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Sensors, smart structures technology and steel structures

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Abstract. This paper deals with civil infrastructures in general, sensor and smart structure technology, and smart steel structures in particular. Smart structures technology, an integrated engineering field comprising sensor technology, structural control, smart materials and structural health monitoring, could dramatically transform and revolutionize the design, construction and maintenance of civil engineering structures. The central core of this technology is sensor and sensor networks that provide the essential data input in real time for condition assessment and decision making. Sensors and robust monitoring algorithms that can reliably detect the occurrence, location, and severity of damages such as crack and corrosion in steel structures will lead to increased levels of safety for civil infrastructure, and may significantly cut maintenance or repair cost through early detection. The emphasis of this paper is on sensor technology with a potential use in steel structures.

Keywords: sensor; smart materials; smart structures; steel structures; structural control.

1. Introduction

This paper deals with civil infrastructures in general, sensor and smart structure technology, and smart steel structures in particular.

As is well known, civil infrastructure systems solidly underpin a nation's commerce and economy and uphold the life of its society. Additionally, these infrastructure systems have longer service lives when compared with any other kinds of commercial and manufactured products, and are rarely replaceable once they are erected and used. Yet the technology – hardware and the integrated software – for developing smart structures, which is one of the ultimate challenges of engineers, is still in its embryonic stage.

Reliability, performance, safety and security, service life and life-cycle costs are the primary concerns for public works or civil infrastructures systems, including bridges, transportation systems, high-rises, etc. In order to sustain performance, reliability and safety of such structures, it is essential to have accurate and real-time information about the structural integrity or health condition of the structures (Liu, *et al*. 1993). Traditionally information regarding the health of a structure is obtained through scheduled and labor-intensive inspections and analysis, which may not provide the necessary hard engineering information during the critical time before the catastrophic failure strikes.

Sensing and data measurement of physical parameters in civil structures pose a unique challenge, and also introduce exciting research opportunities – particularly for structures on which the locations for

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placement of sensors to measure key structural variables are inaccessible.

Steel is a very popular construction material and steel structures accounts for a significant market share of civil engineering structures including buildings and bridges. Compared to other construction materials such as concrete, steel has its own unique properties and damage patterns. In particular, steel structures are susceptible to corrosion and fatigue, which are major threats to aging infrastructures. For example, cables made from high-strength steel wires, which are critical components in suspension or cable-stayed bridges, are generally susceptible to corrosion. The failure of bridge cables would cause severe damage to bridges that could lead to serious service interruption and significant economic loss. Fatigue is another critical factor that could significantly reduce the service life of steel bridges and often requires lengthy and costly inspection and retrofit. In the US, there are a substantial number of older steel bridges that are deteriorating at an alarming rate. Maintenance needs for older bridges have far outpaced available resources and therefore innovative design, monitoring and maintenance approaches are highly desired.

Steel structures are also subjected to damage caused by environmental loadings, such as strong earthquakes. Immediately after the 1994 Northridge Earthquake in California, USA, and 1995 Kobe Earthquake in Japan, surveyors found a surprising number of welding connection failures in steel moment-frame buildings that had been designed for seismic loads. Lack of accurate and reliable inspection and detection techniques that are wireless sensor based has been a major road block toward if, what and where to do for subsequent retrofit Therefore, developing cost-effective sensor technology for rapid post-earthquake condition assessment and retrofit decision making is in clear demand.

In the following sections, research and issues related to the title subjects, e.g,, in structural control, sensors and smart structures, and in smart steel structures will be addressed, in that order.

2. Structural control

In addition to sensor and monitoring technologies needed to reliably assess the conditions of structures, the desire to control or avoid damage to components of gravity-load-bearing frames in buildings following recent major earthquakes (e.g. the 1994 Northridge earthquake, 1995 Kobe earthquake, and 1999 Chi-Chi earthquake) has spurred the development of passive and active structural control systems in the past two decades. In a passive or active structural control system, the main structural system is intended to have little or no damage while supplemental damping devices are designed directly to dissipate all or a substantial percentage of seismic input energy. Such damping devices are designed to be accessible, easily replaceable or reconfiguring after a major earthquake event. Since these supplemental damping devices are often not part of the gravity-load-bearing system, if needed they can be more easily replaced without compromising the integrity of the structure.

