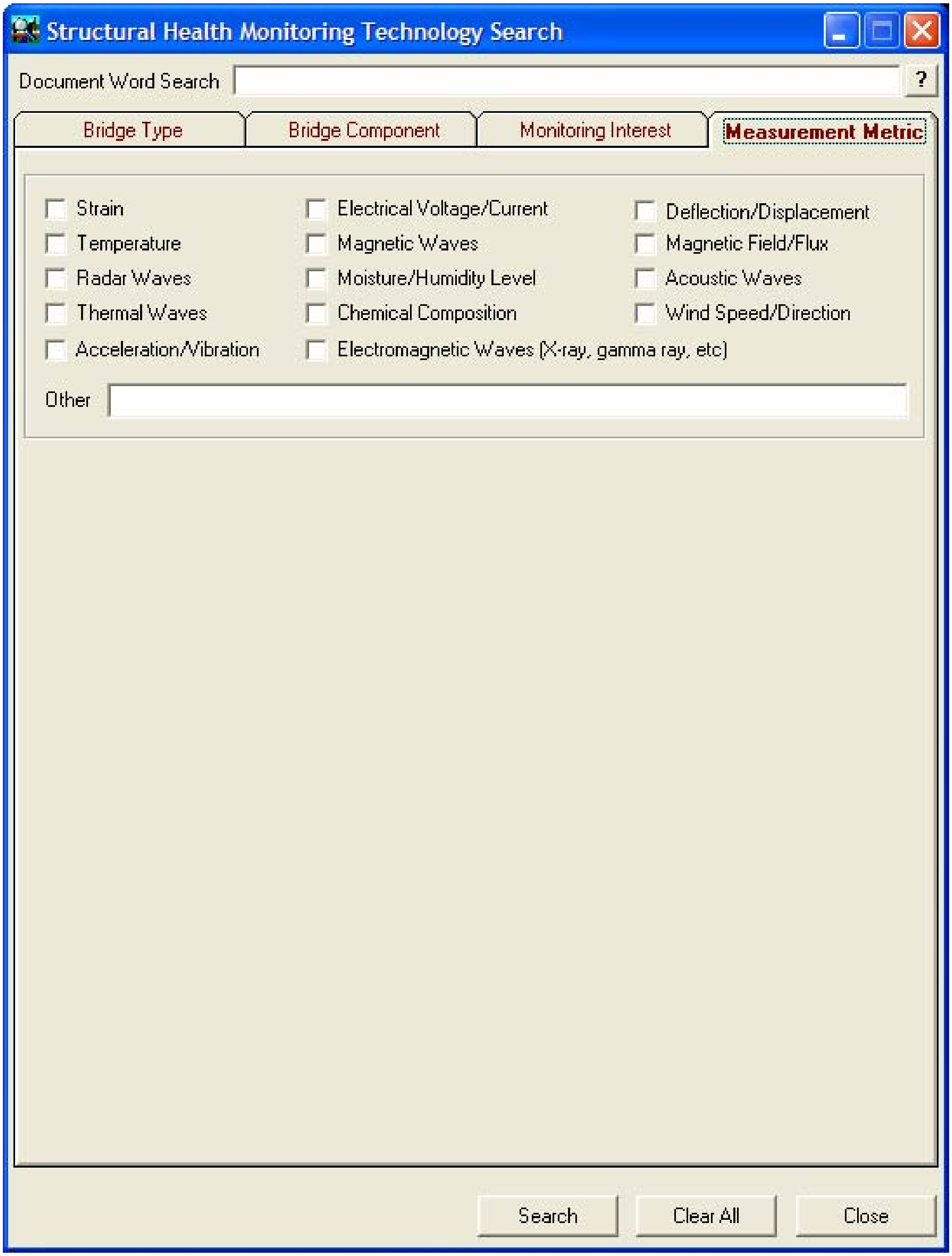


Figure 9. Measurement Metric category for conducting a "checkbox" search.

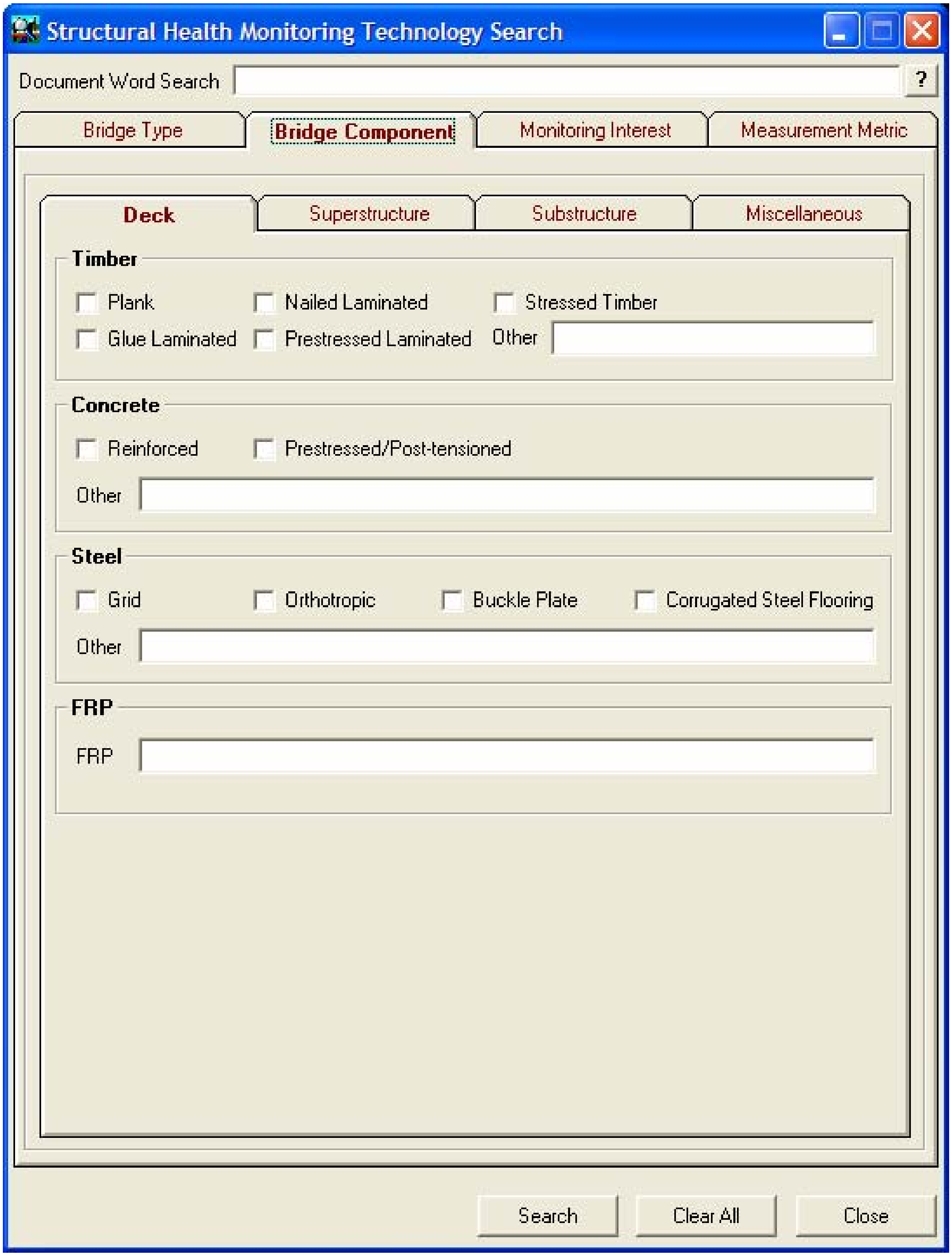


Figure 10. Deck subcategory (Bridge Component) for conducting a "checkbox" search.

