REVIEW OF NONDESTROYIVE EVALUATION TECHNIQUES OF CIVIL INFRASTRUCTURE

By Kevin L. Rens, P.E., Terry J. Wipt, P.E., and F. Wayne Klaiber, P.E.

ABSTRACT: To properly maintain our public infrastructure, civil engineers must learn new methods of inspection technology. Current inspection techniques required for our nation's bridges as well as locks and dams primarily consist of visual and subjective observations. When these inspections indicate that a structural or functional problem may be developing, many times more sophisticated inspection technology may be required. Nondestructive (NDE) testing methods can provide an answer to further determine the extent of a structural or functional problem. This paper presents the abbreviated results of a detailed literature review to identify the most widely used NDE techniques applied to civil engineering structures. In addition, a short questionnaire was developed and sent to state highway organizations. The literature suggests that acoustic emission testing is widely used while the questionnaire revealed that ultrasonic testing is most popular among state highway agencies.

NEED

Better inspection techniques are needed for our deteriorating infrastructure. Recently, many reports have been published concerning the state of deterioration of public-works systems. Statistics released in the fall of 1989 revealed that 238,357 (41%) of the nation's 577,710 bridges are either structurally deficient or functionally obsolete (Turrione 1990). A proposal announced by the National Science Foundation (NSF 1992) states:

The infrastructure deteriorates with time, due to aging of the materials, excessive use, overloading, climatic conditions, lack of sufficient maintenance, and difficulties encountered in proper inspection methods. All of these factors contribute to the obsolescence of the structural system as a whole. As a result, repair, retrofit, rehabilitation, and replacement become necessary actions to be taken to insure the safety of the public.

Another example of deteriorating infrastructure occurs in our nation's waterways. The U.S. Army Corps of Engineers (USACE) operates more than 600 hydraulic structures (lock chambers, flood-control dams, power houses, etc.). About 70% of these hydraulic structures are over 20 years of age; 49% are more than 30 years old; and 26% were constructed prior to 1940. Approximately one-half of the Corps' 269 lock chambers along inland waterways have reached or exceeded their 50-year design life by the turn of the century (Kao 1989). A primary navigation structure in the inland U.S. waterways are miter lock gates. The anchorage system for the gates is a primary component that connects them to the concrete wall. Failure of the anchorage system can be catastrophic and without warning. For example, in the late 1980s a failed anchorage system at Lock and Dam 14 on the Mississippi River caused unscheduled maintenance to make the lock chamber operational. A similar failure has occurred on the Illinois Waterway at LaGrange Lock and Dam. Many times the embedded anchorage is badly corroded and a sudden failure could be developing. Current inspection techniques consist of removing the surrounding concrete and inspecting the previously hidden steel. Nondestructive (NDE) techniques are needed to determine the strength and serviceability of this embedded connection. Without on-going inspection programs to detect maintenance problems when they are small, unwanted downtime will be required to solve several neglected problems. An unscheduled two-week maintenance shutdown has enormous effects on the entire transportation network, especially on river transportation.

MAINTENANCE NOW RECOGNIZED

Civil engineers are only beginning to embrace the new role of "maintainers"—they have not put their energy and money into this, yet; however, things are starting to change. While the trend is moving toward maintenance, many civil engineers are just starting to accept its role. For years the emphasis has been on the more glamorous designing and building of new highways and structures. The new emphasis on maintenance in state highway agencies can be seen in the current reorganization of the Iowa Department of Transportation (DOT). The maintenance office, which had been under the old highway division, has been elevated to a division level equal to the highway project development office, which includes design and construction for new facilities.

The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 initiated by the Federal Highway Administration was created in part to fund long-term research projects that address problems of the next century. The trend toward maintenance has been growing since the interstate system was nearing completion in the late 1970s and 1980s. The last section in Glenwood, Colorado, was completed in 1993. The 1991 ISTEA changed federal funding habits such that there is no longer any interstate funding. The federal maintenance trend has been sparked by a number of bridge collapses in the late 1970s and 1980s. The bridge inventory system was established in the late 1970s to establish an inspection and evaluation system to maintain our nation's bridges. A similar program was developed in 1984 by the USACE. The USACE established the repair, evaluation, maintenance, and rehabilitation (REMR) program to focus more attention on the deterioration rates of hydraulic and navigation structures.

A recent statement by Livingston (1993), a member of the ISTEA committee, stated that NDE is needed to monitor the condition of infrastructure. Livingston also stated that NDE priorities should be focused in the area of fractures, cracks, and corrosion as well as the causes and rates of these distresses. To keep structures fully functional and structurally...
safe, inspectors must determine the overall condition of the total system. A suitable inspection program should (1) measure the structural characteristics in situ; (2) assess the current operating or serviceability condition accurately; (3) reduce current inspection costs; and (4) require a minimum of specialized training. Nondestructive evaluation (NDE) methods can help address these problems. Use of NDE in the assessment of various components of the U.S. infrastructure has significantly increased in the past few years. There were two full sessions of infrastructure presentations (Thompson and Chimenti 1993) at a recent annual NDE conference. Just a few years ago this same conference had only a few papers related to the NDE evaluation of steel and concrete structures. Similar trends are occurring at the NDE center at Iowa State University where researchers are investigating the application of NDE techniques to civil works structures. It was reported that in many cases the appearance of a bridge can be misleading in terms of its load-carrying capabilities (Bakht and Jaeger 1990). In such cases, inspections and field testing are required to reliably evaluate the bridge.