Development of structural control systems is in part due to several coordinated research efforts, largely in Japan and US and partially funded by NSF, marked by a series of milestones listed in Table 1. The effectiveness and limitations of active control systems for dynamic response reduction are shown in Fig. 1. One of the most challenging aspect of active control research in civil engineering is the fact that is an integration of a number of diverse disciplines, including computer science, data processing, control theory, material science, sensing technology, as well as stochastic processes, structural dynamics, and wind and earthquake engineering. These coordinated efforts have accelerated the research-to-implementation process. Control systems have been installed in more than 40 full-scale building structures in four countries, as well as have also been used temporarily in construction of

Table 1 Structural control research – milestones

Year	Event
1989	US Panel on Structural Control Research (US-NSF)
1989	First actively controlled building constructed in Tokyo
1990	Japan Panel on Structural Response Control (Japan-SCJ)
1991	Five-year Research Initiative on Structural Control (US-NSF)
1993	European Association for Control of Structures
1994	International Association for Structural Control (IASC)
1994	First World Conference on Structural Control (Pasadena, CA, USA)
1998	China Panel for Structural Control
1998	Second World Conference on Structural Control (Kyoto, Japan)
2002	Third World Conference on Structural Control (Como, Italy)
2004	IASC becomes International Association for Structural Control and Monitoring (IASCM)
2006	Fourth World Conference on Structural Control (San Diego, CA,USA)

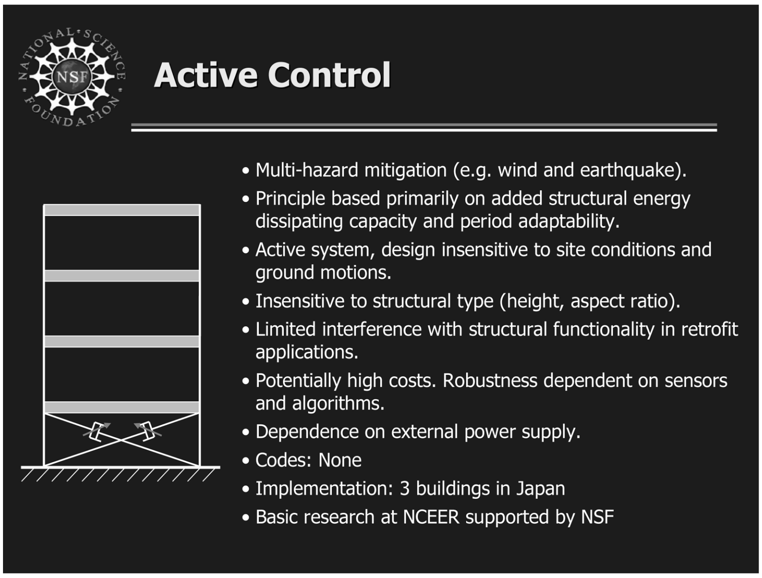


Fig. 1 Active control for dynamic response reduction

numerous bridge towers or large span structures (e.g., lifelines, roofs).

Most recently, smart damping (also known as semi-active control) strategies have been shown to be particularly promising, offering the reliability of passive devices, yet maintaining the versatility and adaptability of fully active systems, without requiring the associated large power sources. Studies have shown that appropriately implemented smart damping systems perform significantly better than passive devices and have the potential to achieve, or even surpass, the performance of fully active systems, thus allowing for the possibility of effective response reduction during a wide array of dynamic loading conditions (Dyke, *et al*. 1998). Examples of such devices include variable-orifice fluid dampers, controllable friction devices, variable stiffness devices, adjustable tuned liquid dampers, and MR/ER dampers (Spencer and Nagarajaiah, 2003). Recently constructed buildings in Japan have employed nearly 800 smart dampers. Most notable application is the new seven-story National Museum of Emerging Science and Innovation in Tokyo, built with a semi-active structural control system using MR dampers.

3. Sensor technology and smart structure research

Sensors have been used for detection and measurement of various kinds of data and quantities such as temperature, strain, pressure, and other dynamic force and response and environmental parameters. As such they are developed through multiple disciplinary sources such as materials, engineering of various fields, and others. Naturally sensors are also found being used in all diverse occasions such as to: monitor and diagnose, provide surveillance and status, evaluate and improve performance, derive control actions, protect from damage and failure, gather information and enhance intelligence, etc.

Sensors and associated technologies have significantly evolved over the last three decades. While the physics behind the transduction process may have not achieved major and revolutionary advances, the overall sensor technology has experienced major strives for enhancements. Over all sensor technology has progressed on three fronts: focus, level of intelligence, and its architecture.

