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Chapter 15
Advanced Inspection Methods

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Chapter 15
Advanced Inspection Methods

Topic 15.1 Timber

15.1.1 Introduction

Advanced inspection methods give inspectors the ability to further evaluate suspected defects found during a visual inspection. They can also be used to perform inspections on members that are not accessible. Advanced inspection methods usually require calibrated testing equipment, a professionally trained technician to perform the testing, and a professional that has expertise in interpreting the advanced inspection results. However, it is beneficial to have an understanding of the various advanced inspection methods.

There are two main classifications of advanced inspection methods. The first is labeled nondestructive testing or evaluation (NDT or NDE). This classification pertains to advanced inspection methods that do not impair the usefulness of the member being tested. Other testing, the second main classification, covers advanced inspection methods that affect or destroy the structural integrity of the member being tested.

New technology is making the use of these highly technical systems economically feasible for bridge inspection. From this fact, advanced inspection methods are becoming more popular for the routine inspection of bridge members. Current and future studies have been focusing directly on relating results from advanced inspection methods into Bridge Management Systems ratings.

This Topic describes the different types of nondestructive and other test methods for timber bridge members and the general methods for each.

15.1.2 Nondestructive Testing Methods

Sonic Testing

A Sonic Testing device is used to detect decay or other low density regions in timber members. Starting about six inches below the ground line, probes are pressed on opposite sides of the timber member. A trigger trips a hammer that sends a sound wave down one probe, through the member, and up the other probe to a dial (see Figure 15.1.1).

Figure 15.1.1 Sonic Testing Equipment

This method eliminates the need for making holes in timber members. Members testing positive for decay are then drilled or cored to determine the detailed nature of the deficiency. A dial reading that is low, compared with that of a good member of similar diameter, indicates decay or another low density region that delayed the sound wave within the member. However, it is a good idea to take several readings on the member since the readings are nearly instantaneous, and the Sonic Testing equipment needs to be checked frequently for proper calibration.

Used by trained personnel, Sonic Testing works well with Douglas fir and western red cedar. However, it does not work as well with southern pine members because of the high incidence of ring shakes.

Spectral Analysis

Spectral Analysis, sometimes called stress wave, uses sonic waves to produce stress waves in a timber member. The stress waves are then used to locate decay in timber members. The stress waves travel through the timber member and reflect off the timber surface, any flaws, or joints between adjacent members at the speed of sound. It is known that stress waves travel slower in decayed members than in sound members. If the member's dimensions are known, the amount of time it takes for a stress wave to travel the known distance can indicate that deficiencies are evident due to longer stress wave timings.

Stress waves are also used to determine the in-situ strength of timber members. Sound timber members transmit waves at higher velocity than decayed wood. The velocity of the stress wave can be calculated by obtaining time of flight readings over a set length. The velocity can be converted in to a dynamic modulus of elasticity, which in turn, allows properly trained personnel to estimate the strength properties of the wood.

First, a stress wave is induced by striking the specimen with an impact device that is instrumented with an accelerometer that emits a start signal to a timer. A second accelerometer, which is held in contact with the other side of the specimen, serves to detect the leading edge of the propagating stress wave and sends a stop signal to the timer. The elapsed time for the stress wave to propagate between the accelerometers is displayed on the timer.

The use of stress wave velocity to detect wood decay in timber bridges and other structures is limited only by access to the structural members under consideration. It is especially useful on thick timbers or glulam timbers where hammer sounding is not effective. Note that access to both sides of the timber member is required.

The transmission time is affected by such properties as growth ring orientation, decay, moisture content, and preservative treatment.

Figure 15.1.2 Stress Wave Timer

Ultrasonic Testing

Ultrasonic testing (UT) consists of high frequency sound waves introduced by a sending transducer. Discontinuities in the specimen interrupt the sound wave and deflect it toward a receiving transducer. The magnitude of the return signal allows a measurement of the flaw size. The distance from the transducer to the flaw can be estimated from the known properties of the sound wave and of the material being tested. Ultrasonic testing can be used to detect cracks, internal flaws, discontinuities, and sub-surface damage (see Figure 15.1.3).

Figure 15.1.3 Ultrasonic Testing Equipment

In timber bridge members, ultrasonic testing can be used to determine the in-place strength of timber bridge members, both above and below water. The load-carrying capacity of the member is correlated to the member's wave velocity normal to the grain and to its in-place unit weight.

Vibration

A newer type of nondestructive testing that can determine the condition of timber bridge members deals with the use of vibrations (see Figure 15.1.4). This nondestructive evaluation method is based on the philosophy that sound timber members vibrate at a certain frequency. While testing a timber member, if the member vibrates at a different frequency than the established theoretical frequency, the member may have deterioration present. Vibratory testing methods in timber members are basically used to determine the member's modulus of elasticity. From this, other properties of the timber member can be established.

Figure 15.1.4 Vibration Testing Equipment

15.1.3 Other Testing Methods

Boring or Drilling

While drilling and coring are the most common methods for detecting internal deterioration in bridges, boring is seen as the most dependable and widely used method for detecting internal decay in timber. Drilling and coring are used to detect the presence of voids and to determine the thickness of the residual shell when voids are present. Boring permits direct examination of an actual sample from a questionable member. A timber boring tool is used to extract wood cores for examination (see Figure 15.1.5).

Figure 15.1.5 Timber Boring Tool

Drilling is performed using a rechargeable drill or a brace and bit. An abrupt decrease in drilling resistance indicates either decay or a void. However, wet wood and natural voids can falsely suggest decay. Decay can be based on how the auger type drill bit pulls its way through the wood or on measuring the torque resistance on the bit as it penetrates the wood. Drilling is usually done with a power drill or hand-crank drill equipped with a 3/8 inch to 3/4 inch diameter bit. If decay is detected, the inspection hole can be used to add remedial treatments to the wood. While samples are generally not attainable, observation of the wood particles removed during the drilling process can provide valuable information about the member. The depth of preservative penetration, if any, can be determined, and regions of discolored wood may indicate decay.

Coring with timber boring tools also provides information on the presence of decay pockets and other voids, and coring produces a solid wood core that can be carefully examined for evidence of decay. The use of increment cores for assessing the presence and damage due to bacterial and fungal decay requires special care. Cleaning of the timber boring tools is necessary after each core extraction to eliminate transfer of organisms. There are several cleaning agents available to clean the timber boring tools or drill bits that work well. Core samples that do not show visible signs of decay can be cultured to detect the presence of potential decay hazards. Many laboratories can provide this service. Core samples are more commonly used to detect the presence of internal decay pockets and to measure the depth of preservative penetration and retention. Culturing provides a simple method for assessing the potential decay hazard and many laboratories provide routine culturing services. Because of the wide variety of fungi near the surface, culturing is not practical for assessing the hazard of external decay.

A decay detection device is a newer drilling and logging tool. It operates upon the principle that a drill moving through sound wood encounters more resistance than a drill moving through decayed, and/or soft wood. It records the resistance, using a pen, paper, and rotary drum arrangement so that a permanent graphic record of the test is generated. Sound wood produces a series of near vertical markings on the record, however, when decayed wood is encountered, the resistance drops and the markings assume a more horizontal or diagonal pattern. By studying the resulting record, an experienced operator can determine if decay exists and can estimate the approximate location and size of the decayed area (see Figure 15.1.6).

Figure 15.1.6 Inspector Using Decay Detection Device

Bore holes can provide an entrance for bacterial and fungal decay to gain access to the member. Inspection methods that destroy or remove a portion of the wood, splinters, probe holes, and borings may become avenues for decay entry if not properly treated at the conclusion of the inspection. As such, the holes need to be treated with a preservative and plugged after testing. Failure to properly treat the wood may result in accelerated decay development or deterioration in the structure.

Moisture Content

Moisture meters can be used to determine moisture content in a timber member (see Figure 15.1.7). Moisture contents exceeding 20% indicate the condition of the wood is conducive to decay. As a sliding hammer drives two electrodes into the wood, a ruler emerging from the top of the hammer measures the depth. These electrodes can measure moisture content to a depth of approximately 2 1/2 inches. Because the high moisture content of decaying wood causes steeper than normal moisture gradients, the meter is useful for determining the extent of decay.

Figure 15.1.7 Moisture Content Equipment

Probing

Probing consists of inserting a pointed tool, such as an ice pick, into the wood and comparing its resistance with that of sound wood. Lack of resistance or excessive softness to probe penetration may reveal the presence of decay. Two forms of probing are a pick test and a shell-thickness indicator.

A pick test consists of removing a small piece of wood with a pick or pocketknife (see Figure 15.1.8). If the wood splinters, it is probably sound wood, and if it breaks abruptly, it is probably decayed wood. Since the pick test only removes a small portion of the timber member, it may be considered a physical testing method. See Topic 6.1.7 for more information.

Figure 15.1.8 Pick Test: Sound Wood, Decayed Wood

A shell-thickness indicator is a thin, metal, hooked rod used to determine the thickness of solid, but not necessarily sound, wood. The rod is inserted into a hole made by coring or drilling and is then pulled back with pressure against the side of the hole. The hook easily attaches to the edge of a decay pocket, making it possible to determine the depth of the decay and the solid wood.

Field Ohmmeter

The field ohmmeter measures electrical resistance to detect decay in timber members (see Figure 15.1.9). It is best used in wood with a moisture content of at least 27 percent, a value indicative of decaying wood. A probe is used consisting of two twisted, insulated wires with the insulation removed near the tip. This probe is inserted to various depths into a hole with a diameter of 3/32 of an inch. If the electrical resistance changes as the probe goes deeper, this indicates decay or a defect.

While this device effectively detects decay, it can also produce misleading readings on sound timber. Consequently, drilling or coring needs to be done on suspect members to verify results. Like sonic testing, the field ohmmeter needs to be recalibrated frequently.