Civil engineering structures are unique and complicated. Typically they are massive in size, interact with soil, are partially or completely submerged, are difficult to access, and contain architectural obstructions. Bakht and Jaeger reported that nearly every bridge has some behavioral aspect that can escape the attention of even experienced analysts. In addition, field inspection conditions are usually adverse. Livingston (1993) of ISTEA states: “NDE researchers many times do not realize the ‘field conditions’ that are involved in many civil works inspections.” All of these problems complicate any global inspection program.

PROCEDURE

The objective of this project was to thoroughly review the inspection techniques that are being utilized in the NDE field and evaluate their effectiveness for civil engineering structures. It was also necessary to review the general theory of several NDE techniques. NDE testing can offer assurances, in varying degrees, of the soundness of a structure or mechanical part. Many NDE techniques are used in industry and research laboratories today, but, with the current state of the art, only a few of them can be applied to civil engineering. These methods are detailed in this paper. A questionnaire was also developed and sent predominantly to state highway agencies to indicate the depth of NDE applications on public-works structures. This paper presents approximately one-third of the references and information cited in the project report (Rens et al. 1993).

AVAILABLE NDE TECHNIQUES

During the course of this study, some methods were found to be better suited for civil engineering applications. These methods—called major NDE techniques—include acoustic emission, thermal, ultrasonic, and magnetic methods, which are either proven techniques in the laboratory and field or appear very promising for application to civil works structures. In addition, these methods can be used for the global or overall monitoring of large or complicated structures.

Techniques that were determined to not be well suited for civil engineering field applications are classified as minor NDE techniques in this work. These include X-radiography, electrical techniques (e.g., electrochemical and AC impedance methods), and newer techniques that include shearography, sonar, and impulse radar. The techniques have been used in a variety of applications with varying degrees of success. Although not officially called an NDE technique by many individuals, vibration signature testing was also classified as a minor tech-

nique. With the exception of vibration signature analysis, the other minor techniques are not discussed in this paper. Refer to the project report for expanded and complete documentation on both the major and minor NE techniques, including summaries of each cited reference (Rens et al. 1993). The following sections briefly explain the theory and applications of five different NDE techniques.

ACOUSTIC EMISSION

**Introduction**

Acoustic emission (AE), which utilizes high-frequency sound waves, is an NDE testing technique that has been applied to civil engineering structures. The basic principle behind AE is that a developing flaw emits bursts of energy in the form of high-frequency sound waves. By separating background noise from AE, the ongoing condition of a structure can be monitored. Several other terms that have been used to describe this phenomena include: stress wave emission, microseismic activity, and microseismic emission (Matthews 1983). AE is a highly sensitive technique that detects microscopic events in a material. Because the events consist of elastic waves that propagate into the material, it is not necessary to focus on the exact location of the source vent to detect it; one only needs to surround the event. Thus, AE is a passive monitoring technique relying on remote sensors. This contrasts with other NDE techniques such as radiography, pulse-echo ultrasonics, or eddy current, which require 100% volumetric scanning for flaw/defect isolation. AE is therefore more efficient than these other techniques with respect to inspection time and preparation, which results in cost savings. In many applications AE is far more sensitive than other NDE techniques. Many times this sensitivity is used only to locate flaw/defect areas and the detailed sizing and classification are left to other NDE techniques.

AE testing has been used for several years. The concept was first applied to the structural monitoring of a bridge in 1939. Watchmen located in anchor houses of a suspension bridge reported that on quiet nights they could detect the sound of cable strands fracturing. Soon after this event a decision was made to recable the bridge (Hopwood 1988). In the early 1940s, the U.S. Bureau of Mines prepared a document entitled “Use of Subaudible Noise for Prediction of Rock Bursts,” which noted that the noise rate of stressed rock pillars increased as the structure became more highly loaded. These noises were later termed “rock talk” (Hopwood 1988; Scott 1991).

Kaiser published a paper in the early 1950s entitled “Results and Conclusions of Sound in Metallic Materials Under Tensile Stress” (Scott 1991). This research is generally accepted to be the beginning of acoustic emission as it is known today. Kaiser discovered an effect that bears his name and is discussed later in this section.

**Theory**

**General**

AE can be defined as a transient elastic wave generated by the rapid release of energy within a material. These emissions can come from plastic deformation such as grain boundary slip, phase transformations, and crack growth. The energy released by a single dislocation is normally too small to detect, but many dislocations are detectable by acoustic emission equipment (Kisters and Kearney 1991; Moslehy 1990). AE signals are defined by two categories: burst or distinct pulses and continuous emissions. Burst emissions are categorized as crack propagation and continuous emissions as movements or

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dislocations (Kisters and Kearney 1991). The location model theory is used to locate the position of the AE activity. These include: point location, zone isolation, and order of arrival. For example, in point location the position of the AE source can be calculated, given the location of the sensors on the structure and the sequence and arrival times of signals from various sensors. In the linear location model (point location) for flaw location (Mosley 1990), the distance of the flaw from a particular transducer can be calculated from a burst signal. These models are discussed in more detail by Scott (1991).