Smart structures technology, an integrated engineering field comprising sensor technology, structural control, smart materials and structural health monitoring, might revolutionize the design, construction and maintenance of civil engineering structures. Within the past few years, rapid progress has been made in the area of smart structures technology, which has received increased attention from researchers and practitioners.

The core of smart structure engineering is the sensor technology as sensors provide the essential data input for processing and utilization by smart structures. For example, the proper functioning of any structural health monitoring system or structural control system relies on accurate sensor data input to the system. Major factors behind the accelerating interest in these areas are the exponential growth in smart materials, electronics, wireless communication, MEMS, structural health monitoring, structural control and information technology, resulting in novel smart sensors with wireless communication, structural control devices, and robust and efficient data analysis and interpretation system. As a result, researchers in academia, government laboratories, and industry are advancing the state-of-the-art of the smart structures technologies with respect to improving the performance, management, and operation of steel structures, as well as effective prioritization of post-disaster rebuilding and recovery actions.

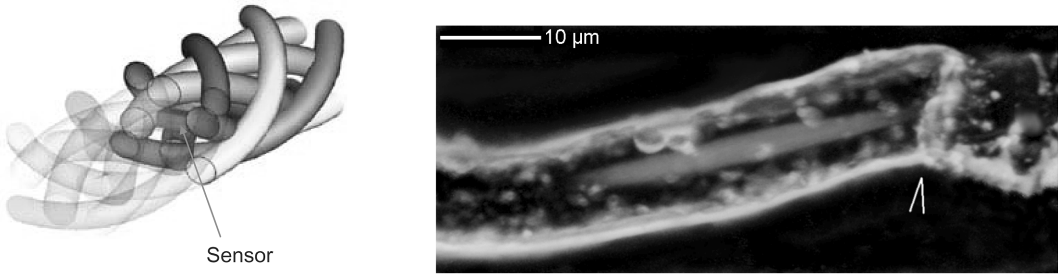
To date, wireless sensors have been proposed for the task of monitoring the response of large-scale civil structures. Wireless sensors have recently received considerable interests among civil engineering researchers because they are easy to deploy, and possess flexibility in sensor network configuration (Spencer, *et al*. 2004, Lynch and Loh 2006). Consequently the concept of wireless sensing can be extended to play a more encompassing role within the smart structure framework. Current research is exploring the inclusion of actuation capabilities within a wireless sensor prototype that allows the wireless sensor to command structural control actuators (Lynch, *et al*. 2006). The wireless sensing network is responsible for the collection of structural response data (e.g. floor accelerations), wireless transmission and communication of response data, calculation of control forces, and application of corresponding force commands to the MR dampers.

Current trends in structural health monitoring (SHM) is towards the use of large-scale sensor networks (defined by hundreds of sensing nodes) to provide a high-resolution, multi-dimensional picture of the operating condition of the monitored structure. Manual data analysis, because it is slow and subjective, is impractical for handling the massive quantity and high dimensionality of sensor data generated by large-scale sensor networks in on-line SHM systems. Innovative approaches are direly needed to enable automated SHM; hence, analysis methods must be properly matched the data generation capability of on-line SHM systems. Most relevant to addressing this need is an emerging field termed knowledge discovery from databases (KDD), which is concerned with the theoretical and practical issues of extracting knowledge from large size data sets. Therefore, it is also critical to develop goal focused, self aware sensor intelligence to convert data to useful information that will provide efficacious knowledge; high-performance and low-cost computation; inexpensive wireless communication technology for harsh operation environments; and minimum power-dependence and energy sources capable of scavenging power from the environment. Considering these pioneering technologies and the required characteristics associated with the sensor technology, it is clear that new research and development have to be initiated to realize the anticipated transformation of engineering practices of all fields.

Nature has produced extraordinary sensory systems in biological species that exceed the capabilities of a broad range of man-made sensors. Understanding the physical, chemical, and biological processes that are responsible for these sensory abilities may produce a blueprint for replicating or reconstructing them in man-made devices. Research involving the mimicry of biological systems, called biomimetics, is a branch of biotechnology that abstracts good designs from nature to enable a new generation of man-made materials and structures previously unimaginable. This interdisciplinary field, which engages researchers from the field of biology, chemistry, materials science, engineering, and physics, provides opportunities to develop new technologies by exploiting millions of years of nature's evolutionary design and achievements. Biosensing & bioactuation has been recently selected by NSF as a potential area of the broad research frontier that can be developed to cut across the interests of three existing research directorates: Engineering, Bio-Sciences, and Math & Physical Sciences.