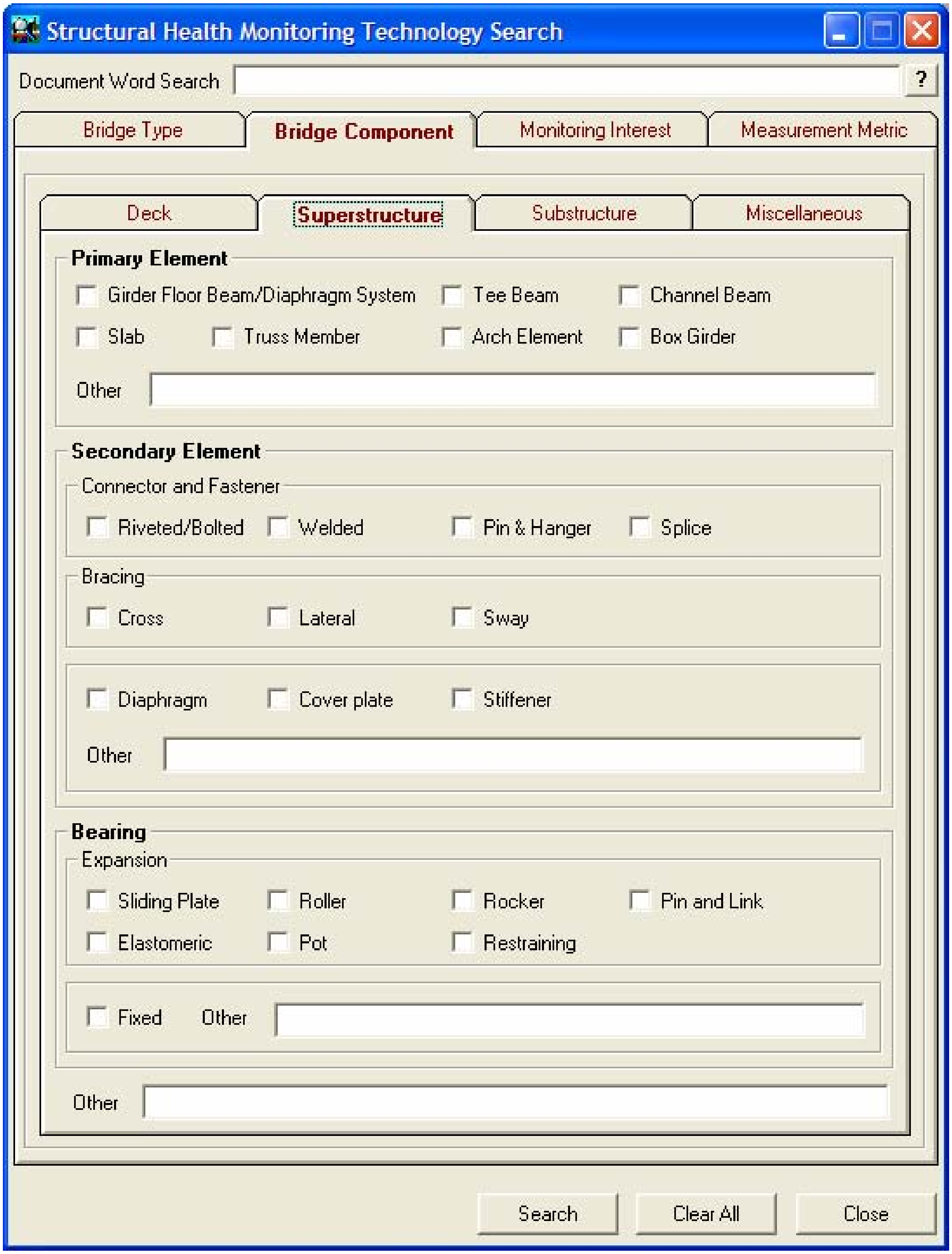


Figure 11. Superstructure subcategory (Bridge Component) for conducting a "checkbox" search.

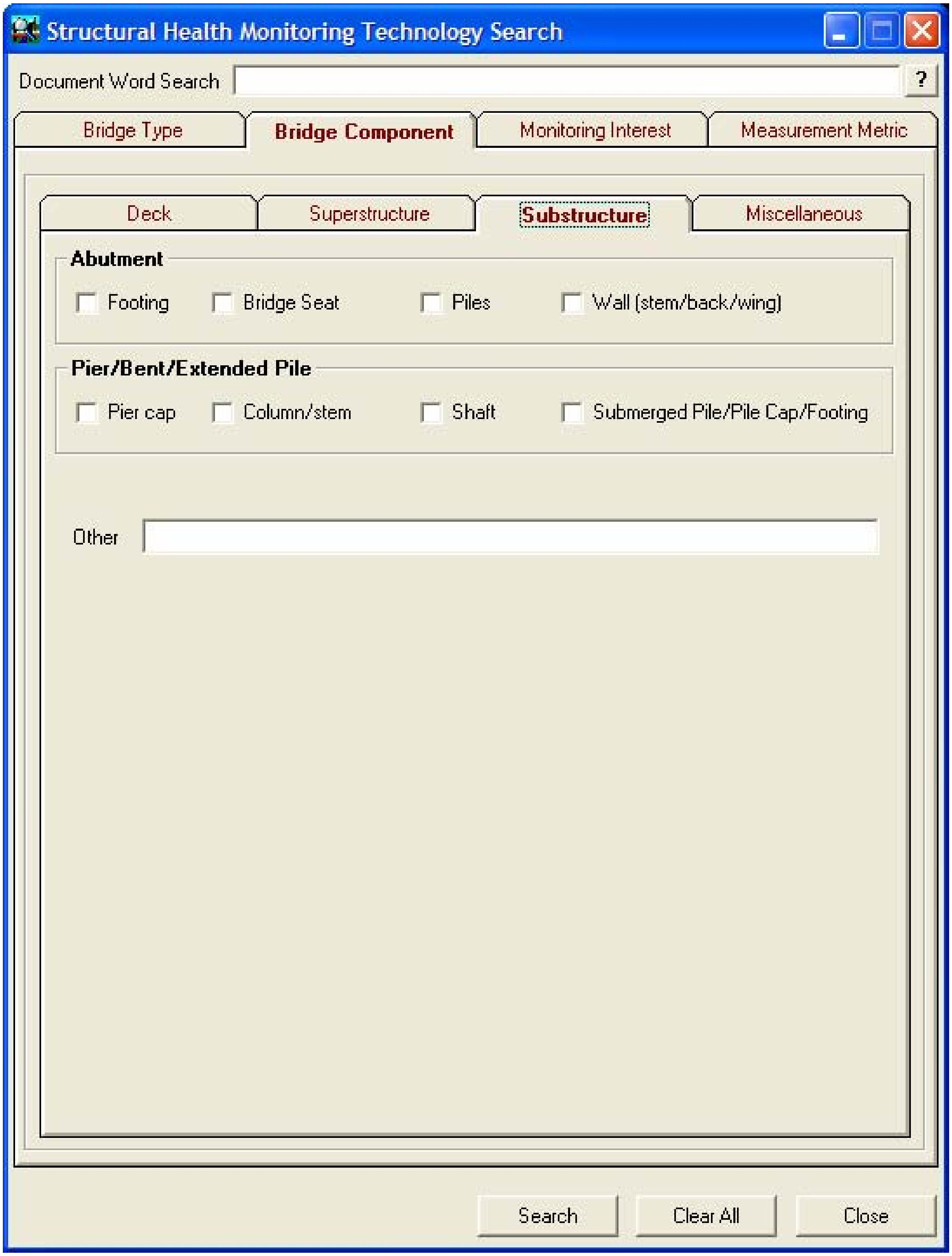


Figure 12. Substructure subcategory (Bridge Component) for conducting a "checkbox" search.