**Kaiser Effect**

Generating AEs usually requires that a stress be applied to the structure tested. A unique property of AE is that it has a memory known as the Kaiser effect. If a material is loaded, unloaded, and then reloaded, AEs will not be produced until the previous highest load is surpassed (Mosley 1990). This feature has very practical consequences—it can be used to detect crack propagation, such as fatigue crack growth and stress-corrosion cracking. Additional theory can be found in several other references (Jacobs et al. 1991; Matthews 1983; McIntire 1987; Scott 1991).

**Applications**

AE has been used to monitor and examine the behavior of metals, ceramics, composites, rocks, and concrete for rupture, yielding, fatigue, corrosion, stress concentration, and creep (Kisters and Kearney 1991). Additional AE applications to concrete structures include crack detection, expansion joint evaluation, in-situ stress, and fracture toughness. AE has also been used to monitor the behavior of fiber-reinforced plastic, asbestos, and mortars. Power and electric companies have used AE on aerial devices and associated equipment to determine the safety of equipment used by their personnel. Other applications include evaluating the structural integrity of cables; AE techniques have been used to determine the number of wires that break when a cable is loaded. The Federal Republic of Germany has used AE to determine the safety of earth embankments. Similar studies on earth structures and soil have been performed in the United States. All of these applications are discussed fully, along with complete documentation, in the project report (Rens et al. 1993).

There are several PhD dissertations on the subject of AE monitoring of bridges. Ghorbanoorpoor (1987) published a study on steel bridge component cracking. Ghorbanoorpoor concluded that AE monitoring could be used to monitor and detect small cracks in high-stress bridge structures. Matheson (1987) published a study on the AE of fatigue cracks in steel. He concluded that crack growth rate is only possible from AE signals that occur at peak load. The presence and location of cracks can be determined from secondary AE sources that result from crack closure, friction, and crushing of corrosion products. This phenomena was also reported by Clark (1992). Azmi (1989) published a study on the AE monitoring of bridge components and developed a model that predicts the stages of crack growth based on AE signal strength.

Several studies related to AE monitoring of steel bridges have been conducted (Ghorbanpoor and Rentmeester 1993; Gong et al. 1992; Hopwood 1988). An older study on AE for flaw detection of bridges was first published in the 1970s by the Federal Highway Administration (FHWA 1975, 1978). Gong et al. (1992) reported results from AE monitoring of 36 steel railroad bridges. The number of active cracks and the crack safety index is reported for each of the bridges. Ghorbanpoor has published recent work on the AE of bridges (Ghorbanpoor and Rentmeester 1993). Similar to his findings in his PhD dissertation, he concluded AE to be an effective tool in determining fatigue crack activities in steel bridges. Similar studies were reported at a recent conference on NDE (Prine 1993; Yen et al. 1993). Generally, all of these studies have the same scope of determining crack conditions in structural steel bridge members. A traditional field application of acoustic emission is being performed at the University of Kentucky (U.K.) (Hopwood 1988). The project team has determined AE to be a promising method for the large-scale NDE testing of structures. The research team placed several sensors on critical structural bridge members, as well as in the region of known cracks and dents. Those areas were monitored for a given period of time while the structure was stressed by normal service loads. Improved AE instrumentation helped separate mechanical noise from flaw-related noise by pattern recognition. In general, the instrumentation evaluates the data and compares three criteria to determine whether they meet pattern recognition related to crack activity. The three criteria are that (1) cracks produce many AE events over a short period of time (an event rate criteria); (2) AE events have a discrete energy level (an energy criteria); and (3) crack AE tends to come from a very localized area (location criteria). Data meeting these three parameters are designated as crack related.

The U.K. research team has field-tested these techniques on nine bridges containing varying degrees of AE activity. Potential crack-prone areas were identified and visible cracks were classified as propagating or nonpropagating cracks.

**AE Summary**

AE is applicable to civil engineering structures and bridge inspections and can be used in conjunction with other NDE techniques. Inspection methods are often complimentary. For example, visual techniques can be used to identify a problem area that can be further analyzed by AE. A quote from a recent engineering manual states "acoustic emission is presently being used to monitor crack propagation in bridges. This technique can be easily adapted to steel lock and dam structures" (Kisters and Kearney 1991).

Generation of AEs usually requires that a stress be applied to the structure. Bridge structures can be loaded manually or naturally by traffic and wind. Materials undergoing welding are stressed thermally. Miter lock gate structures are stressed by emptying and filling the lock chamber.

The Kaiser effect has very practical applications in monitoring crack growth or overstress and can compliment a structural inspection by detecting areas of overstress as well as stress concentrations around dents and cracks. Electronic data processing greatly simplifies interpretation of the results. AE equipment can detect active and propagating flaws; however, data interpretation can be difficult for complex geometrical structures.

Probably the most desirable attribute of AEs with respect to bridge or lock inspections is the ease of in-service monitoring of structural components. The overall goal of any type of bridge inspection procedure should be to avoid interrupting the flow of traffic. The AE in-service inspection capability offers this advantage. One other major advantage, especially for bridge inspections, is that the equipment is not affected by extensive rough surfaces since the transducer contact surface is small and requires minimal preparation of the structural component surface.