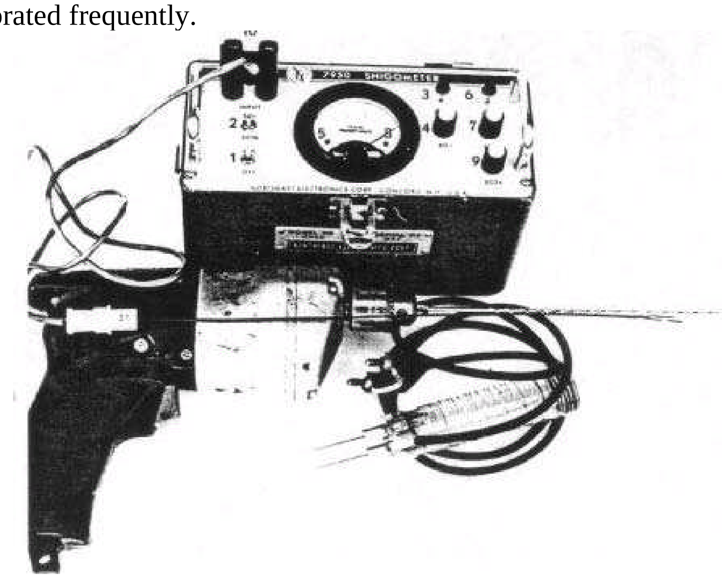

Figure 15.1.9 Field Ohmmeter Equipment

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Advanced Inspection Methods

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Topic 15.2 Concrete

15.2.1 Introduction

Advanced inspection methods give inspectors the ability to further evaluate suspected deficiencies found during a visual inspection. They can also be used to perform inspections on members that are not accessible. Advanced inspection methods usually require calibrated testing equipment, a professionally trained technician to perform the testing and a professional that has expertise in interpreting the advanced inspection results. Bridge inspectors need to have an understanding of the various advanced inspection methods.

There are two main classifications of advanced inspection methods. The first is labeled nondestructive testing or evaluation (NDT or NDE). This classification pertains to advanced inspection methods that do not impair the usefulness of the member being tested. Other testing, the second main classification, covers advanced inspection methods that may affect the structural integrity of the member being tested.

New technology is making the use of these highly technical systems more economically feasible for bridge inspection. From this fact, advanced inspection methods are becoming more popular for supplementing visual inspection methods predominately used for routine inspection of bridge members. Current studies have been focusing directly on relating results from advanced inspection methods into Bridge Management Systems ratings.

This Topic describes the different types of nondestructive and other test methods for concrete bridge members and the general methods for each.

15.2.2 Nondestructive Testing Methods

Acoustic Wave Sonic/Ultrasonic Velocity Measurements

An evaluation of concrete decks can be accomplished with sonic or ultrasonic acoustic wave velocity measurements. This method delineates areas of internal cracking (including delaminations) and deteriorated concrete, including the estimation of strength and elastic modulus. A mobile automated data acquisition device with an impact energy source and multiple sensors is the principle part of a computer-based monitoring and recording system for detailed evaluation of bridge decks. Bridge abutments and concrete support members are tested using the same recording system with a portable, hand-held sensor array (see Figure 15.2.1 and 15.2.2). The system works directly on either bare concrete or through wearing surfaces such as asphalt. It can distinguish between debonded asphalt and delaminations, and it is effective for a detailed evaluation of large areas.

Figure 15.2.1 Portable Hand Held Sonic/Ultrasonic Testing Sensor Array System

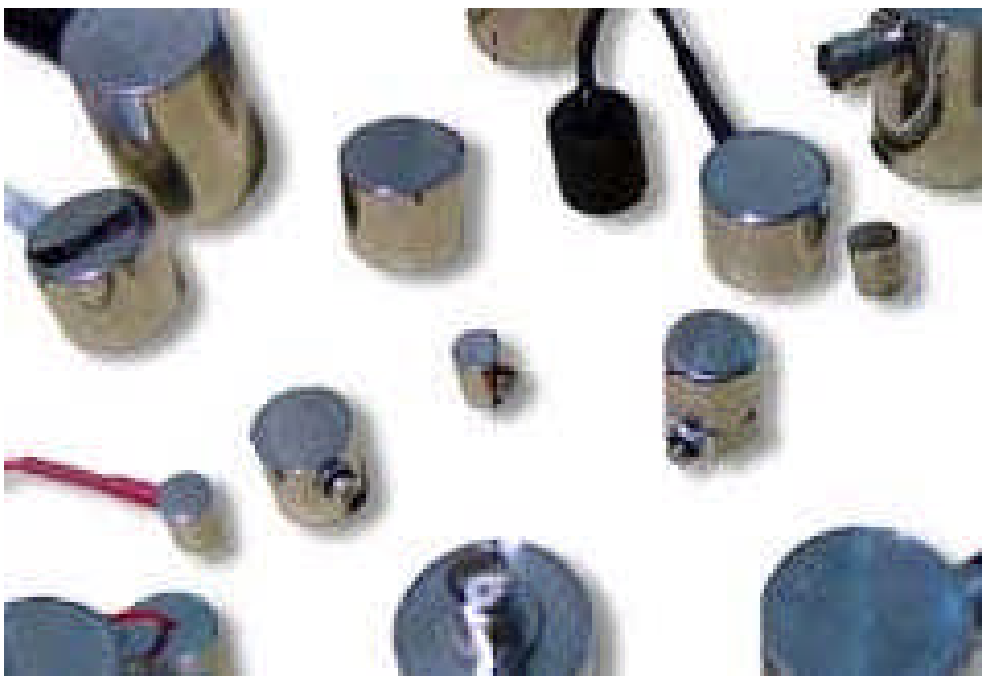

Figure 15.2.2 Acoustic Emission Sensors

Electrical Methods

Half-cell potentials are used to evaluate the corrosion activity of reinforcing steel embedded in concrete (See Figure 15.2.3). Commonly known as CSE (Copper Sulfate Electrode) tests, reinforcing bar networks are physically accessed and wired for current detection. Half-cell electrical potentials of reinforcing steel are measured by moving the CSE about the concrete surface. As the CSE contacts concrete over an actively corroding rebar, voltage is registered. Measured potential values reflect levels of corrosion activity in the rebar. Higher potential measurements indicate corrosion activity. This kind of survey can be used to determine core sample locations.

Figure 15.2.3 Half-Cell Potential

Delamination Detection Machinery

Delamination detection machinery is based on sonic responses and can be used to inspect concrete decks (see Figure 15.2.4). The portable electronic instrument consists of three components: a tapping device, a sonic receiver, and a signal interpreter. The instrument is moved across the deck as acoustic signals are passed through the deck. These signals are then received and electronically interpreted, and the output is used to generate a plan of the deck showing delaminated areas. This method can be used on concrete decks with asphalt covered surfaces, although accuracy decreases.

Figure 15.2.4 Delamination Detection Machinery

Ground-Penetrating Radar

Ground-Penetrating Radar (GPR) is a geophysical method that uses high-frequency pulsed electromagnetic waves to acquire subsurface information. An important benefit of this method is the ability to measure the thickness of asphalt covering. It can also be used to examine the condition of the top flange of box beams that may otherwise be inaccessible.

An electromagnetic wave is radiated from a transmitting antenna, and travels through the material at a velocity which is determined primarily by the electrical properties of the material. The wave spreads out and travels downward; however, materials with different electrical properties can alter its path. Upon encountering a buried object or boundary with different electrical properties, part of the wave energy is reflected or scattered back to the surface while part of its energy continues its downward path. The wave that is reflected back to the surface is captured by a receiving antenna, and recorded on a digital storage device for later interpretation (see Figure 15.2.5). The most common display of GPR data is one showing signal versus amplitude, and is referred to as a trace. A single GPR trace consists of the transmitted energy pulse followed by pulses that are received from reflecting objects or layers.

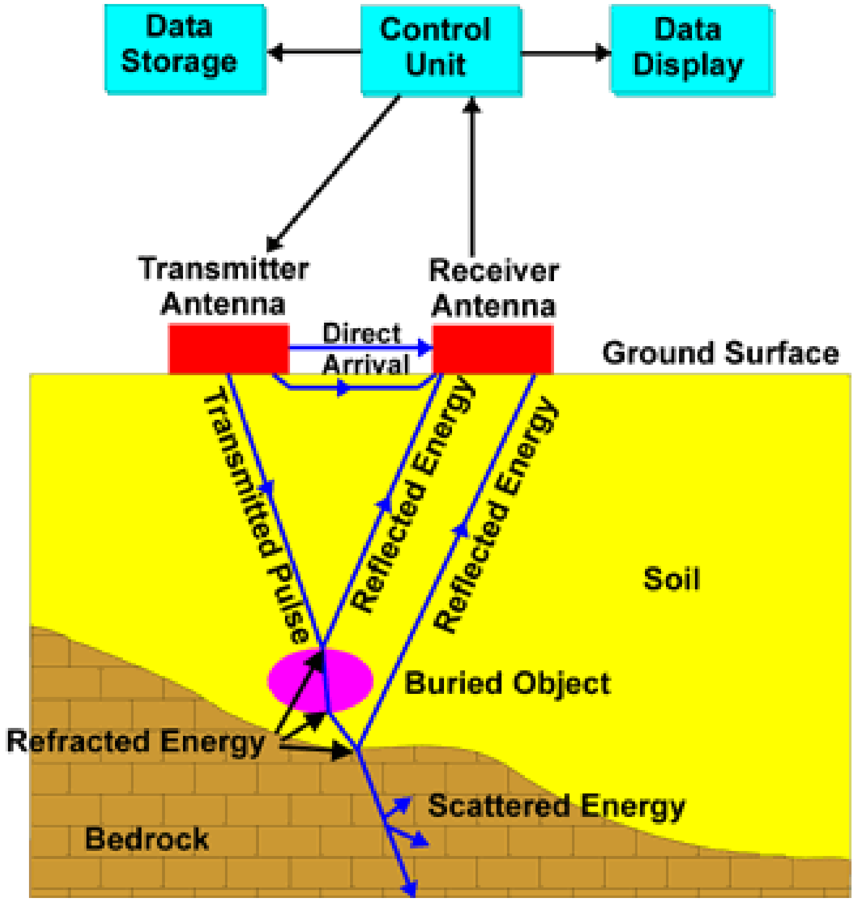

Figure 15.2.*5* Schematic of Ground-Penetrating Radar

GPR is used to map geologic conditions that include depth to bedrock, depth to the water table, depth and thickness of soil and sediment strata on land and under fresh water bodies, and the location of subsurface cavities and fractures in bedrock.