4. Smart materials

Smart or active materials have been an area of challenging research, which could provide new corner stone for smart structures and systems. Smart materials can respond to external/internal stimuli with a significant change in a property in a controlled way. Research is being carried out to create — through characterization, modeling and prototyping--new materials which have multiple functionalities by mimicking sensory nerve systems or muscular actuating systems of a human or other bio-living body. These materials, such as piezoelectric materials (including PZT, PVDF, and piezoelectric composite), shape memory alloy, and magnet-rheological fluids and magneto-strictive materials can be solid, fluid, or viscoelastic. For civil, mechanical, or aerospace engineering applications, smart polymer-based, cement-based or composite smart materials have been investigated, for example, through embedded microelectronic sensors and microcontrollers within fiber braids and weaves when used in composite fabrication (Nemet-Nasser 2004), as shown in Fig. 2(a). These sensors and controllers would form interaction sensor nodes (mimic distributed human nerve system) to enact structural health monitoring. Further efforts have been undertaken to develop bio-inspired or bio-mimic organic compound such as forisomes (Shen and Shoureshi 2005, Shen, *et al.* 2006). Forisome is a plant protein, which has shown to be capable of superior sensing and actuating. In recent studies it has been shown that by applying a pH or calcium concentration shift forisomes can be stimulated in repetition contract and expansion anisotropically with speed. The strain can reach 30% along its longitudinal axis and more than 200%



(a) (b)

Fig. 2 (a) Smart fiber braids with embedded sensors and conductors; (b) Forisomes as sensor and actuator

radially. Forisomes are micron sized aggregations of proteins that respond within 50 ms to concentration variations of the calcium ion and pH, as shown in Fig. 2(b). Forisomes perform an anisotropic change of shape during which their volume increases more than three-fold. This process is independent of ATP, and is driven by the binding of Ca2+ (or change of pH) to the protein matrix. It is fully reversible (swell and shrink) on a similar time-scale by removal of Ca2+, and can be induced electrically *in vitro*.

In order to realize smart structures with self-healing capabilities (namely, durable, force-resistant, and ageless structures) a new paradigm that integrates several engineering and technological disciplines needs to be developed and there are several core disciplines that need to be integrated to establish the necessary expertise and technologies that enable smart structures. These disciplines are: Structural Engineering, Seismology and Geotechnical Engineering, Intelligent Structural Control, Structural Health Monitoring, Adaptive Materials, Wireless Sensor Technology and Self-Organizing Networks.

Shape memory alloy (SMA) based energy dissipating devices have received growing interests for seismic hazard mitigation application, as evidenced by an increase of literature in the past decade (e.g. Clark, *et al*. 1995, Wilde, *et al*. 2000, Dolce, *et al*. 2000, Ocel, *et al*. 2004, Janke, *et al*. 2005, Wilson and Wesolowsky 2005, Isalgue, *et al*. 2006, Zhu and Zhang 2007). The hysteretic behavior of shape memory alloys is dependent on their chemical composition as well as thermal conditions. For example, at ambient temperature $T < M_f$, SMA exhibits a fat hysteresis loop typical of mild steel, but its residual deformation after unloading is completed can be fully recovered through a temperature increase. Here Mf denotes the martensite finish temperature, below which the microstructure of SMA materials is fully martensitic. This shape recovery is called shape memory effect, which is due to a micromechanical phase transformation from the martensite phase to the parent austenite phase. Another important characteristic of SMA materials – superelasticity or pseudoelasticity, which involves quite significant hysteretic damping with zero residual strain upon unloading, is often utilized to dissipate vibration energy in structures. SMA exhibits the superelastic behavior at ambient temperatures $T > A_f$, where A_f refers to the austenite finish temperature, above which the microstructure of SMA is fully austenitic. The superelastic behavior of SMA is due to a stress-induced phase transformation from austenite to martensite. Since martensite is stable only at the presence of externally applied load, a reverse transformation takes place upon unloading, and after fully unloading is completed, the material will return to its original undeformed shape. Among many types of SMAs, Nickel-Titanium based alloy is the most widely used one because of its superior ductility and high fatigue life. The effectiveness of Nitinol-based energy dissipation devices for passive control of civil engineering structures was demonstrated through an experimental study by Clark, *et al*. (1995). Ocel, *et al*. (2004) tested two full-scale partially restrained connections which consist of four large diameter Nitinol bars connecting the beam flange to the column flange and serve as the primary moment transfer mechanism. The ability of SMA braces to control the seismic response of RC framed structures was assessed through shaking table tests of a 1/3.3-scale, three-story, two-bay RC plane frame, which was designed for low seismicity and low ductility (Dolce, *et al*. 2005). More recently, Zhu and Zhang (2007) studied the seismic behavior of a concentrically braced frame system with self-centering capability, in which a special type of bracing element termed reusable hysteretic damping brace (RHDB) is used. The RHDB is a passive energy dissipation device with its core energy dissipating component made of superelastic Nitinol wires.