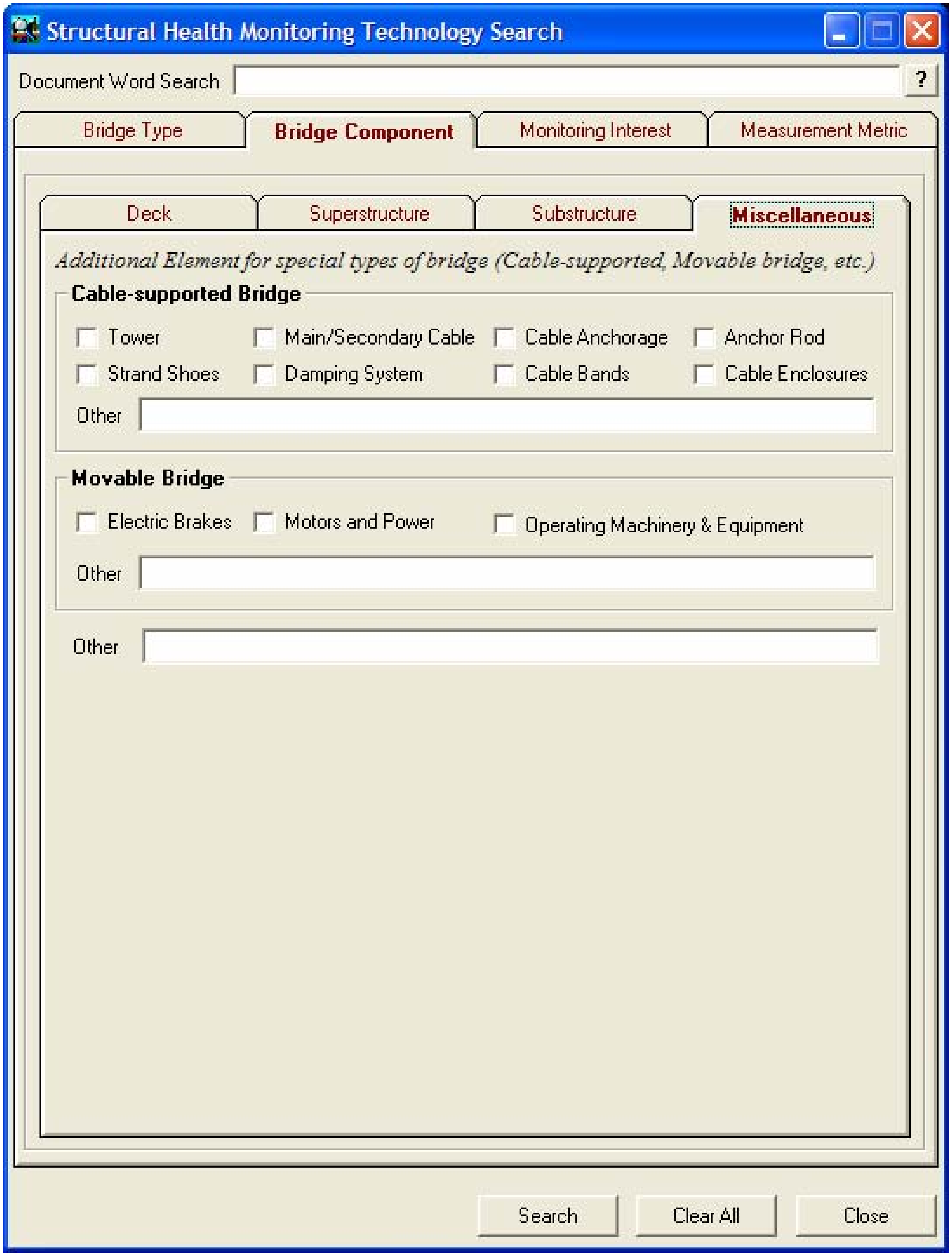


Figure 13. Miscellaneous subcategory (Bridge Component) for conducting a “checkbox” search.

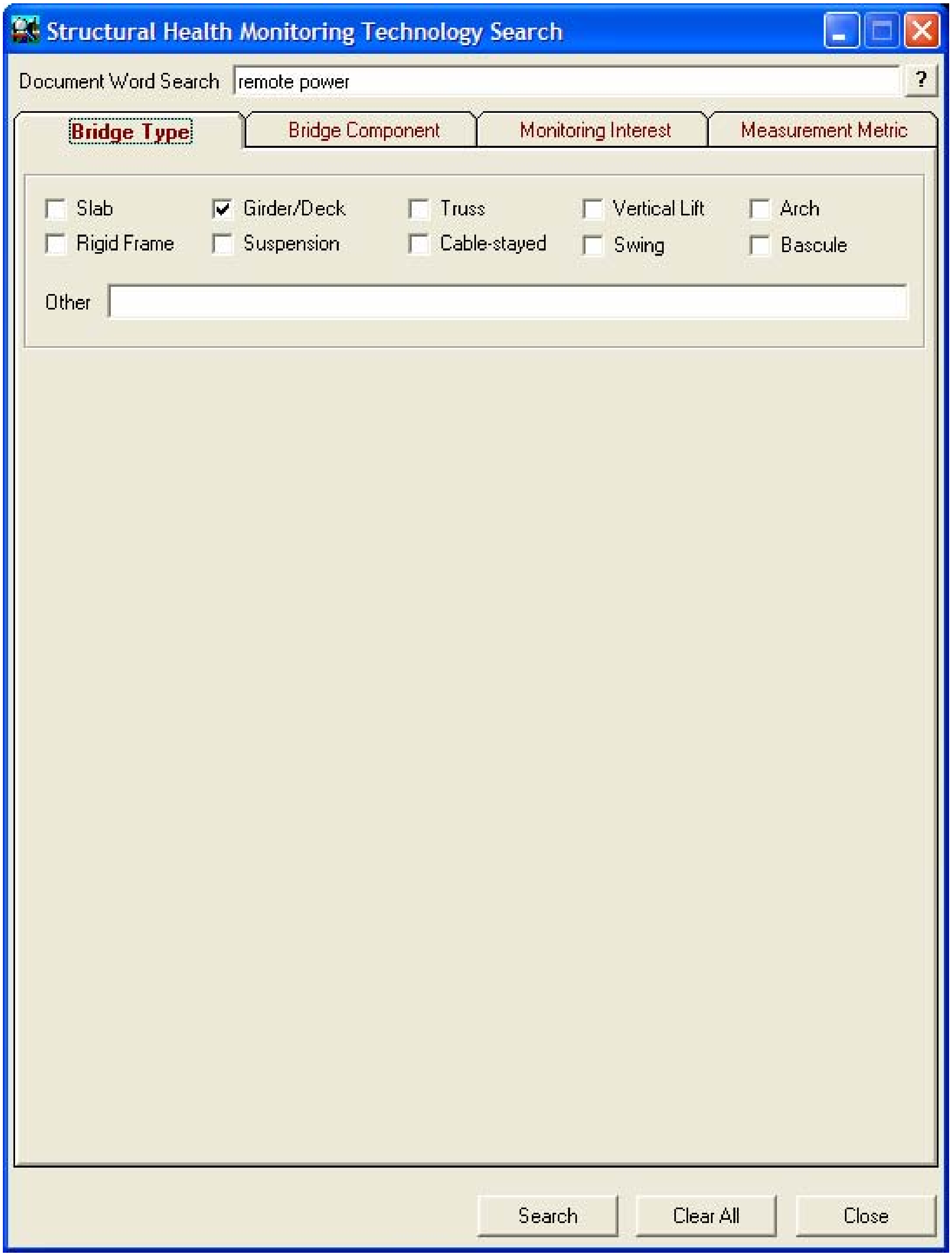


Figure 14. Selection of “Girder/Deck”.