Other applications include the detection of delaminations and flaws in reinforced concrete bridge elements; location of post-tensioning ducts in prestressed concrete elements; location of objects such as pipes, drums, tanks, cables, and boulders; mapping landfill and trench boundaries; mapping contaminants; and conducting archeological investigations. GPR has been used for concrete bridge element and tunnel lining inspections.

Ground Penetrating Radar for Bridge Decks

Ground penetrating radar (GPR) technology is nearing full acceptance as a method to assess the condition of bridge decks, in particular, delaminations between concrete and rebar.

Importantly, GPR is an NDE technology, as opposed to cutting core samples from concrete decks. It can provide information on asset condition that can be used to plan and execute effective and efficient repair programs. The principal issue with GPR technology is slow rate of data capture when the depth of evaluation is more than approximately 3 inches.

Electromagnetic Methods

Advancements in ground penetrating radar have led to the development of the High Speed Electromagnetic Roadway Measurement and Evaluation System (HERMES) Bridge Inspector. This system was built by the Lawrence Livermore National Library to detect delaminations in concrete decks caused by reinforcement corrosion. The HERMES Bridge Inspector sends high frequency electromagnetic pulses from sixty-four radar antennas into a bridge deck while travelling over the structure. The device is set up in a trailer mounted towing vehicle and is made up of a computer workstation, storage device, survey wheel, control electronics, and the sixty-four antenna modules or transceivers (see Figures 15.2.6 and 15.2.7). The system can inspect up to a 6 foot 3 inch width at a time with maximum speeds of up to sixty miles per hour. At speeds of around twenty miles per hour, the system can sample the concrete deck every 9/16 inch in the direction of travel. Output information can be reconstructed to show cross-sections of the deck being inspected. The depth of penetration depends on time and the material type. An 11-13/16 inch penetration in concrete can be accomplished in about six nanoseconds.

Figure 15.2.6 The HERMES Bridge Inspector (Outside)

Figure 15.2.7 The HERMES Bridge Inspector (Inside)

Pulse Velocity

Pulse velocity methods are used to evaluate relative quality of concrete and estimate compressive strength. The pulses pass through the concrete and the transit time is then measured. The pulse velocity is then interpreted to evaluate the quality of the concrete and to estimate in-place concrete compressive strength.

This equipment analyzes concrete in decks by measuring velocity of sound waves. Some equipment generates sound waves by shooting BB's on to the deck. The time for the waves to return depends on the integrity of the concrete.

Flat Jack Testing

The flat jack method was originally developed to test the in situ stress and deformation of rock and is now being applied to masonry structures. A portion of the horizontal mortar joint is removed, and the flat jack (an envelope made of metal) is inserted and pressurized to determine the state of stress. For deformation testing, two flat jacks are inserted, one directly above the other and separated by five or six courses.

Impact-Echo Testing

Sound wave reflection is a method for nondestructive evaluation of concrete and masonry, based on the use of impact-generated stress (sound) waves that propagate through the structure and are reflected by internal flaws and external surfaces.

This method can be used to determine the location and extent of flaws such as cracks, delaminations, voids, honeycombing and debonding in plain, reinforced and post-tensioned concrete structures. It can locate voids in the subgrade directly beneath slabs and pavements. It can be used to determine member thickness or locate cracks, voids and other defects in masonry structures where the brick or block units are bonded together with mortar. This method is not adversely affected by the presence of steel reinforcing bars.

A short-duration mechanical impact, produced by tapping a small steel sphere against a concrete or masonry surface, produces low-frequency stress waves that propagate into the structure and are reflected by flaws and/or external surfaces (see

Figure 15.2.8). The wavelengths of these stress waves propagate through concrete almost as though it were a homogeneous elastic medium. Multiple reflections of these waves within the structure excite local modes of vibration, and the resulting surface displacements are recorded by a transducer located adjacent to the impact. The piezoelectric crystal in the transducer produces a voltage proportional to displacement, and the resulting voltage-time signal (called a waveform) is digitized and transferred to a computer, where it is transformed mathematically in to a spectrum of amplitude vs. frequency. Both the waveform and spectrum are plotted on the computer screen. The dominant frequencies, which appear as peaks in the spectrum, are associated with multiple reflections of stress waves within the structure, or with flexural vibrations in thin or delaminated layers.

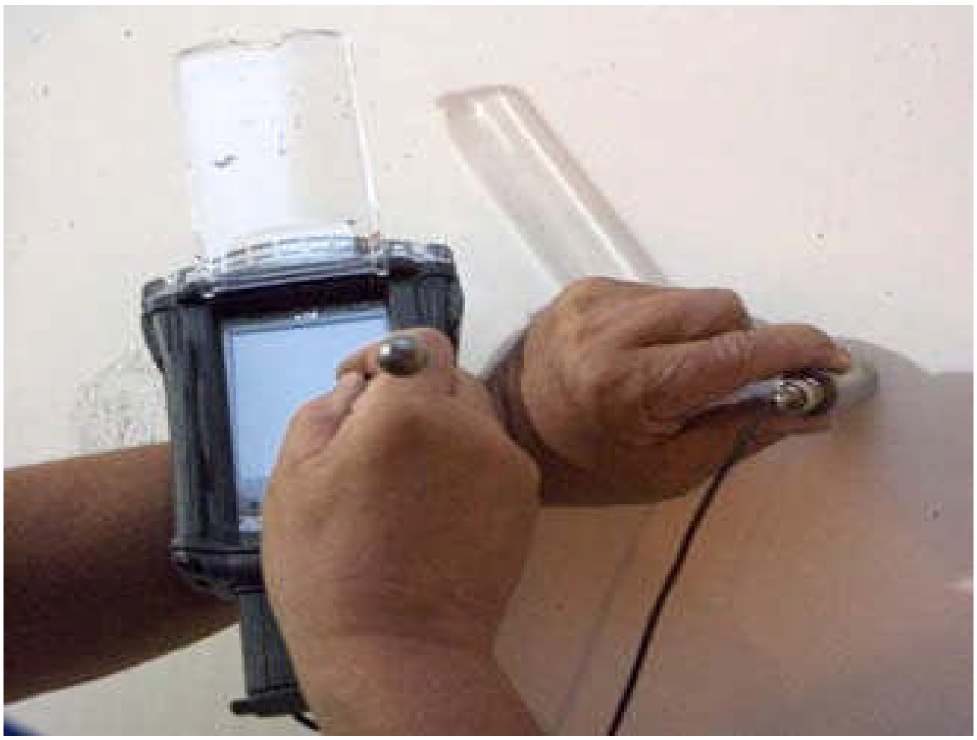

Figure 15.2.8 Impact-Echo Testing Equipment

Infrared Thermography

NDE inspection using thermography is based on imaging surface temperatures of a specimen in order to infer subsurface delaminations or defects (see Figure 15.2.10). The basic theory is that heat conduction through a material is altered if a delamination is present (see Figure 15.2.11). In this example the temperature of the deck is greater than the surrounding air. With no internal defect, heat flow through the deck is relatively uniform. An image of the surface temperature of the deck then produces an image that is relatively uniform. If a delamination is now present inside the specimen, the heat flow is altered. In this example, the surface of the deck above the delamination appears to be higher in temperature than the remainder of the deck. The rest of the deck that is not delaminated appears cooler than the delaminated area (see Figure 15.2.9).

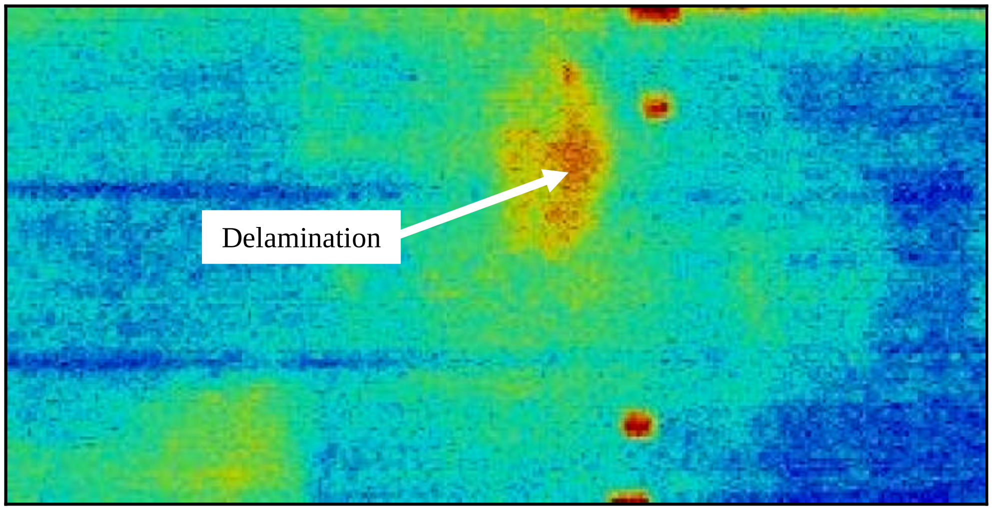

Figure 15.2.9 Deck with Area of Delamination (Warmer Colors)