5. NSF's sensors research program

Due to the rapid advance of sensor, wireless networking and information technologies, and integration of information to the design, manufacturing, operation and maintenance of real-world engineering systems, it is now a time to transform engineering from the past data-poor to the future data-rich world. Recognizing the broad-based interest and great impact potential, NSF's Directorate for Engineering launched a major 3-year research initiative in fiscal year 2003 and invested a total of approximately $125 millions over three years on sensors and sensing networks. The initiative emphasizes on multidisciplinary research that seeks to advance fundamental knowledge in new sensor technologies, including sensors for sensing and detection of toxic chemicals, explosives and biological

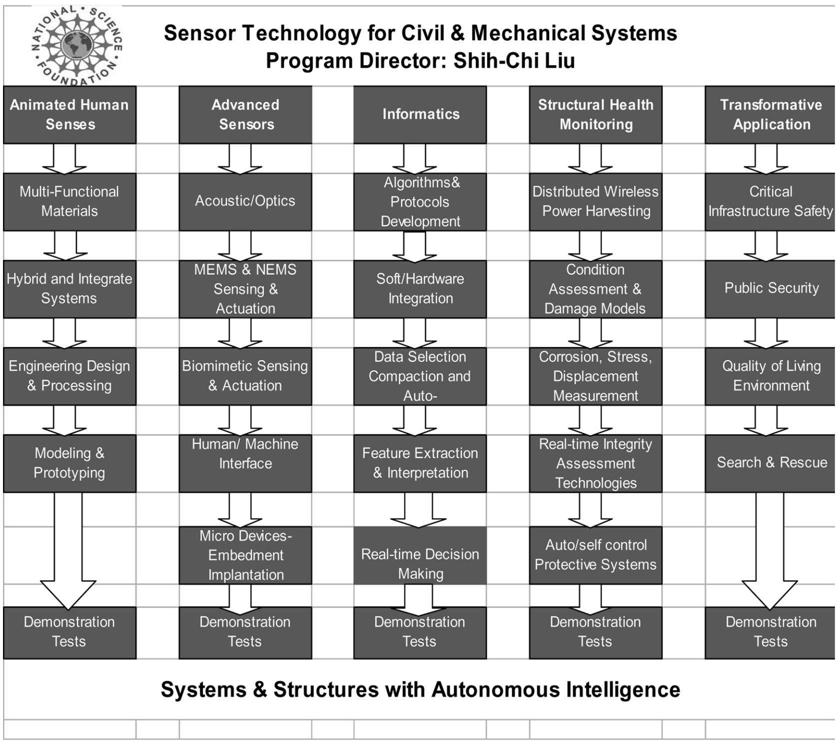


Fig. 3 NSF sensor technology program chart

agents, sensor networking systems in a distributed environment, the integration of sensors into engineered systems, and the interpretation and use of sensor data in engineering and decision-making processes.

Three research thrust areas are identified for solicited proposals in this initiative:
· Design, Materials and Concepts for New Sensors and Sensing Systems
· Arrayed Sensor Networks and Networking
· Interpretation, Decision and Action Based on Sensor Data

Over the years repaid advances have been made in a wide variety of areas through NSF and other sponsored research and development program. In the typical mode of NSF program, international cooperative research has been vigorously pursued between US-Europe, US-Japan and US-China. Collaboration between NSF and Other US research sponsor agencies has also been well established. A latest NSF Sensor's program chart, which describes the current and future interests and needs, is shown in Fig. 3.