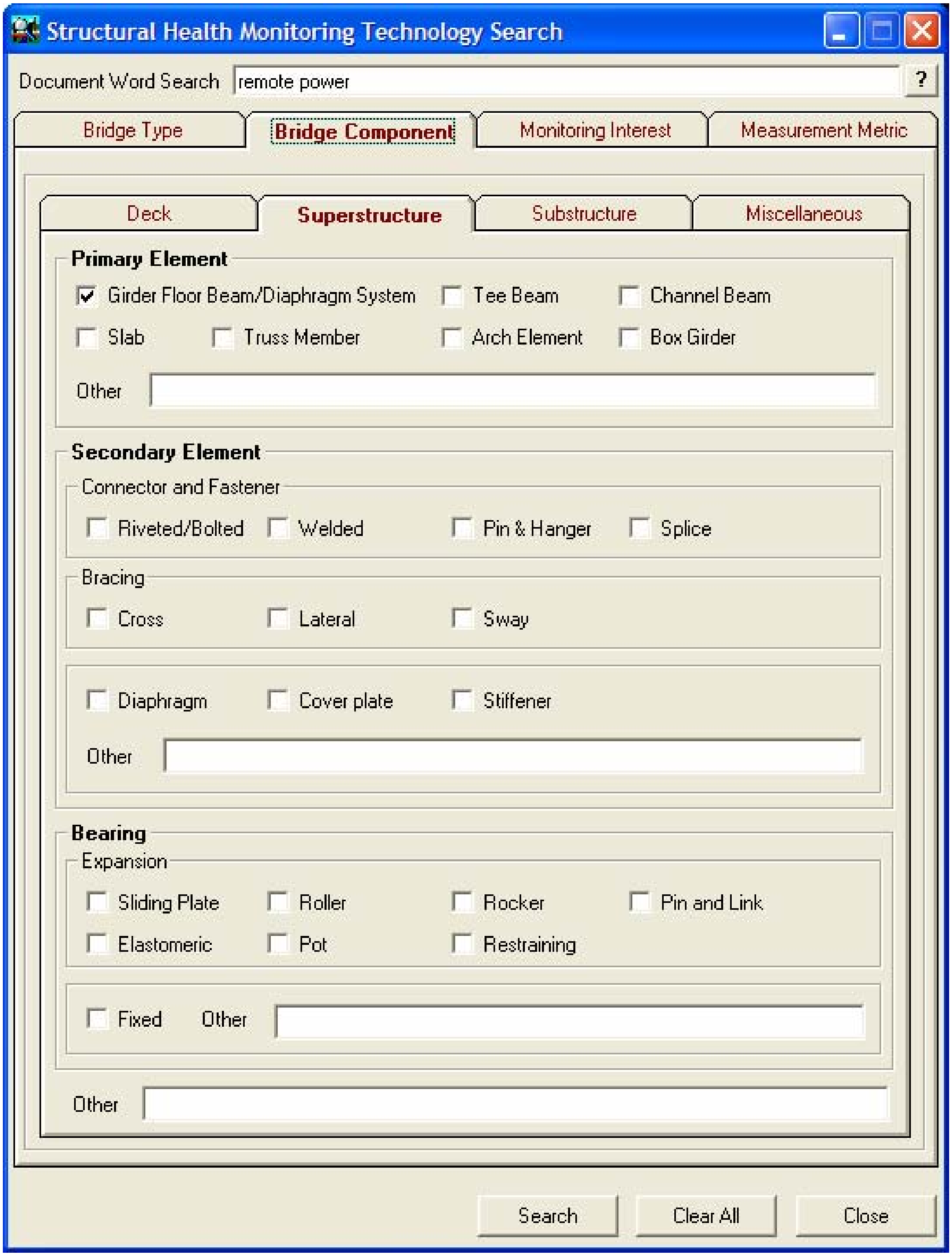


Figure 15. Selection of “Girder Floor Beam/Diaphragm”.

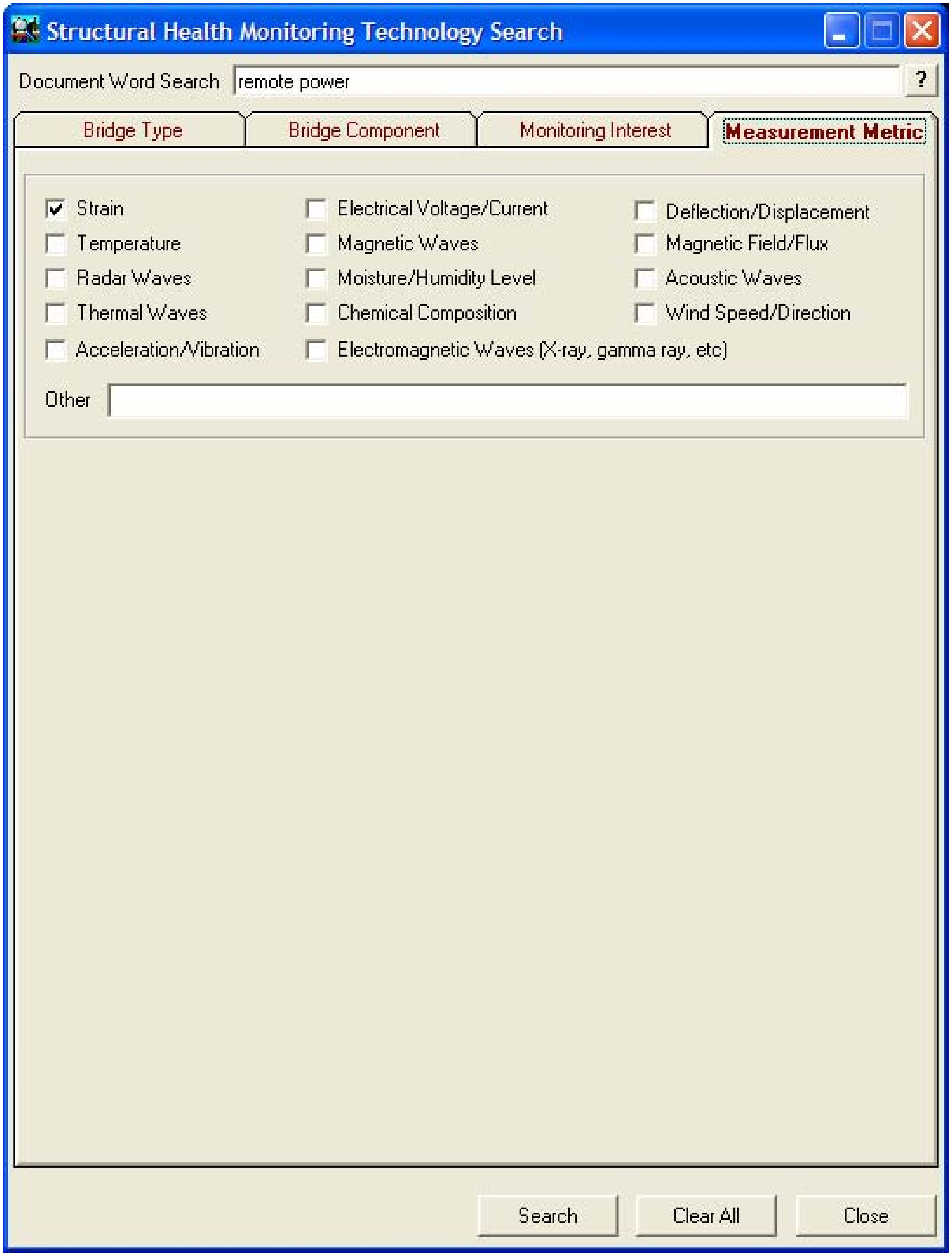


Figure 16. Selection of “Strain”.

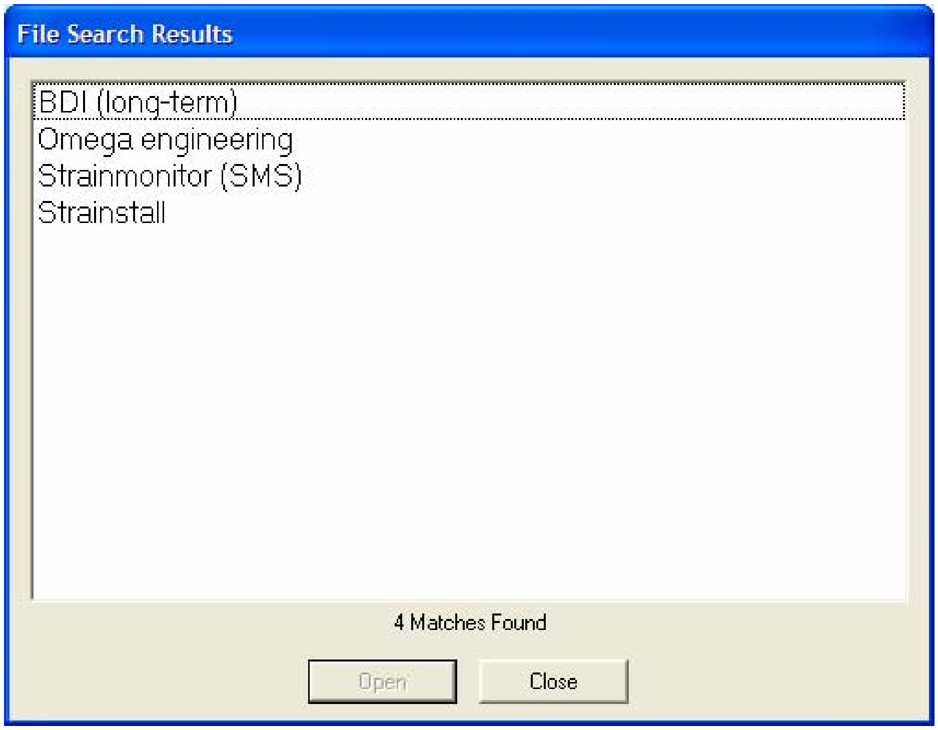


Figure 17. Search results.