**THERMAL METHODS**

**Introduction**

A wide range of materials has been evaluated using infrared (IR) emissions. A recent USACE technical report states, "Large structures can be loaded cyclically and stresses can be
determined in-situ" (Kisters and Kearney 1991). Areas of localized weakness or deterioration caused by a crack or corrosion can be detected. Stress concentrations in joints or areas of high fatigue show up as "hot spots" in IR scans. The basic principal behind IR emissions is that equipment measures temperature changes caused by tension or compression on the surface of a part or structural member. Since this equipment can measure temperature changes within a few tenths of 1°C, it can be used in a variety of industrial situations and is being utilized in the field.

Thermal analysis techniques have been used for several years. The phenomenon of an elastomer material (rubber) changing temperature upon tensile stretching was first discovered in 1805 by Gough, who performed simple tests on strands of India rubber. In metallic materials, the first genuine observation of the thermoelastic effect was made by Weber who noted the frequency of a vibrating wire did not change as quickly as expected when a tensile force was applied. He reasoned that this gradual frequency change was due to a temporary change in temperature of the wire as higher stress was applied. Vibratory thermoelastic effects were studied by Tamman and Warrentrup in 1937 and by Zener in 1938 (Harwood and Cummings 1991). In 1967 Belgem compiled all the existing theories and became the first scientist to use IR radiometry to estimate the amplitudes of dynamic stresses (Stanley 1987).

In 1978, after four years of research, the British Admiralty Research Establishment developed a laboratory prototype called stress pattern analysis by thermal emission (SPATE), which further developed the relationship between stress and temperature changes. Current SPATE versions use powerful computers that allow large structural areas to be scanned (Harwood and Cummings 1991).

Theory

Stress pattern analysis using thermal emission is based on measuring the thermoelastic effect in structural materials. Compression and tension cycles (fatigue) produce heating or cooling of the solid (Kisters and Kearney 1991). Pressure in an area of a solid show up as a stressed region where heat is generated or absorbed. This is known as the thermoelastic effect, i.e., the change of temperature that accompanies elastic deformation of a body.

Thermal effects can be monitored in two ways; however, both ways involve heating the structure or specimen and measuring the flux change. Thermal effects can be obtained by physically heating the structure with lamps (until thermal equilibrium is reached) or applying stress reversals to fatigue the structure or part. In each of these methods, the change in heat can be related to stress or areas of deterioration. Thermal properties can be measured during the day or night as long as heat transfer is taking place on the structure, i.e., the surrounding environment has a different temperature from that of the part or structural system.

The advantages and disadvantages of SPATE are listed in the following section. In addition, one-dimensional and two-dimensional defect reconstruction (inverse problem) from data recorded from the thermal equipment is under study (Krapz and Cielo 1991). Further theory on thermal methods can be found in Connolly (1991) and Jacobs et al. (1991).

Applications

IR emission has been used in a variety of applications, including the inspection of air-frame structures, automotive and farm components, turbine blades, and chains; it has also been used to detect stress concentrations in welds. Stress analysts have been the major users of this equipment for designing and modifying structures to determine areas of stress and to reveal areas of overstress (Kisters and Kearney 1991). Other applications include the scanning of offshore oil-rig joints and electrical control panels to identify potential electrical problems. These applications are fully discussed in Rens et al. (1993).

An extensive field application of IR emissions on concrete structures is being performed by Greiner consultants of Baltimore, Md. (Commentary 1988). The project team has used IR scanning to inspect concrete bridge decks for debonding and delamination conditions and for determining the corrosion levels of reinforcing steel. The IR method required five days to inspect 1,000,000 sq ft of bridge deck. Based on the results of this global inspection procedure, an engineering economic analysis was performed and an optimum repair and maintenance solution was determined. This study showed that structural problems can be identified and located quickly, causing minimal disruption to traffic since the system is remote. A similar inspection technique is used in Canada (Manning and Masliwec 1990) and at the University of Wisconsin-Milwaukee (Zachar and Naik 1992).

Thermal techniques have been used to analyze steel corrosion levels. Louisiana State University has used infrared spectroscopy to identify developing rust phases and weathering characteristics of steel coupons taken from deteriorating bridge spans. Recently, the National Aeronautics and Space Administration (NASA) Langley Research Center evaluated aircraft structure corrosion and debonding by thermal techniques (Winfree et al. 1993). In this study, portable thermographic equipment was used to quantify the extent of material loss due to corrosion as well as to identify regions of debonding. As contrasted with point-source NDE techniques (eddy current, X-ray, pulse-echo ultrasound), thermal methods can be used to scan large areas. Harwood and Cummings (1991) cite the following advantages and disadvantages for thermal stress monitoring. The advantages include: fast data acquisition, minimal surface preparation, works good on complex geometries, high sensitivity, no contact needed, portable, and usable during the day or evening. The disadvantages include: high first cost, structure to be fatigued or heated for thermal activity, and only surface stress obtainable (no internal stress).

Thermal Summary

The application of thermal stress monitoring can be applied to the inspection of bridge structures. The output of a complete thermal scan usually consists of stress maps or contours that can be used to determine structure integrity. IR scanning can help monitor fatigue connections and, as indicated in Prabhu et al. (1993) and Watanabe and Shoji (1991), it can monitor differences in corrosion levels of structural steel.

Thermal stress monitoring requires no contact with the surface of the structure thus eliminating the tedious task of mounting strain gauges for measuring stress concentrations. IR emission has been used significantly in the laboratory, but because of the size of testing equipment, field applications have been rare. As with all NDE methods, microprocessing increases the cost significantly.