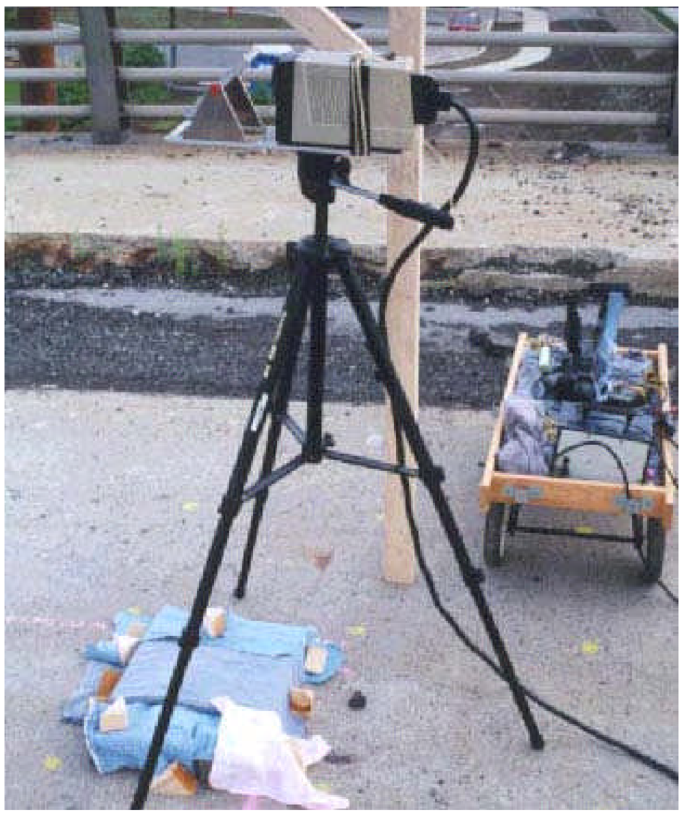

Figure 15.2.10 Infrared Thermography Testing Equipment

Thermographic measurements are complicated by a number of issues. Probably the most significant is that a thermal camera does not directly measure the temperature of a specimen. The camera measures radiant flux that needs to be converted to temperature. The measured radiant flux is not only a function of the surface temperature, but is a function of the emissivity of the specimen. Emissivity is a material property that describes how well an object emits or absorbs energy. Two objects at the same temperature but with different emissivities appear as different intensities in an infrared image. Shadows or other uneven heating of a specimen are also a concern. Other environmental factors, such as water, snow, or ice on a specimen, alter results as well. Also, the method is sensitive to material property differences on the specimen surface. Surface defects, such as oil stains, water, and skid marks, show up in the infrared data.

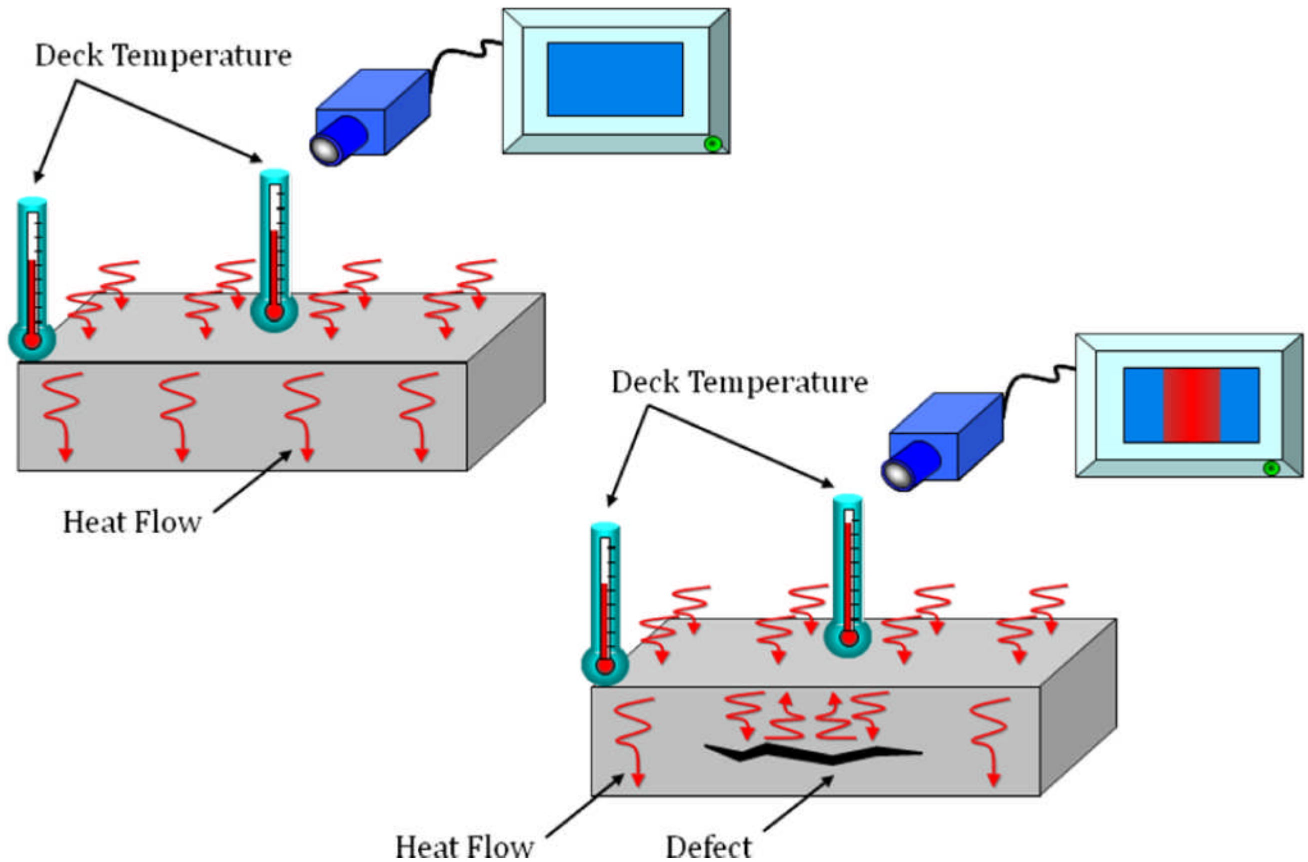

Figure 15.2.11 Schematic of Thermal Imaging

Laser Ultrasonic Testing

Laser ultrasonic testing provides information about flaws in concrete and about the position of steel reinforcement bars, which cannot be obtained with the non-laser ultrasonic testing described in this Subtopic. Laser-generated acoustic wave measurements with high stress amplitudes provide information about the quality of the concrete at various depths from the surface. Reinforcing steel does not cause misleading results in laser ultrasonic testing as it does in non-laser ultrasonic testing.

Magnetic Field Disturbance

Advanced inspection methods have been developed that can evaluate fatigue damage to steel reinforcement in concrete members. The device is known as the magnetic field disturbance (MFD) system and can be used on reinforced and prestressed concrete. The system maps the magnetic field across the bottom and sides of the beam. A discontinuity in magnetized steel, such as a fracture in a rebar or a broken wire in a steel strand, produces a unique magnetic signal. Research has been encouraging for detecting fatigue-related damage due to the significantly different magnetic signals for corroded reinforcing.

Neutron Probe for Detection of Chlorides

A neutron probe can be used to detect chlorides in construction materials. The materials are bombarded with neutrons from a small portable source. Measuring the gamma rays bouncing back provides a spectrum showing different elements, one of which is chloride. A major potential application that remains to be tested is measuring chlorides in reinforced concrete to determine corrosion hazard. Another potential application includes inspecting suspension bridge cables.

Nuclear Methods

The primary use of nuclear methods is to measure the moisture content in concrete by neutron absorption and scattering methods. These moisture measurements are then used to determine if corrosion of reinforcement is likely to occur. A more direct measurement of the rate of corrosion is more useful to the bridge inspector,

Pachometer

A pachometer is a magnetic device used in determining the position of reinforcement (see Figure 15.2.12). Magnetic methods do not detect concrete defects or deterioration directly. However, they can detect regions of inadequate cover, which is often associated with corrosion-induced deterioration. Magnetic methods can be used to measure cover in the range of 0 to 3 inches to an accuracy of about 1/4 inch.

Figure 15.2.12 Pachometer Testing Equipment

Rebound and Penetration Methods

Rebound and penetration methods measure the hardness of concrete and can be used to predict the strength of concrete. The rebound hammer (also known as the Swiss hammer) is probably the most commonly used device to measure the penetration resistance of hardened concrete. A spring-loaded device strikes the surface of the concrete, and based on the response, the compressive strength of the concrete can be determined. This inspection method can be used to compare the quality of the concrete in different parts of concrete bridge components. However, only the surface of the concrete is being tested, and the strength value is relative.

Another common penetration device utilizes a pistol-like driving device that fires a probe into the surface of the concrete. The probe is specifically designed to crack aggregate particles and to compress the concrete being tested.

Both of these tests are considered practical primarily with concrete that is less than one year old. However, when used in conjunction with core sampling, these tests can also be used to determine significant differences in concrete strength of older bridges.

Ultrasonic Testing

Ultrasonic testing can provide valuable information regarding the condition of concrete bridge members. However, the method can be difficult to use with reinforced concrete members, and some skill is required to obtain usable results.

Large cracks and voids can be detected since the path of the pulse travels around any cavity in the concrete and time of transmission is therefore lengthened. The presence of steel parallel to the line of transmission provides a path along which the pulse can travel more rapidly, causing misleading results. Therefore, it is generally desirable to choose paths that avoid the influence of reinforcing steel.