4. REVIEW OF SELECTED SHM TECHNOLOGIES

In this chapter, selected SHM technologies are discussed. For convenience, this chapter is divided into "*Smart* SHM Systems", "State-of-the-Art SHM Systems", "Other SHM Components" and "Emerging SHM Technologies." The "*Smart* SHM Systems" and "State-of-the-Art SHM Systems" sections provide information on some of the SHM systems identified and currently being used. For these sections, classification as either "*Smart*" or "State-of-the-Art" was made following the previously given definitions. The "Other SHM Components" section gives a brief description of various SHM components that are advanced but are not a complete SHM system or have not been integrated into a complete system. The "Emerging SHM technologies" section gives information on some of the identified SHM systems/components technologies that are currently being developed. The research team does not necessarily endorse any of the specific technologies. The research team simply selected some of the synthesized technologies thought to best represent the collection of identified systems and technologies.

4.1. SMART SHM SYSTEMS

The lack of reliable inspection equipment to detect wire breaks within strands or cables can pose a serious problem for bridge owners. In order to address concerns about this problem, Pure Technologies, Ltd (of Calgary, Alberta, Canada) developed an acoustic-based monitoring system, called 'SoundPrint,' that can continuously detect wire breaks in prestressed beams and other cable supported structures [11]. The system uses an array of acoustic sensors distributed throughout a structure to measure the energy or dynamic response generated when tensioned steel wires fail. When the system detects a possible wire break, the data from the events are filtered and automatically transmitted via the Internet to a central data center where proprietary software is used to generate reports summarizing the time, location and classification of each recorded event through signal processing and analysis. An alarm is automatically triggered when a wire break is detected and an authorized engineer is notified for an appropriate action to be taken. Since its introduction in 1994, the SoundPrint acoustic monitoring system has demonstrated its capabilities and effectiveness in monitoring the deterioration of prestressing tendons and cables of suspension bridges, cable-stayed bridges, prestressed concrete bridges, and other structures in many countries.

4.2. STATE-OF-THE-ART SHM SYSTEMS

4.2.1. Fiber Optic Sensor-based Monitoring System

Recent advances in fiber optic technologies are making the application of non-intrusive, ubiquitous, multipurpose SHM systems more feasible. A SHM system with the fiber optic sensing capability offers key advantages including high-resolution and measurement capabilities that are immune to radio frequency (RF) interference, electromagnetic interference, random drift, and temperature interferences that may not be possible with traditional sensing technologies. An optical fiber-based SHM system for the global monitoring of structures, called SOFO monitoring system, was developed by SMARTEC SA of Switzerland [12] and has been used on numerous bridges throughout the world. It is a real-time, continuous and autonomous monitoring system capable of measuring deformations over a long measurement basis and providing quantitative data on structural behavior with a micrometer resolution and long-term stability. The SOFO software allows automatic and scheduled measurements and real-time, simultaneous display of several different views within the same window. It is also capable of the management of warning states in the form of pre-warnings and thresholds; the software can trigger an alarm based on a user-defined action (e.g., sound, phone call, e-mail, etc.). The system has proved to be effective in different applications when specific thresholds can be pre-defined.

A similar fiber optic sensor (FOS) based monitoring technology was developed by OSMOS [13]. It is a long-term, continuous remote monitoring system for monitoring global structural changes through an integration of components in or on the structure. A signal processing monitoring station used by the OSMOS system consists of a master unit and a slave unit and is used for measuring, evaluating and displaying signals from various sensors. The slave registers measurement values from the sensors, while the master processes and displays the signals. A database server archives the raw data and accumulated configuration data. Operating via a modem and a webserver, the entire system can be configured online. A patented 'dashboard' feature provides the information concerning the state of the monitored structure. The system also allows alarms to be generated via e-mail, fax, or any other user specified means when exceeding predetermined thresholds.

The Iowa State University Bridge Engineering Center has developed a FOS-based monitoring system that combines “State-of-the-Art” sensors, wireless communication, real-time web-based viewing of bridge performance, “on-the-fly” data checking, and off-line conversion to engineering parameters. This system, that combines off-the-shelf technologies with specially developed software algorithms, is believed to be the first system capable of removing both long- and short-term temperature effects from long-term continuous data. The system is capable of providing information for assessing the current state of a structural system and for evaluating the long-term performance trends through common engineering parameters (e.g., load distribution, end restraint, stress-cycle counting, etc.).

4.2.2. Integrated, Internet-based On-line Monitoring System

The idea of a Internet-based SHM system is to provide automatically processed information to the end user via the widely accessible world wide web (WWW). Kinemetrics, Inc. of Pasadena, California developed an On-line Alerting of Structural Integrity and Safety (OASIS) system that provides real-time, continuous on-line monitoring of structures [14]. The OASIS system is an integrated hardware and software system that combines high-resolution dynamic measurements with real-time data communications and data processing, capable of reporting a current state, and the likely future state of the structure or components. It is also capable of providing autonomous, real-time graphical alerting of structural and environmental conditions using on-screen imaging and audible alarms.

A long-term, on-line monitoring system, called Wind and Structural Health Monitoring System (WASHMS), has been developed by the Hong Kong Polytechnic University and implemented on three long-span cable-supported bridges (Tsing Ma Bridge, Kap Shui Mun Bridge and Ting Kau Bridge) in Hong Kong [15]. The WASHMS for these three bridges consists of over 800 permanently installed sensors including accelerometers, strain gauges, displacement transducers, anemometers, temperature sensors, level sensors and weigh-in-motion sensors installed on each bridge combined with recently developed data management systems. The system was designed so that the data could be transferred to an Internet server through a telecommunication system to control the entire system and to provide information on the condition of the bridges. Due to a large amount of data generated, the system utilizes a geographic information system (GIS) technology that is capable of providing a computerized database management system for the capture, storage, retrieval, analysis, and display of temporal-spatial data. Currently the developers are working on developing tools to analyze the large volume of generated data.

4.2.3. Real-time Kinematic GPS-based Monitoring System

Recent advances in Global positioning system (GPS) technology make displacement measurements under static and dynamic conditions easier. The advantage of GPS systems is that relative displacements can be measured in real time to assess potential damage to a structure. In 1999, the State of California Department of Transportation (Caltrans) launched a GPS-based SHM project on the Vincent Thomas Bridge in Los Angeles Harbor, the San Francisco Bay Bridge, and the Golden Gate Bridge in San Francisco, California to evaluate the feasibility and capability of GPS technologies for monitoring long-span bridges [16]. The system utilized a high precision Real-Time Kinematic GPS (RTK-GPS) and wireless communications technologies. In general, a networked RTK system uses a differential carrier-phase positioning with at least two GPS receivers (one base and one or more rover receivers). A RTK system transmits raw code and carrier data from the base and rover receivers to a computer that processes and calculates the positions. This effectively reduces the processing requirements needed in the GPS receivers by using the processing power of a separate personal computer. Caltrans demonstrated that networked RTK-GPS is a good tool for identifying differential movements that may indicate potential problems in a post-disaster situation. With the initial success with the RTK-GPS technology, a new SHM project was deployed on the Carquinez Bridge in California in early 2004 for monitoring real-time displacement measurements under traffic, wind, and seismic loads.

4.3. OTHER SHM COMPONENTS

In this section, SHM components/characteristics considered to be “advanced” in nature, but not part of a complete system are briefly discussed. While not complete, these components/characteristics may form the basis for configuring an SHM system that has desirable properties and features.

4.3.1. Sensors

The most common type of sensors used in SHM application includes displacement sensors, strain sensors, vibrating wire sensors (both temperature and strain), force sensors, and temperature sensors. Typically kinematic quantities (e.g., strain, displacement and acceleration) and environmental quantities (e.g., temperature, humidity, wind, etc.) are the two main quantities that are typically desired by a sensor based SHM system. For example, displacement transducers and settlement devices can be used to measure and monitor deflection, settlement, joint openings, and other movements of bridge members. Strain sensors are normally used to measure the change in the length of an object per unit length. Numerous research projects and technical reviews have shown that conventional sensors are easily be affected by changes in external factors such as temperature, humidity, cable length, magnetic or electric fields, etc. These factors make it difficult to obtain stable and reliable readings over the long term. These common problems that are often encountered with conventional sensors can be overcome as advanced sensing technologies become more available for bridge applications.

Smart Structures, LLC of Rantoul, Illinois [17] developed magnetoelastic (ME) sensors that can be used to monitor stress and corrosion in steel. The principle employed to develop the ME sensor was based on the magnetic permeability of a material that can be measured indirectly by using a charge coil placed next to, or around, the material allowing the varying current or voltage to be related to the stress quantity. The sensor was developed to fit with a magnetic shield to isolate it from external dynamic and static magnetic fields. It is capable of monitoring the stress within bridge cables and certain type of steel reinforcement in concrete. A sensitivity study showed that the sensor was insensitive to varying environmental conditions [16].