ULTRASOUND

Introduction

Ultrasound refers to sound that is too high pitched for the human ear to hear. Under normal circumstances, the ear can perceive sound up to 20,000 cycles per second. Because sound travels at particular speeds in any one material, the distance it has traveled can be determined by measuring the lapsed time. This distance can be quantified by taking the sound velocity times the elapsed time.

Like other NDE techniques, ultrasonic concepts have been
in existence for many years. Piezoelectricity, which is the fundamental principle behind the relationship between electricity and mechanical vibrations in transducers, was discovered by Curie in 1880. In spite of this discovery, no important use was made of it for more than 35 years (Glickstein 1960). In 1917 Langevin developed a method for detecting submarines using a piezoelectric substance mounted to the bottom of a ship (Glickstein 1960). Submarines in the area could be detected by means of echoes; this method is called echo ranging. Even greater advances in echo ranging sonar were made during the Second World War. The modern era is based on the technological developments of circuitry, transducer design, and computer advancements.

Theory

General

Two types of ultrasonic testing are available. The more traditional method is called pulse echo, while the other recently developed method is called direct-sequence, spread-spectrum, ultrasonic evaluation (DSSSUE). This new technique, which was developed at the Center for Nondestructive Evaluation (CNDE) at Iowa State University (ISU), uses a continuous-transmission technique that increases the detection sensitivity when compared to conventional pulse-echo methods. This improved sensitivity can be used to overcome the signal attenuation in large structures and to detect small changes in the structure. In the DSSSUE system, a mechanical part or structural member is "flooded" with ultrasound. Changes in aggregate properties such as volume, shape, dimension, composition, acoustic velocity, etc. are measured in one single test. In pulse-echo systems, scanning is required to get a complete acoustic signature of the part in question.

Pulse Echo

In pulse-echo systems, a wide-band pulse of acoustic energy is introduced into the test object. The pulse propagates in the material and is scattered or reflected from the various object surfaces and from inhomogeneities within the object. Because flaws such as cracks, corrosion, inclusions, and voids represent major material inhomogeneities, considerable acoustic energy is scattered or reflected back to the receiving transducer where the corresponding return signal is recorded as amplitude versus time (an A-scan). The position of a flaw can be determined by scanning the test object and recording the round-trip transit time of the pulse; i.e., the transit time and flaw location are directly related. Pulse returns from various locations can be isolated according to their respective transit times by bracketing the received signal with a time window.

DSSSUE

In the DSSSUE system (Afzal and Russell 1993; Bae and Russell 1993; Kayani et al. 1993; Russell 1993), a continuously transmitted signal of wide-band acoustic energy is used to flood the test object with ultrasound. As with pulse-echo systems, this signal also propagates in the material and is scattered or reflected from the various object surfaces and from inhomogeneities (such as flaws) within the object. However, unlike pulse-echo systems, there is no equivalent "time of arrival" or transit time concept inherent in the resulting correlation function. What the DSSSUE system really does is to measure the composite characteristic of the entire acoustic system (structure and transducers) and measure the cross-correlation functions between the various input and output transducers of the composite system. The advantage of this approach is that the cross-correlation functions represent signal natures for the test object that can be used to detect changes in object characteristics, such as volume, shape, dimension, composition, density, homogeneity, and acoustic velocity. The ability to measure the changes of so many of the properties of the structure may give the DSSSUE system a significant advantage over pulse-echo systems. For example, a fatigue crack will show up as a spike in the cross-correlation waveform that makes up the characteristic signature for the structure. When a baseline cross-correlation signature is established, a condition assessment can be made by comparing the baseline signature with one taken at a later point in time. The difference in the two signatures is a direct indication of the flaw.

Applications

Ultrasound has been used on all metals and alloys, welds, structural members, forgings, and castings (Kisters and Kearney 1991). Ultrasound has been applied to crack detection of concrete structures, thickness measurements, and corrosion detection; it has also been used to determine cracks and inclusions in welds. Recently, ultrasound has been used in the field to determine the quality of bridge welds, bridge pin integrity, and the measurement of corrosion in steel bridges. Ultrasonic techniques have also been used to detect corrosion damage in aircraft structures. For complete documentation of these applications, refer to the project report (Rens et al. 1993).

Ultrasonic Summary

Pulse-echo ultrasonic methods tend to work well for local flaw detection in both laboratory and field applications and is being extensively used by state departments of transportation to determine the extent of fatigue cracks. The DSSSUE technique looks very promising for global evaluation applications of large, complicated, structural systems.

MAGNETIC METHODS

Introduction

Magnetic methods can be used to test ferromagnetic materials such as steel bridges to determine structural parameters such as stress, strain, microstructure, and to detect flaws. Hysteresis properties such as permeability, coercivity, and remanence are known to be sensitive to stress, strain, grain size, and thermal properties. Other magnetic methods such as magnetic particle, magnetic flux, and eddy currents can be used to determine flaws such as cracks, voids, corrosion, and section loss.

Although there are several different magnetic methods, all of them fall into one of two categories: (1) flaw detection; and (2) stress detection. Flaw detection methods include magnetic particle inspection (MPI), eddy current (EC), and magnetic flux leakage (MFL) techniques. Stress detection methods include magnetic Barkhausen effect (MBE), magnetic acoustic emission (MAE), hysteresis, residual field, and magneto elastic methods (MIVC).