Smart Concrete

Carbon fiber-reinforced cement can be used as a strain-sensing coating on conventional concrete. This coating allows the sensing of strain similar to strain gauges. The resistance can be measured by having electrical contacts attached to the member.

Strain gauges are expensive compared to the structural material, and they often become detached during use. This method could be much more reliable in sensing strain in structures.

Smart concrete is in early stages of development.

Radiography

Radiographic inspection is a nondestructive testing technique used to evaluate concrete for signs of hidden flaws which could interfere with its function. It is accomplished with the use of radiographs, images generated by bombarding the concrete under inspection with radiation. X-ray and gamma ray radiographic inspection are the two most common forms of this inspection method.

Carbonation

Carbonation of concrete is the result of the reaction of carbon dioxide and other acidic gases in the air, and it can cause a loss of protection of the reinforcing steel against corrosion. The depth of carbonation in a concrete bridge member can be measured by exposing concrete samples to a solution. Uncarbonated concrete areas change color, while carbonated concrete areas remain colorless.

15.2.3 Other Testing Methods

Core samples can be used for many of the following other advanced inspection tests. Usable cores can normally be obtained only if the concrete is relatively sound. If possible, cores need to have a diameter three times the maximum aggregate size. Core holes need to be filled with non-shrink concrete grout. Since removing a concrete core may weaken the member, exercise caution and do not remove from high stress areas.

Concrete Permeability

Air and water permeability can be measured by drilling a small hole into the concrete, sealing the top with liquid rubber, and inserting a hypodermic needle. Air permeability can then be determined by filling the hole with water and measuring the flow in to the concrete at a pressure similar to that of rainfall. However, this method is seldom used in bridge inspections.

Concrete Strength

Actual concrete strength and quality can be determined only by removing a concrete core and performing such laboratory tests as:

- Compressive strength
- Cement content
- Air voids
- Static modulus of elasticity
- Dynamic modulus of elasticity
- Splitting tensile strength

Endoscopes and Videoscopes

Endoscopes and videoscopes are viewing tubes that can be inserted into holes drilled into a concrete bridge member (see Figure 15.2.13). Light can be provided by glass fibers from an external source. Some applications of this method include the inspection of the inside of a box girder and the inspection of hollow post-tensioning ducts. Although this is a viewing method, it is considered to be a destructive method because some destruction is necessary for its proper use in concrete.

Figure 15.2.13 Remote Video Inspection Device

Moisture Content

Moisture content in concrete serves as an indicator of corrosion activity. Moisture content can be determined using nuclear methods (refer to Topic 15.2.2) or from concrete samples taken from the bridge and oven dried in a laboratory

Petrographic Examination

Petrographic examination is a laboratory method for determining various characteristics of hardened concrete, which are useful in determining the existing condition and predicting future performance. This advanced inspection method is able to detect Alkali-Silica Reaction (ASR) products.

Reinforcing Steel Strength

The actual properties of reinforcing steel can only be determined by removing test samples. Such removal of reinforcing steel can be detrimental to the capacity of the bridge and needs to be done only when such data is essential.

Chloride Test

One of the current standard test methods used to assess the resistance of concrete to penetration of chloride ions is the rapid chloride permeability test. This test, officially known as AASHTO T 277-93, “Electrical Indication of Concrete’s Ability to Resist Chloride,” measures the charge passed through a concrete specimen subjected to sixty volts (direct current) for six hours. Variable results have been reported with the rapid chloride permeability test when certain mineral admixtures such as silica fume were included in the concrete mixture and when calcium nitrite (included in some corrosion inhibitors) or reinforcing steel have been present. The test specimens are two inches long and four inches in diameter in the rapid chloride test. The rapid chloride test uses sodium hydroxide ponded on the top of the specimen, and a solution of sodium chloride at the bottom of the specimen. The specimen is initially subjected to thirty volts (direct current), and the resulting current determines the voltage to be applied for the duration of the test. The voltage is applied for three different time periods varying anywhere from 2 to 96 hours. Following the test, the specimen is split in half and a silver nitrate spray is applied to identify the depth of chloride penetration in to the specimen.

ASR Evaluation

One test for ASR evaluation, often referred to as the accelerated mortar bar test, has been accepted by ASTM and AASHTO. The test involves casting mortar bars that contain the subject aggregate (either coarse or fine), which is processed to a standard gradation. The mortar bars are then removed from their molds after 24 hours and placed in water at room temperature. The temperature of the water is then raised to 176 degrees Fahrenheit in an oven, and the mortar bars are stored in this condition for the next 24 hours. After the bars are removed from the water, they are measured for initial length and then submersed in a 1 normal (N) NaOH solution at 176 degrees Fahrenheit, where they are then stored for 14 days. Length change measurements are made periodically during this storage period. The total expansion at the end of the 14-day soaking period typically is used in specifications, although the expansion limits specified by different agencies vary.

Another method is a qualitative ASR field test that utilizes colored dyes. This test is performed on a broken surface of a concrete core, where reagents are then applied. If ASR is present, the reagents turn different colors indicating if ASR is just beginning or if ASR is in an advanced stage. This field test is relatively inexpensive and can be carried out completely on-site with easy-to-interpret results.

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Topic 15.3 Steel

15.3.1 Introduction

Advanced inspection methods give inspectors the ability to further evaluate suspected deficiencies found during a visual inspection. They can also be used to perform inspections on members that are not accessible. Advanced inspection methods usually require calibrated testing equipment, a professionally trained technician to perform the testing and a professional that has expertise in interpreting the advanced inspection results. However, bridge inspectors will have an understanding of the various advanced inspection methods.

There are two main classifications of advanced inspection methods. The first is labeled nondestructive testing or nondestructive evaluation (NDT or NDE). This classification pertains to all advanced inspection methods that do not impair the usefulness of the member being tested. Other testing, the second main classification, covers all advanced inspection methods that affect or destroy the structural integrity of the member being tested.

New technology is making the use of these highly technical systems economically feasible for bridge inspection. From this fact, advanced inspection methods are becoming more popular for the inspection of bridge members. Current and future studies have been, and will be focusing directly on relating results from advanced inspection methods into Bridge Management Systems ratings.

This Topic describes the different types of nondestructive and other test methods for steel bridge members and the general methods for each.

15.3.2 Nondestructive Testing Methods

Acoustic Emission Testing

Acoustic emission (AE) testing has been used for many years, but is now becoming a more standardized and available method.

This inspection method detects elastic waves generated by the rapid release of energy from within a test object by such mechanisms as plastic deformation, fatigue and fracture. When a structure is under certain load levels, it will produce an acoustic sound that ranges between 20 KHz and 1 MHz. The sound that is generated is known as acoustic emissions. Acoustic emission testing uses ultrasonic microphone to listen for sounds from active deficiencies and is very sensitive to deficiency activity when a structure is loaded beyond its service load in a proof test. This process can detect flaws and imperfections such as the initiation, growth and growth rate of fatigue cracks in steel structural members, friction, corrosion, deformation, cracks opening and closing, weld discontinuities, the failure of bonds, fibers and filaments in composite materials and the appearance of potentially hazardous flaws in metal or synthetic pressure vessels.

Most sounds produced by materials under stress are inaudible; however there may be a portion that exists as audible sound, based on the magnitude and type of deformation, flaw growth or failure.

Bridges contain a large number of joints, welds and connections that are potential initiation points for fatigue cracks. Acoustic emission monitoring is used for early detection of fatigue cracks in fracture critical bridge members and to monitor the relative activity of existing fatigue cracks. Advanced signal processing and correlations to parametric measurements are used to separate noises generated by dynamic loading, loose connections, rivets and crack growth (see Figure 15.3.1).

Commercial systems are available, based on wave propagation properties. When energy is released (for example: high-tensile wire failures or concrete cracks), waves propagate in the material. Acoustic sensors distributed along the structure can detect and record the signal. Computer processing of the signal will then provide valuable information about the event including: location, origin, energy, and frequency (see Figure 15.3.1).