Most conventional corrosion monitoring systems for steel reinforced structures utilize embeddable probes that generate low amplitude electric signals and are subject to corruption from nearby electromagnetic interference (EMI) sources such as power lines, radios, cell phones. To address these limitations, Virginia Technologies, Inc. of Charlottesville, Virginia [18] developed a fully embeddable corrosion monitoring sensor, called the embedded corrosion instrument (ECI-1), incorporating electrodes and signal processing electronics. It is capable of measuring parameters important to long-term corrosion monitoring including linear polarization resistance, open circuit potential, resistivity, chloride ion concentration and temperature. The ECI-1 contains a chloride threshold indicator, a temperature sensor, a conductivity and resistivity sensor, a polarization resistance sensor, and an open-circuit potential sensor. Each ECI-1 is a digital peripheral connected on an embedded local area network. They communicate with each other and an external datalogger using the SDI-12 industry standard protocol. The data can be collected on-site with a laptop computer or accessed remotely with RF/wireless data connection.

4.3.2. Data Acquisition and Processing

Typically two different methods have widely been used for collecting and recording data from sensors. For a local SHM system with a small number of sensors or for a system that only requires a measurement at infrequent intervals, a portable or hand held indicator can be used to collect and store the data. Traditionally, SHM systems had analog sensors and Analog/Digital (A/D) converters at the data acquisition location to convert the analog signal into a digital format. Newer systems incorporate digital sensors to avoid A/D conversion at the central point to enable more reliable communication and relieve the central data acquisition from the conversion load. Some devices allow measured parameter values to be read directly in the proper engineering units and storing the data that are later downloaded for further analysis. For a global SHM system with a large number of sensors, or for a system that requires data to be collected and processed frequently or continuously, more complex systems are employed that can collect and process data from an array of sensors at predetermined time intervals.

Some deficiencies to system integrity may occur when sensors are located far from the data acquisition system. In practice, the distance from sensors to a data acquisition system can normally range from couple of feet to several hundreds of feet. As the distance becomes longer, the analog signal may degrade due to unexpected noise sources present along the cable length. Also, it is possible that the change in monitored response from structural damage may be smeared and blended in with those from other factors such as temperature and excitation. Since data are normally measured under varying conditions, data normalization is very important in data processing. Data normalization is a procedure to separate signal changes caused by operational and environmental variations of the system from structural changes. If various unknown sources are involved, where not all sources directly related to structural changes can be eliminated, statistical quantification though appropriate measurements can be employed. Significant research is currently underway for optimizing the data acquisition regimes for maximizing benefits from the real-time data while minimizing the data processing and archival costs.

The CR series data acquisition systems, developed by Campbell Scientific, Inc. [19], have been used in numerous SHM projects. The CR series include basic systems with just a few channels to expandable systems that measure hundreds of channels that are compatible with most commercially available sensors. Channel types include analog (single-ended and differential), pulse counters, switched excitation, continuous analog output, digital I/O, and anti-aliasing filtered. Scan rates can be programmed from a few hours up to 100,000 times per second, depending on the model used. Limited data processing can be performed on-board with no additional post processing required in some cases. The data collection platform provides a server based archiving system. This combined with the processing capabilities can provide a reliable foundation for short- and long-term bridge monitoring.

4.3.3. Communication

Traditional data collection systems are mostly based on wire-connected instrumentation where sensors are placed at critical points along a structure and connected to a central data acquisition system with cables of various types (coaxial, etc.). These wire-based systems typically have high installation and maintenance costs. The use of an Ethernet local area network (LAN) can mitigate the problems associated with thick bundles of transmission wires and make a SHM system robust against electromagnetic interference. By using Ethernet LAN in SHM applications, multiple sensor types can also be interconnected, thereby reducing the number and length of wires, and changes to the SHM system cam be easily implemented by simply adding more connections.

Another way to overcome problems associated with wired communication is to use wireless technology. Advanced Telemetrics International (ATI) of Spring Valley, Ohio [20] developed a wireless remote telemetry system known as the ATI 2000. The ATI 2000 series can be used for remote monitoring or testing of bridges. Up to 32 remote wireless transmitters connect directly to sensors and transmit any type of sensor signal to conveniently located receivers, eliminating the need for cabling. Some features of the ATI 2000 series include; immunity to electromagnetic interference, dust, oil, moisture, etc.; remote power transmitter management from the receiver; transmitter auto turn off when battery is too low (prevents damage to the battery); autozero for each channel at the receiver; transmitter battery-low and data transmission status indicators at the receiver; and initial offset indicators at the transmitter (indicates if excessive offset present). A recently developed 2060B series transmitter, housed in a weatherproof NEMA 4x enclosure, can supply excitation to sensors and transmit signals up to 4 miles (line of sight).

4.3.4. Data Management

As current trends in SHM move toward the development of a real-time, continuous monitoring paradigm, the ability to efficiently transfer and manage a large amount of data is required. Even with digital signal processing (DSP) boards and algorithms, massive data transfer is still required if the monitoring is performed remotely. Also, if not properly processed, data may be subjected to a loss of some useful information hidden in the recorded data through data compression and condensation. Experience has shown that the data transfer and management tasks involved in traditional SHM systems is non-cost effective [21]. In recent years, the economic considerations and other challenges have led the traditional SHM system to evolve toward serial systems, in which the number of transmission mediums is reduced by utilizing a robust communication protocol such as the Universal Serial Bus (USB). Concurrently, modern Internet-based database technologies allow utilizing various conceptual retrieval interfaces, and corresponding visualization and analysis tools for a better management of the large amount of data and information.

An Internet-based monitoring system, called the Real-time Integrated Surveillance and Control System (RISCS), was developed by the Drexel Intelligent Infrastructure and Transportation Safety Institute and implemented on the Commodore Barry Bridge (CBB) that spans the Delaware River between Pennsylvania and New Jersey [23, 23]. The developers constructed an Internet-based measurement and image database utilizing various conceptual retrieval interfaces, and corresponding visualization and analysis tools. The Internet portal interface and database were designed to allow an authorized viewer to navigate raw data, preview data graphs, extract specified information (such as analytical data, reports, images, video clips and CBB CAD models), save the retrieved data to a local computer hard-disk and modify information. The database system is capable of providing fast and various displays, dynamic webpages and multimedia displays. Research is currently underway for optimizing the data acquisition regimes for maximizing the benefits from the real-time data while minimizing the data processing and archival costs.

Although currently available hardware technologies appear to allow large amount of data to be collected, the ability to analyze and understand the massive datasets in a concise manner appears to be still lacking. In most SHM applications, the raw data alone is rarely of direct benefit to a bridge owner. The true value is predicated when useful information and knowledge are extracted for decision support or exploration on structural health status (e.g., as to whether the structure is healthy enough to continue fulfilling its functions). Clearly, the main issue of the current SHM community is not the lack of measurements, but rather is how to analyze and extract useful information.

4.4. EMERGING SHM TECHNOLOGIES

4.4.1. Fiber Optic Sensors

FOS technology is based on the principle in which the micromechanical resonator acts as the sensitive element of the sensor and has the promise of providing an alternative measurement method not previously available. They are used for detecting structural performance by sending light beams down the fiber optic cable at regular intervals and by measuring changes in time-of-flight.

Various types of FOS are currently being developed and used in bridge applications. Each type is based on a different property of the light waves traveling down the fiber. For example, Fabry-Perot sensor measures interference fringes while the measuring parameter of Fiber Bragg Grating sensors is frequency. Multiple Bragg Grating type sensors can be photo-imprinted along the same fiber, making it feasible to install large scale networks of 1,000 sensors or more with a minimum of cables. Another type of fiber optic based sensor technology that has been recently getting attention is the use of Brillouin optical time-domain reflectometry (BOTDR). It is a distributed optical fiber strain sensor whose operation is based on the Brillouin scattering phenomena.

FOS allow a structure to be continuously monitored with confidence in the usability of the long-term data record. FOS are known to exhibit low mechanical hysteresis and have high shock survivability. They are capable of measuring strains at multiple orders (two or three) of magnitude better than conventional electrical resistance gages. The use of the FOS can also reduce the number of sensors needed for the structure since they are capable of detecting damage along the entire length of the sensor (in the specific case of long-gauge FOS). Advantages of FOS over conventional sensors include its compactness, and freedom from drift and electromagnetic interference [24]. Other advantages include that they can easily be incorporated into various types of measuring devices (e.g., accelerometers, displacement transducers, etc.), and many physical quantities can be measured simultaneously with the proper system design and calibration [25].