Theory

General

Flaw-detection techniques rely on flaws to disrupt the magnetic field, while stress-detection techniques rely on the fact that magnetic properties such as permeability, coercivity, etc., can be related to stress. The general descriptions and theory are discussed fully by Jiles (1990, 1988) and will be briefly defined in the next sections.

Stress-Detection Methods

Stress-detection methods include MBE, MAE, hysteresis, residual field, and MIVC. MBE causes discontinuous changes
in flux density, which is related to residual stress. MAE is dependent on the magnetostriction coefficient, which, in turn, depends on the applied stress. The hysteresis properties are sensitive to stress. Residual field techniques detect changes in strain while the MIVC method measures acoustic velocity, which can be related to stress.

**Flaw-Detection Methods**

Flaw detection methods include MPI, MFL, and EC. MPI uses powder to detect leaks of magnetic flux. The MFL method uses a magnetometer to detect flux change, while EC locates flaws by detecting disruptions in magnetic fields.

**Applications**

Several papers on magnetic methods discussed a variety of applications. For example, MPI techniques have been used to identify fatigue cracks in structural members, gears, pumps and shafts, heat cracks, and weld defects such as undercuttings and lack of fusion (Kisters and Kearney 1991). EC techniques have been used to monitor the condition of nuclear reactors; improved transducer design has helped in image restoration. EC responses due to rectangular flaws are also presented. Magnetic methods have been used to determine the condition of several types of ferromagnetic parts, including corrosion detection in aircraft parts. Many applications involve relating the magnetic properties to stress. Magnetic flux leakage has been used to determine the steel deterioration in concrete and to determine the condition of main cables in suspension bridges. For complete documentation of these applications, refer to the project report by Rens et al. (1993).

A portable magnetic inspection system that is adaptable to many different environments to determine fatigue and creep damage has been developed by Jiles et al. (1988). This device, called the magnoscope, has been used in the field to determine stress gradients in steel railroad bridge girders (Devine et al. 1993).

**Magnetic Summary**

Most magnetic methods have been fully laboratory tested and a few have been used in the field. The magnoscope seems to be the most promising magnetic technique for global testing in the field.

**VIBRATION ANALYSIS**

**Introduction**

Mechanical equipment and structural systems often give warning prior to breakdown. Mechanical or structural problems are almost always accompanied by an increase in vibrational levels that can be measured. The basic principal behind a vibration signature analysis lies in structural vibrations and dynamics. Collectively, these dynamic characteristics form a signature or fingerprint that will not change unless the dynamic parameters are altered. This fingerprint is fundamentally the same as the signature in the ultrasonic section. However, the frequency of vibration signature analysis is on the order of 1 MHz slower. Again, as in all NDE techniques already presented earlier, signal interpretation can be difficult.

**Theory**

The subject of structural vibrations and dynamics is well established and documented in numerous textbooks and papers. Elements that are used to describe a vibrational signature are as follows: (1) natural frequency; (2) structural damping; and (3) mode shapes. These system parameters, called the dynamic response, can be determined from frequency response plots, which can be measured directly from a vibrating structure using accelerometers (Mazurek and DeWolf 1990).

Modal analysis is a tool that has been developed over many years as a method to determine the dynamic response of a structure. To obtain the parameters, a series of tests are carried out on the structure. Accelerometers are attached to a fixed location on the structure and response data are gathered after the structure is excited. Signal processing then creates frequency response plots that are an indicator of frequency and damping. Several different response plots taken at different locations on the structure can be used to obtain mode shapes. Changes in the signatures (frequencies, damping, or mode shapes) indicate that changes such as cracks, dents, corrosion, loose bolts, or other forms of deterioration have occurred in the structure. In this respect, it is similar to the previously discussed DSUSSE method. The wavelength associated with vibration analysis is usually considerably longer than for the DSUSSE method.

**Applications**

Vibration analysis has been used to monitor and examine bearings, pumps, motors, sumps, hydraulic cylinders, shafts, and almost any moving part that will produce vibrations. For example, in gears, tooth deflection under load and tooth wear will give rise to tooth meshing frequency (Kisters and Kearney 1991). This application is of interest to the writer because many USACE sector-lock gate structures (costal structures) are driven by a bull gear and roller rack. Other applications include condition monitoring of rotating machinery where vibrational trends are measured at random times to help schedule appropriate maintenance activity (Renwick 1984). European practice has used dynamic response to help determine void areas under concrete slabs (Armstrong et al., unpublished paper, 1990). Vibrational signature analysis has been applied in offshore platforms by observing changes in structural dynamic parameters (Rubin 1988). The most extensive laboratory/field application of vibration signature analysis is being performed at the University of Connecticut (Mazurek and DeWolf 1990). The project team has concluded that an ongoing vibration signature monitoring program is effective in determining structural degradation. The University of Connecticut research team used a small-scale laboratory bridge model and placed accelerometers along the bridge spans. Mock vehicles were driven over the bridge and a series of tests were performed. First, verification tests were performed to compare modal analysis techniques to other vibration analysis techniques. These tests correlated well with modal analysis. Second, before vibration signature analysis to detect structural degradation could be performed, the effects of normal operating conditions had to be accounted for. Tests were performed to see how vehicle velocity, roadway roughness, and vehicle mass affect structural dynamics parameters. The results of these tests show modal parameters to be consistent with the baseline verification study case, with the exception of modal amplitudes in regard to vehicle mass. The mass of the vehicle affected the vibration level more than expected.