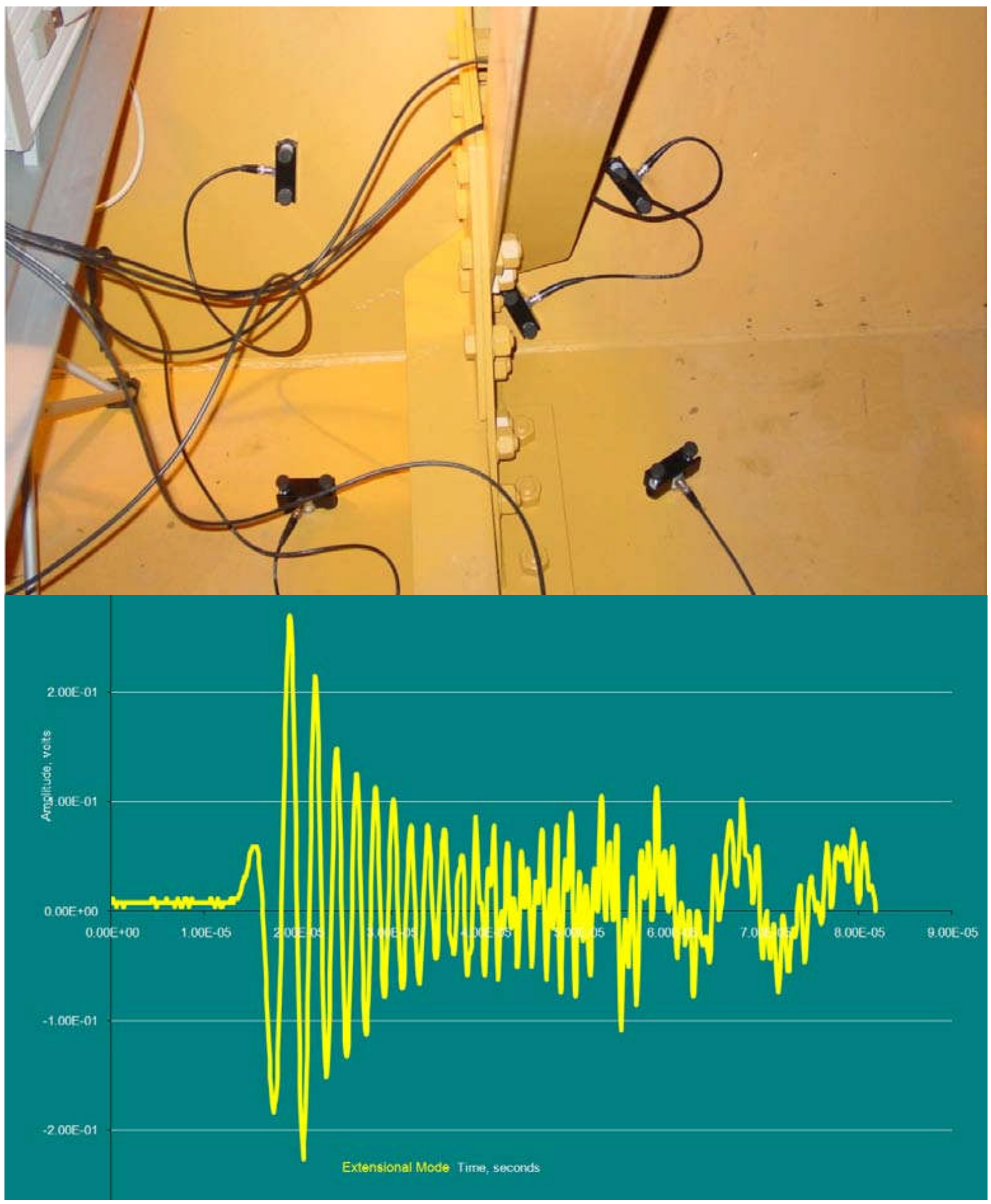

Figure 15.3.1 Acoustic Sensors Used to Determine Crack Propagation

The main advantage of these systems is the recording and real-time analysis of the waves themselves, allowing automatic filtering by the acquisition unit according to preset criteria. The events of interest are stored in the acquisition unit and automatically available for analyses.

Devices can be used to monitor areas that already are cracked or cracked areas that have been retrofitted. The device is a portable, modular multi-channel system that can be mounted close to the area being monitored (see Figure 15.3.2). The system can be directly connected to a computer or it can be accessed through wired or wireless modems for data collection.

Figure 15.3.2 Inspector Using Acoustic Emissions to Determine Crack Propagation

Limitations of acoustic emission testing include AE being a non-repeatable test. Once a test is completed, it cannot be repeated due to the flaw growth being an irreversible process. Also, deficiencies are not detectable if they are not growing or flexing. Therefore, if the deficiency is not increasing in size, acoustic emission testing will not be able to locate the crack. The bridge may also cause interference with testing. If background noise exists, that noise would be similar to the sound energy released by a flaw. For this reason, the wires need to be properly shielded against background noise. Lastly, the acoustic emission testing unit is relatively expensive and also requires the additional cost of an operator.

Corrosion Sensors

Corrosion sensors are being developed that use environmental variables such as dirt and duration of wetness to indicate the degree of corrosion of a steel structure.

Smart Coatings

The National Science Foundation's Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center has developed "Smart Paint" – paint with microencapsulated dyes that outline a fatigue crack in a bridge or other highway structure as the crack forms and propagates.

Japanese scientists have also developed paint that sends out electrical signals which are picked up by electrodes placed on either side of the paint's resin layer if the structure or material begins to vibrate. The greater the vibration, the greater the electrical signal. This paint could enable engineers to monitor vibrations throughout the lifetime of a structure, allowing them to calculate much more accurately when fatigue is becoming a problem. The new paint is a much easier way of measuring vibrations than conventional strain gauges.

Dye Penetrant

A dye penetrant test (PT) can be used to define the extent and size of surface flaws in steel members (see Figure 15.3.3). The test area is cleaned to bare metal to remove all contaminants, a penetrant is applied to the surface by spray or brush, and excess penetrant is removed by wiping or water rinsing. Once the penetrant has dried, a white developer is applied, which draws the dye out of the irregularities and defines the extent and size of surface flaws. Bridge inspectors commonly use this method since it does not require extensive training or expensive equipment. A limitation of this method, however, is that it reveals neither the depth of cracks nor any subsurface flaws. Another important factor when performing dye penetrant testing is the penetrant dwell time. This is the amount of time that the penetrant is allowed to remain on the surface before the excess is wiped off. Factors that effect the dwell time include:

- Temperature of the member being tested and the penetrant type
- Ambient air temperature (higher temperatures require shorter dwell times)
- Humidity (low humidity causes penetrant to dry out rapidly)
- Size and shape of the discontinuity (hairline cracks need more time than large ones)
- Material type
- Penetrant removal type and manufacturer's recommendations

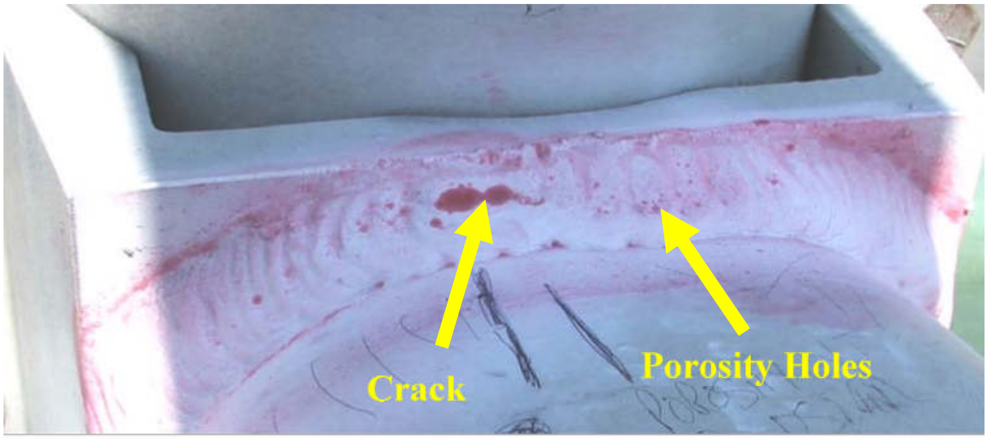

Figure 15.3.3 Detection of a Crack Using Dye Penetrant

Limitations of dye penetrant testing include only showing what defect is on the surface and nothing further in on the specimen. For a proper reading, clean the surface, which includes the paint. In order to see if there is a crack present, the inspector needs good visual acuity. In addition, a recommended temperature of over 40 degrees Fahrenheit is required to achieve acceptable results using dye penetrant testing.

Magnetic Particle

Magnetic particle testing is useful in detecting surface gouges, cracks, and holes in ferromagnetic materials. It can also detect subsurface deficiencies, such as voids, inclusions, lack of fusion, and cracks, which lie near the surface. Magnetic particle inspection is primarily used to find surface breaking flaws (see Figure 15.3.4) and can also be used to located subsurface flaws. Its effectiveness, however, diminishes quickly depending on the depth and type of flaw. The method consists of magnetizing the member, applying iron filings, and then interpreting the pattern formed by the filings, which are attracted by the magnetic leak.

A magnetic field is induced into the member, and cracks or other irregularities in the surface of the member cause irregularities in the magnetic field (see Figure 15.3.5). This method is also referred to as magnetic field disturbance.

Figure 15.3.4 Magnetic Particle Device Used to Detect Subsurface Flaws

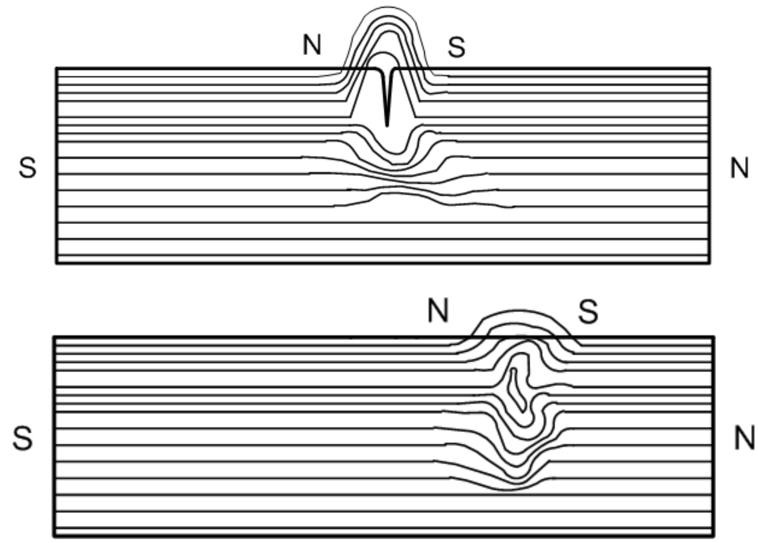

Figure 15.3.5 Schematic of Magnetic Field Disturbance

Limitations of magnetic particle testing include applicability only for members composed of a ferromagnetic material. For some test pieces, removal of the residual magnetism is necessary for an additional expense. The magnetic field requires perpendicular orientation to the principle plane of the defect for detection. In addition, smaller subsurface deficiencies are generally harder to detect than larger deficiencies. Lastly, clean unpainted surfaces help to ensure the maximum sensitivity of the magnetic particle testing unit.

Radiography Testing

Radiography testing (RT) is used to detect and locate subsurface deficiencies such as cracks, voids, and inclusions throughout the internal structure of the material in the fabrication shop and in the field.