4.4.2. Micro-electromechanical Sensors (MEMS)

Another advanced sensing technology that is being popularly explored by numerous manufactures and institutions is MEMS. MEMS are miniature electromechanical sensor and actuator systems that are capable of being optimized in their design for a specific application. The advantage of MEMS is that they can be used in an environment to both sense and actuate. The key difference between conventional sensing technologies and MEMS sensing technologies lies in their intelligence capabilities. The majority of MEMS devices contain an on-board microprocessor within the system. The microprocessor can be typically used for digital processing, conversion from analog to digital, performing basic calculations, and providing interfacing functions.

One advantage of using this technology and its design paradigm in bridge applications is the miniaturization associated with MEMS; MEMS features are typically on the scale of microns (10^{-6}m). This small size allows them to be implemented in applications where conventional devices would be intrusive. The manufacturing process, known as vary large scale integration technology (VLSI), which is similar to those used for manufacturing computer chips, gives a great potential for the mass production of a particular sensor in a cost-effective manner.

One MEMS sensor development currently underway is being completed by Advanced Design Consulting (ADC), Inc. that is developing tether-free, passive sensors [26]. These detectors are slightly larger than a pin-head and can be poured along with the concrete into a bridge deck or road bed with an expected life of 100 years. ADC plans to combine radio frequency identification (RFID) devices with its MEMS sensors. This ultra-small sensor is being designed to monitor moisture, temperature, pH, and the concentration of chloride, sodium and potassium ions within concrete. It will be powered by electrical energy radiated from a hand-held monitoring device and it transmits data and identity information by reradiating that signal. At other times, the sensor remains unpowered.

4.4.3. Wireless Sensors for Corrosion Monitoring

While corrosion monitoring sensors have been available for some time, they have inherent limitations when embedded in concrete. Current sensors typically need power, which increases their size, limits the life span, or require the use of significant cabling. SRI International, working with Caltrans, is currently developing a wireless sensor, called a “Smart Pebble”, that contains a chloride sensor and utilizes a radio-frequency identification (RFID) chip that can be queried remotely for monitoring the level of chloride ingress into concrete bridge decks [27, 28]. The 1.5 in. diameter wireless devices, with a weight of a typical piece of the rock aggregate, are expected to cost less than $100 each. The sensors can be activated by a $1,000 handheld or vehicle-mounted RF identification data logger that gathers the data as it passes over them. The Smart Pebble is designed to remotely powered, thus precluding the need for any lifetime-limiting batteries, and it can monitor chloride ingress to depths of up to 4 in. The sensor is designed to be inserted in the bridge deck either during the construction (or refurbishment) or in a back-filled core hole.

The Johns Hopkins University Applied Physics Laboratory (APL), working with the Maryland State Highway Department, is developing a Wireless Embedded Sensor Platform (WESP), which can be used with a variety of different sensing capabilities, into a unit called the “Smart Aggregate” [29]. The “Smart Aggregate” is an embeddable sensor, which is expected to be suitable for the long-term field monitoring of corrosion in bridge decks. The Smart Aggregate sensors can be embedded during concrete placement. The data reader, which can be mounted on a car or truck, powers the Aggregates as it passes over them and stores the sensor data on a connected PC. Each sensor contains wireless power receiver and data transmission coils and is designed using ceramic hybrid integrated circuit technology to withstand mechanical stresses and the high pH environment of concrete. The sensor, which is roughly the size of a quarter and could cost less than $20 each, is being designed to last for 50 years. The wireless power transmission and data collection approach could eliminate potential problems with batteries, cables and connectors. Researchers have installed several prototype Smart Aggregates in a bridge deck in Montgomery County, Maryland, and are gathering performance data. Two types of different versions of Smart Aggregates are being developed: (i) those measuring the concentration of chloride ions and (ii) those measuring the actual corrosion rate using a sacrificial sensor. APL is in the process of licensing the technology to companies for their manufacture, and it is expected to have this technology available in mid 2005.

4.4.4. Wireless Communication

As was mentioned previously, as a viable alternative to the wired systems, emerging wireless technologies such as radio frequency communication links, cellular phone networks, and others provide an opportunity to remedy the recurring cabling problem of conventional monitoring systems. Due to the potential advantages of wireless technologies over a conventional wired sensing system, a change in the communication industry is shifting the existing technologies into a new system. One example is the General Packet Radio Service (GPRS), a global system for mobile communications that provide users with packet data service over GSM radio channels and external packet data networks. This type of technology is being explored for SHM systems. The most popular protocols that are currently available for transmitting data includes Bluetooth and Zigbee.

4.4.5. Data Processing and Management

The emerging knowledge discovery in databases (KDD) technology may provide a tool for creating an object-oriented information scheme for diagnostic interpretation of data [30]. KDD systems have created opportunities for computational tools that have a degree of cognitive intelligence; commonly referred to as artificial intelligence (AI). As a growing engineering area, the AI concept is frequently being evaluated as a tool for solutions that intelligently understand problems. This intelligent tool evolved from the intersection of research in various fields such as databases, statistics, machine learning, pattern recognition, reasoning with uncertainty, knowledge acquisition for expert systems, data visualization, information retrieval, and high-performance computing [15]. The common AI technology currently being explored is Artificial Neural Networks (ANN). The objective of using ANN approach is to transform the collected data and information into meaningful outputs from collected inputs. As a supervised learning technique, ANN came from the idea of developing an artificial system capable of simulating the function of a human brain or neural system [31]. Due to its powerful capabilities at universal approximation of nonlinear mapping functions with an arbitrary complexity, the ANN approach has been successfully used in different fields of science and engineering. The ANN resembles the human neurons in two respects. First, the network acquires knowledge through a learning process and training. The learning process can be perceived as a type of optimization process. Second, the inter-network connection weights (known as "synapse weights") are used to store the knowledge, which can then be used to solve new problems. Since its introduction, the use of ANN has been gaining interest in bridge monitoring applications as a statistical pattern classifier to identify and predict damage, which can be defined by the occurrence, location, and extent, in structural systems. The use of the AI technology may allow automating the entire process of data analysis, implementing specific algorithms for pattern extraction from data, and integrating the inferred knowledge from data with damage inferring indices for structural health assessment and decision making. Many researchers are currently focusing their effort on integrating the technology with a data management system.

5. SUMMARY AND DISCUSSION

5.1 SUMMARY

The objective of this work was to obtain and synthesize information on advanced health monitoring technologies with a specific interest in those having smart-structure attributes. With the protocol framework developed and discussed, the research team performed a comprehensive literature review and survey of SHM technologies currently in use as well as emerging technologies. Various existing and emerging SHM technologies were identified, carefully reviewed and summarized in an unbiased manner. This final report includes a brief summary of bridge monitoring history, current and future trends of SHM technologies and a series of completed *SHM Technology Evaluation Forms* for each of the synthesized technologies. In addition, a searchable database was developed and included herein that allows easy identification and review of the identified SHM technologies.

5.2. DISCUSSION

The inventory of advanced sensors for SHM application is continuously growing. In the case of long-gage FOS, their use can reduce the number of sensors needed for monitoring a structure since they are capable of detecting changes along the entire length of the sensor. Some challenges, however, still need to be overcome. They are fragile and may suffer damage during installation. The cost associated with interrogation is considered to be high when compared to other conventional monitoring systems. The use of MEMS sensors also appears to have a promising future due to their low power requirements and low cost and can lead to a more feasible SHM system. However, the reliability and measurement accuracy of MEMS sensors are among the concerns that must be overcome before successful implementation.

More advanced SHM technologies are expected to move from demonstration projects into engineering practice in the near future. Many commercially available products can be setup, with additional cost, in a wireless configuration with a battery or self-generating power supply system (e.g., solar panel). The use of wireless sensing and networking technologies eliminates sensor-to-data acquisition through cables and improves the overall reliability. However, this is still an emerging area. Concerns related to loss of data and/or data quality still remain unanswered. Mitigating these concerns by mixing wireless applications with hard-wired applications may be a good strategy. It is the authors' expectation that because the technology has not been completely proven, it will take some time before the significant utilization of these advanced technologies into bridge monitoring systems.