The most valuable application of the University of Connecticut laboratory bridge model was the evaluation of structural degradation and how it affects the vibration signature. Two structural failures were considered: support failure and crack propagation. The bridge model consisted of a double-girder, two-span bridge with three support locations. Each support location had two pins, one on each side of the road. One of the pins was loosened from the center support, the structure was excited, and modal analysis performed. The response spectra showed a significant mode shape change near the released support location. A crack was introduced in one of the two girders at the point of maximum bending moment. The
crack was developed in three stages, reducing the bending moment of inertia to amounts of 81, 68, and 67% of the original cross section. The structure was excited for each different cross section and modal analysis was performed. As in the support removal experiment, the response spectra showed a significant mode shape change near the crack location. The deviation increased for each crack increment.

The University of Connecticut research team has conducted full-scale experiments with results similar to those of the laboratory results. Collectively, the results of this research indicate that the concept of an automated vibration monitoring system is feasible.

**Vibration Summary**

Vibration signature analysis has applications in civil engineering and specifically the REMR lock and dam inspection and rating program. A wide range of equipment is available to measure vibrations. A single frequency band meter yields a simple vibrational reading. Narrow band meters can provide a hard copy of the measured spectra in any parameter (acceleration, velocity, or displacement) (Kisters and Kearney 1991). An inspector can make maintenance decisions and schedule replacement or repair based on the response spectra.

**QUESTIONNAIRE RESULTS**

This section presents the results of an investigation that was undertaken to determine the current NDE trends in civil and construction engineering within the transportation industry (Rens et al. 1993). The investigation involved a survey of various transportation agencies of NDE applications in the civil engineering field. This section contains a portion of the information obtained from questionnaires sent to agencies in the United States as well as to international agencies. The questionnaire form can be found in Rens et al. (1993). Of the 58 questionnaires sent to U.S. agencies, 50 were sent to state departments of transportation (DOTs) and eight to industry. The DOTs returned 94% of the questionnaires while the industry returned 63%. The overall return rate was approximately 90%. The results of the NDE technique survey are summarized in Table 1. All 38 international questionnaires were sent to public-works organizations. Four agencies (10%) responded and the limited results by NDE technique are summarized in Table 2.

**U.S. QUESTIONNAIRE SUMMARY**

Of the 37 responses pertaining to ultrasonic testing (UT), local investigation of pin and hanger assemblies in bridges, castings, welds, bolts, and corrosion thickness are currently being performed. In addition, some agencies use portable ultrasonic testers operated by NDE engineers to determine the extent of corrosion or cracking where potential problems were noted during visual inspections by technicians. One response also indicated use of ultrasound to find flaws in concrete. Table 3 summarizes the ultrasonic applications. According to Table 4, 37 ultrasonic responses include some sort of formal training.

Of the 21 responses related to magnetic testing (MT), a significant amount of magnetic particle testing is used to aid visual inspections. Applications include checking for internal or surface flaws either in structural steel members or in welds. Table 5 shows the applications associated with magnetic testing. Magnaflux and yoke probes appear to be the most widely used magnetic particle devices. Note that EC testing is also a magnetic technique; however, it was a separate category on the questionnaire. According to Table 6, approximately 50% of the responses have some sort of formal training.

Five responses indicate that they contract out large-scale

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**TABLE 1. U.S. Responses by Testing Method**

<table>
<thead>
<tr>
<th>Method</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasonic testing (UT)</td>
<td>37</td>
</tr>
<tr>
<td>Magnetic testing (MT)</td>
<td>21</td>
</tr>
<tr>
<td>Voltmeter (VM)</td>
<td>4</td>
</tr>
<tr>
<td>Rebar locator (RL)</td>
<td>6</td>
</tr>
<tr>
<td>Schmidt hammer (SH)</td>
<td>6</td>
</tr>
<tr>
<td>Dye penetrant (DP)</td>
<td>13</td>
</tr>
<tr>
<td>Radiographic testing (XR)</td>
<td>6</td>
</tr>
<tr>
<td>Eddy-current testing (ET)</td>
<td>6</td>
</tr>
<tr>
<td>Contract out NDE work (C)</td>
<td>6</td>
</tr>
<tr>
<td>Do not use NDE techniques (N)</td>
<td>5</td>
</tr>
<tr>
<td>Other (O)</td>
<td>7</td>
</tr>
</tbody>
</table>