6. Sensing of steel structures

Fatigue and fracture as well as loss of section caused by corrosion are time-dependent performance characteristics that have the potential to jeopardize the integrity of steel structures. For example, when bridge superstructure fails, it is usually because of excessive deterioration by corrosion and /or fatigue cracking rather than inadequate load-bearing capacity. During the past three decades, these conditions have developed in a number of bridges, resulting in loss of service, costly repairs, and concern about the safety of these structures (Fisher, *et al.* 1998). Additionally, wind-induced vibration has also caused numerous fatigue problems in sign, signal, and light support structures (Kaczinski, *et al.* 1998). Sensor technology that can reliably detect the existence of crack and corrosion in a timely manner is of great importance to the longevity of civil infrastructures, especially for steel structures. The emphasis of this section is thus placed on sensor technology for crack and corrosion sensing.

6.1. Crack sensing

Cracking is probably the most common material failure mode in steel structures, and may be the most dangerous, as complete fracture can occur nearly instantaneously and without any advance warning. Harsh environment can compound the cracking problem as they often supplement the mechanisms that are tearing the material apart, thereby accelerating the rate of failure (Craig and Lane 2005). Fatigue is a common cause for cracking in steel structures and deserves considerable attention because it can inflict damage on a material at a stress level that is far less than the material's design limit.

Fatigue inspection and corresponding retrofit actions will lead to a prolonged life and enhanced reliability of structural systems. However, most of today's fatigue inspection practices are performed manually; intensive labor, high cost and variable results are typical of manual operation. It is thus desirable to replace manual inspection with automated on-line crack monitoring technology. Existing nondestructive evaluation (NDE) techniques for fatigue crack detection include eddy current, radiography, acoustic emission, thermography, magnetic particle inspection, ultrasonic testing and etc. Some of the existing NDE techniques have limited use for on-line crack monitoring applications due to either one or a combination of the following problems: accessibility, automation, bulky volume, power supply, environmental noise, long-term durability and etc. Continuous on-line crack monitoring can be achieved through the use of advanced sensors.

Acoustic emission (AE) is based on the principle that ultrasonic acoustic signals are emitted as materials are stressed. Imperfections such as the initiation and growth of fatigue cracks, failure of bonds, areas of corrosion, and loosening of bolts, emit mechanical waves as the structure is stressed; different frequencies are produced for different size and type of defects. These mechanical waves can be registered by AE sensors. These AE bursts can be used both to locate flaws and to evaluate their rate of growth as a function of the applied stress (Chang and Liu 2003). Conventional AE sensors are based on piezoelectric ceramics (e.g. PZT) as sensing material. A MEMS transducer for measurement of acoustic emission events has been reported by Ozevin, *et al.* (2005). This MEMS based transducers has several resonant transducers on a tiny chip, which could be used to detect acoustic emission energy at several different frequencies. More recently, Zhang and Li (2006) studied the feasibility of using piezoelectric paint for acoustic emission sensing, which may provide a low-cost technique for on-line monitoring of fatigue cracks in welds in steel structures. Compared with conventional piezoelectric ceramics, piezoelectric paint have some advantages as AE sensor: ability to cover large areas to enable distributed sensing, conformability to surfaces with complex geometry like weldment, and better bonding between sensor and host structure.

As another aspect of the piezoelectric sensor-based nondestructive inspection techniques for steel structures, two kinds of active sensing-based crack detection techniques have been prevalently investigated during the last ten years: (a) electro-mechanical impedance-based method and (b) ultrasonic guided wave propagation-based method. In the electro-mechanical impedance method, piezoelectric patches are employed to excite a host structure with a high-frequency range (typically, higher than 20 kHz), and simultaneously monitor changes in the electrical impedances (an inverse of frequency response functions) of the patches attached to the host structure (Giurgiutiu, *et al.* 1999, Park, *et al.* 2003, Park, *et al.* 2005a). In the guided wave propagation-based method, a guided wave is induced in the material being inspected, and either ultrasonic signal picked at receiver or reflected waves are interpreted to determine the location and size of cracks (Ihn and Chang 2004, Giurgiutiu 2003, Park, *et al.* 2005b). Kim and Sohn (2007) are developing a new methodology of guided wave based nondestructive testing (NDT) to detect crack damage in a thin metal structure without using prior baseline data. This NDT technique utilizes the polarization characteristics of the piezoelectric wafers attached on to the both sides of the thin metal structure.