Radiography testing requires that the inspector have access to both sides of the structure, with the radiation source on one side and the film on the other side. X-rays or gamma rays are passed through the member and are absorbed differently by the various flaws. When a piece of radiographic film is exposed to the rays, the deficiencies appear as shadows on the film (see Figures 15.3.6). This type of advanced inspection is typically used for full penetration groove welds during fabrication and construction.

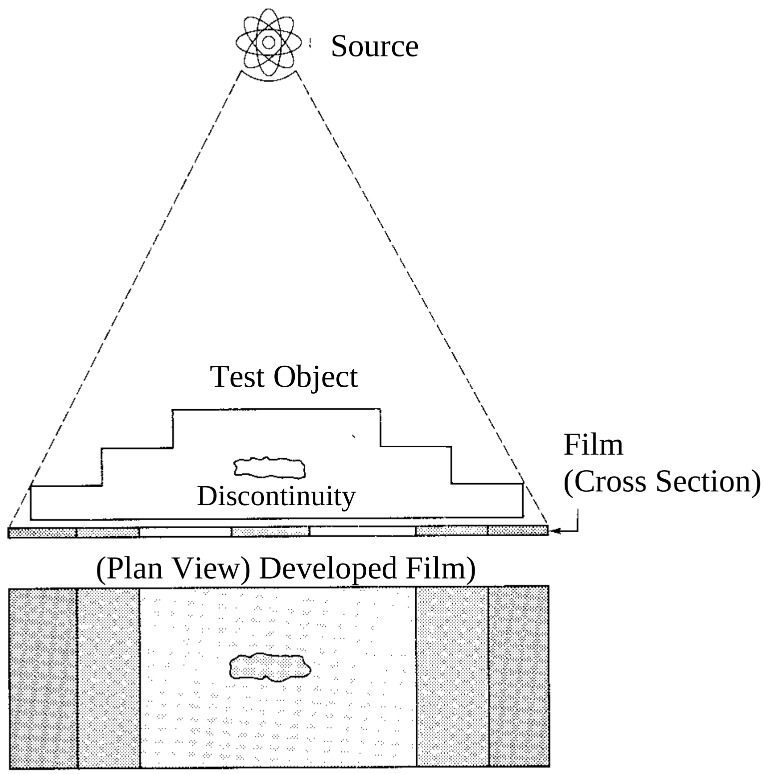

Figure 15.3.6 Radiography Testing

Limitations of radiography testing include requiring access to both sides of the test member for a proper reading. It is necessary to have a high skill level to interpret the readings. Lastly, radiography testing is relatively expensive, especially for thicker members. The cost of an operator needs to be factored into the total cost of radiography testing.

Computed Tomography

Computed tomography uses X-ray and gamma radiation to visualize and produce 2-D and 3-D cross-sectional images of the interior deficiencies of a steel member. The image is captured by a detector array, it is processed by a computer, and it is then reconstructed. This method is similar in many ways to medical CAT scans, and it has great potential for locating discontinuities of all types in steel members (as well as concrete members).

Robotic Inspection

Several companies are currently developing and marketing systems which use high-resolution video cameras on robotic arms attached to permanent falsework underneath the bridge. By remote telescanning, details can be visually monitored, with magnification if needed, without the inspector having to climb to gain access to a detail each time an inspection is desired. While the primary material application for robotic inspection is steel, it can also be used on timber and concrete bridges.

In recent years, the California Department of Transportation (Caltrans) has been working on an aerial robotic inspection system. This system, in the testing and development stage, can allow bridge inspectors to view elevated bridge members from the ground. It is controlled by a remote control that is connected to the system through a 100 ft electrical cord. A fiber optics cable transfers information and images from the aerial device to the ground station. This type of inspection may reduce traffic delays and increase the level of safety for motorists and bridge inspectors.

There have also been robotic inspections performed by unmanned vehicles. Since Hurricane Ike in 2008, the Texas Transportation Institute and the Texas Department of Transportation (TxDOT) gave permission to the Center for Robot-Assisted Search and Rescue for bridge inspection using robotic means. This is achieved by using an unmanned surface vehicle and underwater vehicles (see Figure 15.3.7) that were used to inspect the substructures. The surface vehicle is battery powered and can run for four to six hours based upon the current. It contains an acoustic camera for subsurface inspections and three video cameras to record above the water. The underwater inspection robots can be used for the underwater visual inspection of bridges and debris and mapping debris fields.

Figure 15.3.7 Robotic Inspection: Unmanned and Underwater Inspection Vehicles

Ultrasonic Testing

Ultrasonic testing is frequently used in steel applications and can be used to detect cracks in flat, relatively smooth members, as well as pins by using high-frequency sounds (range of 20 KHz to 25 MHz) pulsed through a material to generate images (see Figure 15.3.8). It can also be used to measure the thickness of steel members, providing detailed information concerning loss of cross section. Ultrasonic testing also has many applications in the inspection of welds, detecting porosity, voids, inclusions, corrosion, cracks, and other discontinuities. This method will involve applying a couplant to the area that is to be inspected and then scanning the area with a transducer, which is attached to the UT machine. Refer to Topic 15.1 for further details about the principles of ultrasonic testing.

Figure 15.3.8 Ultrasonic Testing of a Pin in a Moveable Bridge

Limitations of ultrasonic testing include inaccurate readings for members with a rough surface or complicated geometry. Parallel plates or angles (including built-up members) with a small gap between the elements may also produce inaccurate readings. In additional, flaws that are parallel to the sound waves will not be detected. Skilled operators are required to administer ultrasonic testing, adding to the cost of this NDE method.

Ultrasonic thickness depth meters (D-meters) are miniature versions of an ultrasonic tester which uses a dedicated straight beam transducer (see Figure 15.3.9). The primary difference between an average ultrasonic tester and a D-meter is that ultrasonic testers can determine internal flaws while D-meters can only detect the thickness of the part being tested.

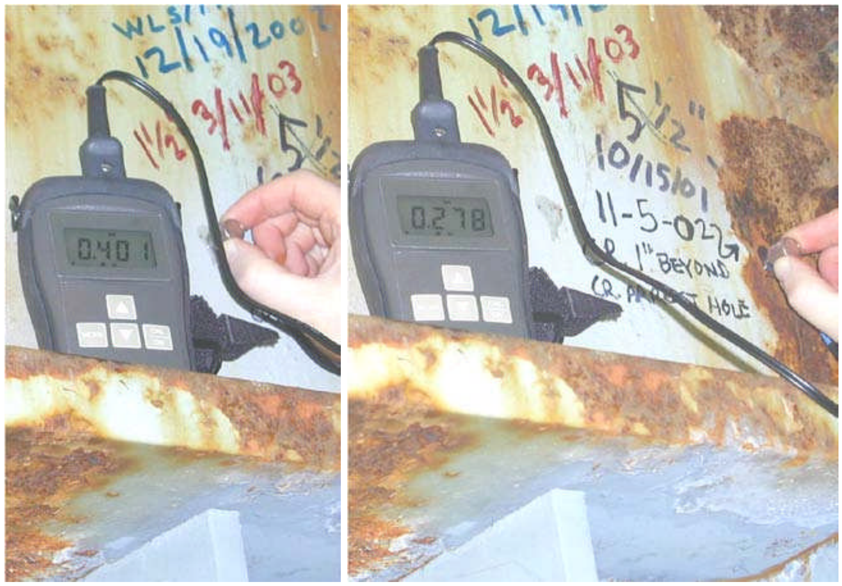

Figure 15.3.9 Ultrasonic Thickness Depth Meter (D-meter)

Phased array units are another form of ultrasonic testing that can be used to test for discontinuities on steel members (see Figure 15.3.10). It is an array that consists of a series of individual elements, transducers, that are separately pulsed, time delayed and processed. Software will allow the operator to modify the beams time delay or phasing. The phased arrays can be controlled electronically to scan, sweep, steer, and focus the beam.

Figure 15.3.10 Ultrasonic Testing of a Gusset Plate Using a Phased Array

Advantages of phased array testing include considerably faster scanning rates (5 to 10 times faster) compared to traditional ultrasonic testing. Multiple angles and frequencies also produce better images, which results in less user-interpretation required by the operator.

Limitations of phased array units include some uncertainty in the technology, as this method is relatively new and not completely proven. For this reason, phased arrays are not universally accepted by bridge owners as a legitimate way to test for deficiencies. Training courses are also required, due to the difficulty in using a portable phased array unit. Lastly, the units are expensive and require an additional cost for a qualified operator.

Eddy Current

This type of electromagnetic method uses AC currents. Eddy current testing (ET) can only be performed on conductive materials and is capable of detecting cracks and flaws as well as member dimensions and variations. This method can be used on painted or untreated surfaces. The system works by monitoring the voltage across a coil that has an AC current flowing through it. When the coil is placed next to the conductive member, the member produces eddy currents that flow opposite to the direction of flow from the coils. Deficiencies in the member disturb the eddy currents, which, in turn, affect the induced current. The affected induced current is monitored through the voltage across the coil. Eddy current testing devices can be hand held devices (see Figure 15.3.11).