**TABLE 2. International Responses by Testing Method**

<table>
<thead>
<tr>
<th>Method</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasonic testing (UT)</td>
<td>0</td>
</tr>
<tr>
<td>Magnetic testing (MT)</td>
<td>0</td>
</tr>
<tr>
<td>Voltmeter (VM)</td>
<td>0</td>
</tr>
<tr>
<td>Rebar locator (RL)</td>
<td>3</td>
</tr>
<tr>
<td>Schmidt hammer (SH)</td>
<td>1</td>
</tr>
<tr>
<td>Dye penetrant (DP)</td>
<td>0</td>
</tr>
<tr>
<td>Radiographic testing (XR)</td>
<td>0</td>
</tr>
<tr>
<td>Eddy-current testing (ET)</td>
<td>1</td>
</tr>
<tr>
<td>Contract out NDE work (C)</td>
<td>0</td>
</tr>
<tr>
<td>Do not use NDE techniques (N)</td>
<td>0</td>
</tr>
<tr>
<td>Other (O)</td>
<td>1</td>
</tr>
<tr>
<td>Fiber scope</td>
<td>1</td>
</tr>
<tr>
<td>Pin hole (permeability)</td>
<td>1</td>
</tr>
</tbody>
</table>

**TABLE 3. UT Applications in the United States**

<table>
<thead>
<tr>
<th>Application</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>9</td>
</tr>
<tr>
<td>Internal flaws</td>
<td>16</td>
</tr>
<tr>
<td>Pin</td>
<td>4</td>
</tr>
<tr>
<td>Anchor bolts</td>
<td>4</td>
</tr>
<tr>
<td>Welds</td>
<td>15</td>
</tr>
<tr>
<td>Pin and hanger</td>
<td>5</td>
</tr>
</tbody>
</table>

**TABLE 4. UT Training in the United States**

<table>
<thead>
<tr>
<th>Type</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASNT level I</td>
<td>6</td>
</tr>
<tr>
<td>ASNT level II</td>
<td>15</td>
</tr>
<tr>
<td>Formal training required</td>
<td>14</td>
</tr>
<tr>
<td>BS and level II</td>
<td>1</td>
</tr>
<tr>
<td>Technical school</td>
<td>1</td>
</tr>
</tbody>
</table>

**TABLE 5. MT Applications in the United States**

<table>
<thead>
<tr>
<th>Application</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface flaw</td>
<td>8</td>
</tr>
<tr>
<td>Subsurface flaw</td>
<td>10</td>
</tr>
<tr>
<td>Welds</td>
<td>6</td>
</tr>
</tbody>
</table>

**TABLE 6. MT Training in the United States**

<table>
<thead>
<tr>
<th>Type</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level II</td>
<td>3</td>
</tr>
<tr>
<td>None or on the job</td>
<td>7</td>
</tr>
<tr>
<td>Formal training required</td>
<td>7</td>
</tr>
</tbody>
</table>
NDE testing. Several agencies use local NDE techniques (UT, MT, DP), but contract out large or complicated jobs. It is suspected that those who indicate that they "currently do not use NDE techniques" actually contract out their NDE work (most likely for AE testing). For example, Wisconsin DOT indicated that it doesn't use NDE techniques; however, the literature showed that significant AE testing had been performed there.

Two DOT response indicated that X-ray NDE is being used. One was used during in-house fabrication of steel beams for weld condition determination. The other used radiography during construction to also determine weld condition. One DOT had recently stopped radiography testing because of the strict regulations that were adopted in 1991. One industrial response indicated that X-rays were used to assist in any questionable NDE evaluations made at the plant. Three other industrial firms use X-ray NDE techniques. Die penetrants (13 responses) are used widely to enhance visual inspections. Apparently, liquid die penetrant testing is also a widely used NDT technique.

INTERNATIONAL QUESTIONNAIRE SUMMARY

Because only four agencies responded to the questionnaire, it is difficult to judge which methods are preferred. However, given that masonry and concrete structures seem to be the predominant building materials, techniques suited to concrete and masonry will probably prevail. The reported methods included: rebar locators, pin-hole permeability devices, fiber-optic scopes, EC, Schmidt hammers, and optical/camera devices.

SUMMARY

A review of current major NDE techniques applicable to large-scale, civil engineering structures has been presented. The literature reveals that AE testing is the most widely used state-of-the-art technique for monitoring conditions of bridges and other large or complicated structures. This method was developed from extensive laboratory and field testing in the mid-1970s to mid-1980s and is currently in the application stage. Thermal techniques have been applied to several civil engineering projects—primarily asphalt and concrete pavement condition assessments. Similar to AE testing, thermal methods are making the transition from the research phase to the application phase. Although magnetic methods have been extensively tested in the laboratory, the field testing of these methods is only just beginning. More than likely, the applications of magnetic methods for field monitoring of civil engineering structures is years away. The new ultrasonic technique, DSSUE, has been developed recently. This technique has the potential to become an effective global monitoring technique for civil engineering applications; however, it is still in the developmental stage. Vibration signature analysis is also a widely used technique from a research perspective. The general consensus being that one has to lose a girder in order to see a signature change. Other techniques, such as pulse-echo ultrasonic, electronic, and radiographic, are effective for local investigations.

An NDE questionnaire was developed and sent to 58 organizations within the United States and 38 organizations within the international community; 90% of the United States organizations responded. Results from this questionnaire indicate that pulse-echo ultrasound and magnetic particle testing methods are widely used by public agencies. Liquid die-penetrant testing is also a popular method. Most large-scale NDE testing is contracted out; based on responses to the questionnaire, AE testing of state bridges is being done mostly by consultants. The literature suggests AE testing to be an application-oriented technique and suitable to field investigations. The questionnaire was distributed mostly to state agencies—those responsible for inspecting and maintaining public infrastructure. Further work is recommended in the area of ultrasonic condition assessment.

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APPENDIX. REFERENCES