Applications of eddy-current NDE include the inspection of welds and corrosion, and the inspection of surface cracks, subsurface cracks, and fasteners in multilayered structures. The eddy current method uses induced magnetic fields to inspect the surface of conductive materials, such as steel or aluminum. Traditional applications of this method are not effective in weld metal due to the wide variation in magnetic material properties. The use of a differential probe that suppresses these variations in material properties allows the detection of cracks in the weld crown and at the weld toe. In recent years, electromagnetic methods for eddy-current inspection have attracted increasing attention. Electromagnetic sensors, based on either Hall effect, anisotropic magneto-resistance (AMR), giant magneto-resistance (GMR) effect, or SQUID have been successfully used for crack detection. Among these, the magnetoresistive sensors offer a good tradeoff in terms of performance versus cost. They have small dimensions, high sensitivity over a broad range of frequency (from hertz to megahertz domains), low noise, operate at room temperature, and are inexpensive (Dogaru and Smith 2001). Giant magneto-strictive material such as Terfenol-D is one type of smart materials.

A sonic infrared (IR) imaging method has also been used for structural defect detection including fatigue cracks by Favro, *et al.* (2001). This is a hybrid ultrasonic/infrared nondestructive technique for detecting fatigue cracks as short as 20 μm in metal samples. This technique uses a short pulse of low frequency ultrasound to cause the crack surfaces to rub or clap, thus inducing frictional heating. The heating is then observed through the use of an infrared (IR) video camera. In the case of a surface-breaking crack, the appearance of the image of the crack takes only milliseconds after the initiation of the ultrasonic pulse. Subsurface cracks become visible to the IR camera with time delays that are determined by diffusion of the heat from the crack to the surface of the sample.

Because bridge cable wires are of much higher yield and tensile strength than steel structural members in cable-supported bridges, they are much more susceptible to stress corrosion cracking. Moreover, environmental conditions within suspension bridge cables, including trapped moisture and partial or complete loss of galvanized coatings, promote chemical reactions that charge hydrogen into the wire. These reactions, in combination with surface attack and pitting that produces stress concentrations, lead to flat transverse stress corrosion cracks in wires (Fisher, *et al.* 1998). Magnetoelastic sensor for monitoring the stress and corrosion in steel cables has been devised by Wang, *et al.* (2001). In this method, the magnetic permeability of steel cables is related to the applied stress and temperature by making permeability measurements using small electromagnetic sensors slipped onto the cable. A guided-wave based non-destructive technique was also devised for stress measurement and damage detection in steel cables or strands (Kwun and Teller 1994, Khazem, *et al.* 2001, Lanza di Scalea, *et al.* 2003). Magnetostrictive transducers are used to excite and detect the waves in the cable.

Additionally, Major hazardous events such as strong earthquakes may cause severe low-cycle fatigue damages in civil engineering structures. An assessment of structural conditions is generally required after such events. However, visual inspection is still the most commonly used approach in practice which can be quite costly and time-consuming, therefore unsuitable for rapid assessment of structural conditions. Small low-cycle fatigue cracks initiated by earthquake loading are difficult to detect for several reasons such as coverage by non-structural elements and difficult access. A well-known example of this problem occurred after the 1994 Northridge Earthquake, where brittle failure of welding cracks were found in the beam-to-column welded joints in a surprising number of steel frame buildings (Bonowitz, *et al.* 1995). Inspection of these connections required a lengthy process involving the removal of the architectural cladding and fireproofing. Disruption of normal activities of the building occupants resulted in significant financial loss and inconvenience. This poses a critical application that requires innovative sensor yet to be developed for crack sensing.

6.2. Corrosion sensing

Corrosion is a major cause of deterioration in steel bridges. In addition to material loss, it can cause unintended fixities, movements, distortion, and fatigue cracks. The consequences of corrosion can range from progressive weakening of a bridge structure over a period of time to sudden failures. Each year the Federal Government and State departments of transportation (DOTs) spend billions of dollars on bridge rehabilitation and maintenance due to corrosion. Elevated rates of corrosive deterioration of steel structures are caused by exposure to aggressive environmental conditions such as poor drainage and debris accumulation (Fisher, *et al.* 1991). Corrosion is the deterioration of a metal or alloy and its properties due to a chemical or electrochemical reaction with the surrounding environment. Forms of failures due to corrosion include (Craig 2005): uniform, galvanic, crevice, pitting, intergranular, and erosion corrosion, selective leaching/dealloying; hydrogen damage; stress corrosion cracking; and corrosion fatigue.