As can be found herein, although there are several technologies with "*Smart*" attributes, the research team was able to identify only one SHM system that satisfied the definition of "*Smart*" used in this work. This system, manufactured by Pure Technologies, utilizes sensed information to determine if a wire break has occurred in either a prestressed concrete structure or a cable-supported structure. Several SHM systems classified at "*Smart*" by the developers are currently in the development stages. However, it is unclear if these systems will, indeed, possess all of the characteristics to be considered truly "*Smart*."

The above facts not withstanding, this work identified many SHM technologies that can, if properly used, be a valuable addition to bridge management activities. These include systems that give the maintenance and design engineer important behavior information using advance features such as wireless communication, advanced sensors, and others.

6. ACKNOWLEDGEMENT

The research summarized in this report was sponsored by the Wisconsin Department of Transportation Wisconsin Highway Research Program. Special thanks are accorded to those who contributed their valuable time by responding to the survey and provided valuable technical comments.

7. REFERENCES

1. Moore, M.E., Phares, B.M., Graybeal, B.A., Rolander, D.D., and Washer, G.A. "Reliability of Visual Inspection of Highway Bridges," Federal Highway Administration, FHWA-RD-01-020, Washington, DC, June, 2001.
2. Rytter, A. "Vibration based inspection of civil engineering structures," Ph.D. Dissertation, Department of Building Technology and Structural Engineering, Aalborg University, Denmark, 1993.
3. *America's Highways 1776-1976*, Federal Highway Administration, Washington, D.C., 1976.
4. *Bridge Inspector's Training Manual/90,* Federal Highway Administration, Washington, D.C., 1991.
5. Status of the Nation's Highways, Bridges, and Transit: Conditions & Performance, Federal Highway Administration, Washington, D.C., 2002.
6. Abba G. Lichtenstein, A.G. "Bridge Rating Through Nondestructive Load Testing," NCHRP Project 12-28(13)A, Transportation Research Board, Washington, DC, 1994.
7. Wipf, T.J., Phares, B.M., Klaiber, F.W., Wood, D.L., Mellingen, E., and Samuelson, A. "Development of Bridge Load Testing Process for Load Evaluation," Final Report TR-445, Center for Transportation Research and Education, Iowa State University, Ames, Iowa, 2003.
8. Chajes, M.J., Shenton, H.W. III. O'Shea, D., and Chaudhri, M. "Bridge Testing to Enhance Bridge Management in Delaware," *9th International Bridge Management Conference* Orlando, Florida, April 2003.
9. Schiff, S.D., and Philbrick, T.W. Jr., "Load Testing for Assessment and Rating of Highway Bridges. Phase I: Review of Current and Experimental Technologies and Practices," Final Report FHWA-SC-99-04, Federal Highway Administration, Washington D.C., 1999.
10. Nowak, A.S. and Szwed, A., "Evaluation of Existing Bridge Structures Using Field Tests", Journal of Roads and Bridges, No. 3, 2002, pp. 81-104.
11. Pure Technologies, Ltd. (www.soundprint.com last accessed on November 5, 2004).
12. SMARTEC (www.smartec.ch last accessed on November 5, 2004).
13. OSMOS (www.osmos-group.com or www.subterra.us last accessed on November 5, 2004).
14. Nigbor, R.L., Diehl, J.G. "Two Year's Experience Using OASIS Real-time Remote Condition Monitoring System on Two Large Bridges," *Structural Health Monitoring, Current Status and Perspectives*, Stanford University, Palo Alto, California, pp. 555-563, 1997.
15. Ko, J.M. "Structural Health Monitoring Large-scale Bridges: Research & Experience," The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, 2004.
16. Loren L. T., "Continuous GPS: Pilot Applications-Phase II," Final Report F-2001-OR-05, FHWA/CA/IR-2003/05, California Department of Transportation, Sacramento, CA, 2003.
17. Smart Structures, LLC (www.smart-structures.com last accessed on November 5, 2004).
18. Virginia Technologies, Inc. (www.vatechnologies.com last accessed on November, 2004).
19. Campbell Scientific, Inc. (www.campbellsci.com last accessed on November, 2004).
20. Advanced Telemetrics International (www.atitelemetry.com last accessed on November 5, 2004).

21. Reda Taha, M., Kinawi, H., and El-Sheimy, N. "The Realization of Commercial Structural Health Monitoring Using Information Technology Based Techniques," *Structural Health Monitoring ISIS 2002 Workshop*, Winnipeg, Manitoba, Canada, 2002.
22. Klucu, E., Qin, X., Barrish, R.A., Jr., Aktan, A.E. "Information Technology and Data Management Issues for Health Monitoring of Commodore Barry Bridge," *Nondestructive Evaluation of Highways, Utilities, and Pipelines IV*, Proceedings of SPIE, vol. 3,995, pp. 98-111, 2000.
23. Aktan, A.E., and Faust, D. "A Holistic Integrated Systems Approach to Assure the Mobility, Efficiency, Safety and Integrity of Highway Transportation," *The first International Conference on Structural Health Monitoring and Intelligent Infrastructure*, Tokyo, Japan, 2003.
24. The 2nd International Workshop on Structural Health Monitoring, Stanford University, Stanford, CA, September 1999.
25. Eric U. "Fiber Optic Sensors," An Introduction for Engineers and Scientists, John Wiley & Son's, Inc. New York, New York, 1991.
26. ADC Press Release, "Making bridges safe from collapse: Advanced Design Consulting receives federal grant to develop MEMS sensors that can be mixed with concrete," Advanced Design Consulting, Inc., Lansing, New York, December 16, 2003.
27. D. G. Watters, P. Jayaweera, A. J. Bahr, and D. L. Huestis, "Design and Performance of Wireless Sensors for Structural Health Monitoring," *Proceedings of Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 21A, pp.969-976, Brunswick, ME, July 29-August 3, 2001.
28. Watter, D.G., Jayaweera, P., Bahr, A.J., Huestis, D., and Priyantha, N. (2003) "Smart Pebble: Wireless Sensors for Structural Health Monitoring of Bridge Decks," *Smart Structures and Materials 2003: Smart Systems and Nondestructive Evaluation for Civil Infrastructures, Proceedings of SPIE*, Vol. 5,057, pp. 20-28.
29. Carkhuff, B.G., Cain, R.P., Weiskopf, F., and Srinivasan, R., "Packaging for a Sensor Platform Embedded in Concrete," *Proceedings of the Structural Materials Technology Conference*, Cincinnati, Ohio, September, 2002.
30. Fayyad, U., Piatetsky-Shapiro, G., and Smyth, P. "From Data Mining to Knowledge Discovery in Databases," AI Magazine, Fall 1996, pp. 37-54, American Association of Artificial Intelligence, Menlo Park, CA, 1996.
31. Albert, N., "Neural Networks for Pattern Recognition," MIT press, Cambridge, Massachussettes, 1993.

APPENDIX

State Engineer's Questionnaire

Bridge Engineering Center

2901 S. Loop Drive, Suite 3100, Ames, Iowa 50010-8632
Phone: 515-294-9501 ~ Fax: 515-294-0467

BRIDGE ENGINEERING CENTER

at Iowa State University

Survey of Structural Health Monitoring of Bridge Structures and Components Using Smart-Structure Technology

This survey is part of a synthesis the Bridge Engineering Center is developing for the Wisconsin Department of Transportation. If you have questions about the survey, please contact Brent Phares, 515-294-5879, bphares@iastate.edu. If you experience difficulties with this web page, please contact the webmaster.

*Required fields

1. Contact information

*Name: ____

*Position/Title: ____

*Organization: ____

*Address: ____

*City / *State / *Zip: ____ ____ ____

*Phone No.: ____

Email Address: ____

2. Have you used any Structural Health Monitoring Technologies with Smart-Structure Concepts?

(•) **Yes** ( ) No

If YES, please continue.
If NO, please forward the email about this survey to others who may be knowledgable about this subject.

Please complete the following section about one (1) technology. After submitting this form, you'll have the opportunity to complete the section below about additional technologies.

3. Please provide general information about technology that you know of or have experience with.

Name of Technology: ____________________

Manufacturer/Developer Name: ____________________

Manufacturer's Phone: ____________________

Manufacturer's Website: ____________________

Manufacturer's Email: ____________________

4. For what purpose is this technology used?

5. Briefly describe any ongoing or completed projects using this technology:

6. Additional comments:

Thank you for completing this survey! [Submit Survey]

Wisconsin Highway Research Program
University of Wisconsin-Madison
1415 Engineering Drive
Madison, WI 53706
608/262-2013
www.whrp.org