Corrosion's effect on structural durability and on longevity of bridges is an important issue. In June 1983, a 100-ft section dropped out of the Mianus River Bridge carry I-95 in Connecticut, killing three motorists and critically injuring three others (Demers and Fisher 1990). A crack undetected before the collapse resulted in the fracture of a segment of the pin supporting the hanger and final collapse immediately followed. Corrosion and the geometric changes it produced at the pin connection played a major role in the development of the cracked pin. In May 2000, at the Lowe's Motor Speedway in North Carolina, an 80-foot section of a pedestrian walkway bridge, collapsed and more than 100 people were injured. The cause for this accident was reported to be due to high levels of calcium chloride in grout, which caused steel cables in the bridge to corrode and collapse. Another example of corrosion-induced economical loss is the BP's recent shutdown of oil transmission line in Prudhoe Bay, Alaska due to discovery of severe internal pipeline corrosion. The shutdown of BP's oil field due to this incident caused a reduction of 8 percent of U.S. oil production in August 2006, a time when oil price was at a very high level.

In bridge cable, the aging of the galvanized wire has caused oxidation of the protective coating as water and contaminants have penetrated suspension bridge cables. After 30 or more years of service the protective coating can be destroyed, particularly at spots where the galvanized coating was thinned from crossing wires and compacting conditions. Stress corrosion and hydrogen embrittlement results as surface pitting develops at these locations (Fisher, *et al.* 1998). Visual inspection by wedging is still the common approach to inspect the corrosion in bridge cable wires.

Electrochemical sensors, designed for wet corrosion environments, have been in use for 4-5 decades. Corrosion occurring in the presence of a continuous, bulk, electrolyte phase can be monitored using conventional electrode configurations. Measurements of atmospheric corrosion with electrochemical sensors, are not easily accomplished due to characteristics of the electrolyte film on the corroding surface. However, thin-film electrolyte characteristics were used in the design of the atmospheric corrosion monitoring device, termed the corrosion coulometer (Granata 1996).

For many years, corrosion of steel reinforcements embedded in reinforced concrete has plagued the longevity of civil engineering structures. An embeddable corrosion monitoring device has been made by a Virginia-based company to provide early warning of conditions that damage steel reinforcement and lead to cracking, spalling, and delamination of concrete bridge decks and support structures (Ross and Goldstein 2003). The integrated circuit in this embeddable device provides electrochemical measurements of corrosion rate with polarization resistance and will measure chemical parameters such as acidity-alkalinity, chloride ion concentration, and temperature. Field testing of this device was carried out in the B623 Lynchburg Bridge in Virginia since March 2002.

Coating of steel structures is a common practice to protect it from corrosion. However, lead was used as a pigment and drying agent in oil based paint for steel structures before 1980s. Lead-based paint is a major source of lead poisoning for children and can also affect adults. Lead is a highly toxic metal that was used for many years in products found in and around our homes. A biosensor developed by Li and Lu (2000) can be used to detect lead. The sensor, which is a combination of gold nanoparticles and a solution of a lead-specific synthetic DNA, can change color when lead is present. The synthetic DNA causes the nanoparticles of gold to aggregate in clusters that give off a blue color. When this comes in contact with lead, the DNA breaks apart, which in turn causes the aggregation of gold nanoparticles to fail and generate a color shift to red. In addition, the intensity of the red color is directly proportional to the amount of lead present, thereby providing the basis for a quantitative measure of lead.

7. Concluding remarks

This papers deals with civil infrastructures in general, sensor and smart structure technology, and smart steel structures in particular. Sensing and data measurement of physical parameters in civil structures pose a unique challenge, and also introduce exciting research opportunities. In order to realize smart structures with self-healing capabilities (namely, durable, force-resistant, and ageless structures) a new paradigm that integrates several engineering and technological disciplines needs to be developed and there are several core disciplines that need to be integrated to establish the necessary expertise and technologies that yield smart structures. These disciplines are: Structural Engineering, Seismology and Geotechnical Engineering, Intelligent Structural Control, Structural Health Monitoring, Adaptive Materials, Wireless Sensor Technology and Self-Organizing Networks.

Fatigue and corrosion have the potential to jeopardize the integrity of steel structures. Sensor technology that can reliably detect the occurrence of crack and corrosion in a timely manner is of great importance to the longevity of civil infrastructures, especially for steel structures. This paper also reviews the sensor technology currently available or under development for crack and corrosion sensing.

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