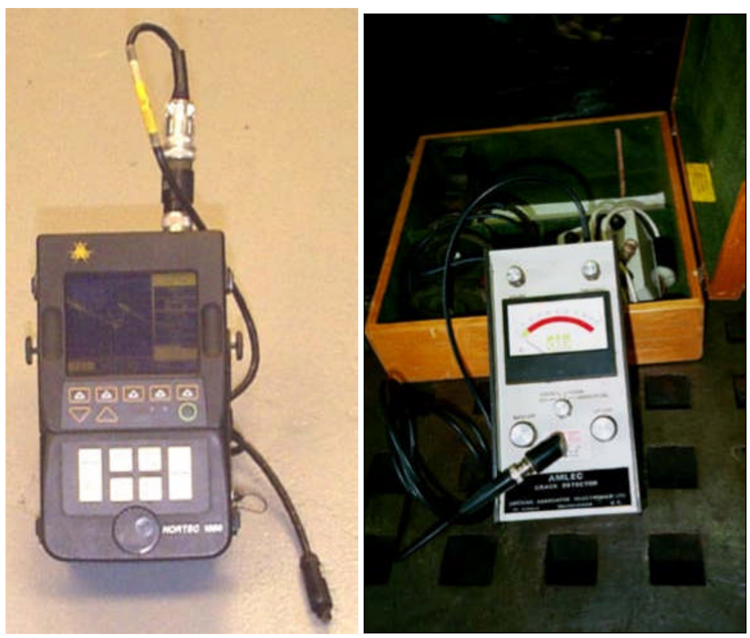

Figure 15.3.11 Hand Held Eddy Current Testing (ET) Instruments

Limitations in eddy current testing include the inability to determine the depth of the crack. This NDE method also does not work with galvanized steel members. Lastly, eddy current testing requires operators with the proper training to correctly interpret the test results, which adds to the cost of the method.

Electrochemical Fatigue Sensor (EFS)

Electrochemical Fatigue Sensors (EFS) is a new nondestructive evaluation method that is used to determine if actively growing fatigue cracks are present in the steel. Data collection and analysis software is provided within the EFS system. The system also consists of an electrolyte, sensor array, and potentiostat. These components are used to apply a constant polarizing voltage between the bridge and the sensor. The sensor is placed near the suspected fatigue crack location on the bridge and then injected with the electrolyte. A small voltage is then applied. The current response of the sensor array, comprised of a crack measurement sensor and a reference sensor, is collected, analyzed and compared with the software. The software will automatically indicate the level of any fatigue crack activity (see Figure 15.3.12).

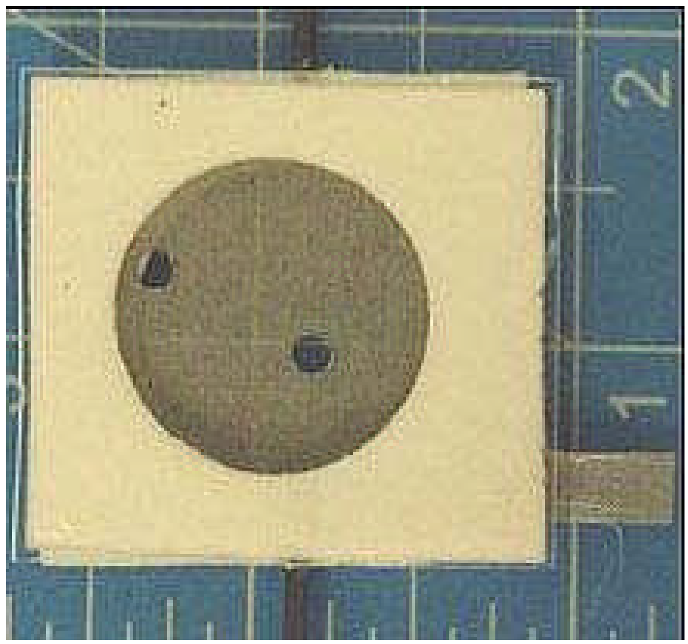

Figure 15.3.12 Electrochemical Fatigue Sensor

Magnetic Flux Leakage

Magnetic flux leakage testing, similar to magnetic particle testing, is a form of nondestructive evaluation developed in Great Britain that has been used over the past few decades on stay cables. This method uses a magnet to magnetize the steel to help detect any corrosion and pitting in steel. Any crack will be detected by sensors that will pick up any distortion of the magnetic field which causes the field to leak from the rope. Various types of sensors, placed close to the rope, are used to help sense and measure any magnetic flux leakage. The types of sensors include coils, Hall sensors or fluxgate sensors.

Laser Vibrometer

Laser vibrometers are used to measure small non-contact vibrations of a stay cable from a large distance. Nothing special needs to be placed or done to the cable. Instead, a low-power laser beam is used, directed at the cables. The response that is measured will be vibration amplitude and frequencies which will be used to determine any vibration of the cables. Those frequencies detected will then be used to calculate the forces that the vibrations are placing upon the cables.

Information concerning various nondestructive testing can be found on the American Society of Nondestructive Testing website: **www.asnt.org**.

15.3.3 Other Testing Methods

Strength tests are considered destructive since they usually involve removing pieces of steel from the bridge. Small pieces cut out of steel members are called test "coupons." The removal method and coupon size have to be suitable for the planned tests. If a coupon is required, consult the bridge engineer to determine the most suitable area of removal. For instance, an inspector will not remove a coupon from the web area over a bearing. An inspector will not recommend removal of a coupon from a high stress zone such as the bottom flange at midspan. Tests may be necessary to determine the strength or other properties of existing iron or steel on bridges for which the steel type is unknown.

The following tests can be conducted only by the destructive method of removing a sample and evaluating it in a laboratory.

Brinell Hardness Test

The Brinell hardness test measures the resistance to penetration of the steel. A hardened steel ball is pressed into the test coupon by a machine-applied load. The applied load and the surface area of the indentation are used to calculate the hardness of the steel. For steel that has not been hardened by cold work, its hardness is directly related to its ultimate tensile strength.

Charpy Impact Test

An impact test determines the amount of energy required to fracture a specimen. A common impact test for steel coupons is the Charpy V-notch test (see Figure 15.3.13). A notched test coupon is placed in a vise, and a hammer is then released from an elevated position, swinging down and hitting the coupon. Since the force of the hammer is concentrated in a notch in the coupon, the stress goes into fracturing the specimen and not into strain. The energy required for fracture is determined based on the mass of the hammer and the distance that it fell and is recorded on the dial located on the striking hammer. This test can be performed at different temperatures to determine if the steel is susceptible to brittle failure.

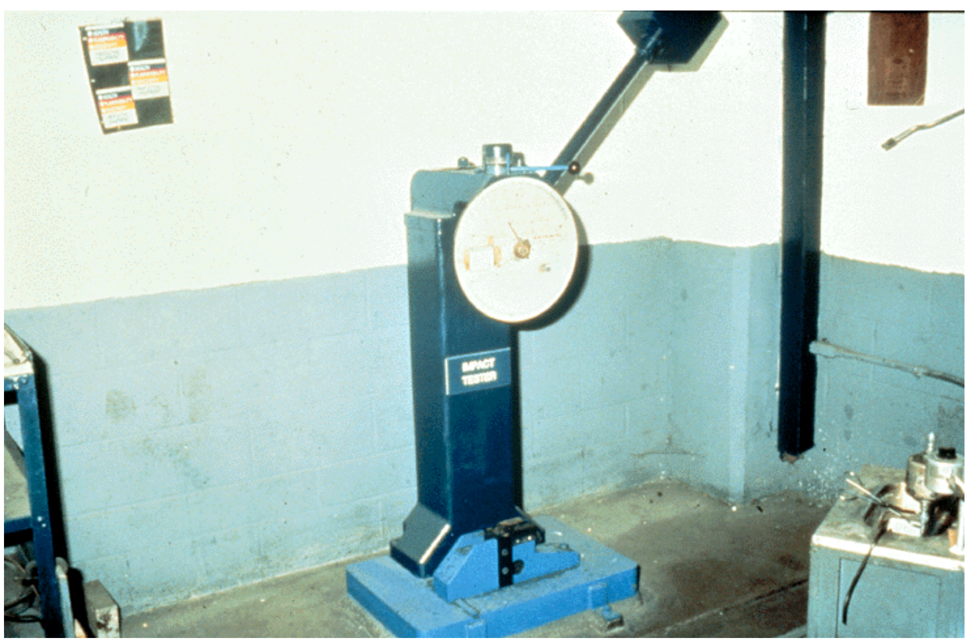

Figure 15.3.13 Charpy V-Notch Test

Chemical Analysis

The chemical composition of the steel is an important indication of whether a weld will crack, either from cold cracking or hot cracking. Tests can be performed on coupons to determine the chemical composition of the steel.

Cold, or delayed, cracking can be approximated using a carbon equivalent (C.E.) equation that is based on the chemical composition of the steel. One such equation, based on the relative proportions of various elements in the steel, is presented in the ASTM A706 rebar specification:

$$C.E. = C\% + \frac{Mn\%}{6} + \frac{Cu\%}{40} + \frac{Ni\%}{20} + \frac{Cr\%}{10} - \frac{Mo\%}{50} - \frac{V\%}{10}$$

C – Carbon	Cr – Chromium
Mn – Manganese	Mo – Molybdenum
Cu – Copper	V – Vanadium
Ni – Nickel	

When the C.E. is below 0.55, the steel is generally not susceptible to cold cracking, and no special precautions are required for welding. However, when the C.E. is above 0.55, the steel is susceptible to cold cracking, and special precautions are required for welding.

Hot cracking occurs as the weld begins to solidify. Hot cracks have almost been eliminated today due to modern welding material formulation.

Tensile Strength Test

The tensile strength is the highest stress that can be applied to the coupon before it breaks Once the test is complete, the tensile strength of the steel can be easily determined. See Topic 5.1, Bridge Mechanics.

The ends of the test coupon are placed in vises on a testing machine. The machine then applies a tensile load to the ends of the coupon. The machine measures the load at which the coupon fails or breaks. This load and the cross-sectional area of the coupon determine the tensile strength of the steel.

Brittle fractures occur without plastic deformation once the yield strength is exceeded. Since there is no plastic deformation, there is no warning that a fracture will occur. The fracture that is formed on a brittle fracture will be flat (see Figure 15.3.14).

Ductile fractures occur once the yield strength has been exceeded, causing the specimen to elongate and "neck down" (also known as plastic deformation) and eventually breaking if the load is not removed (see Figure 15.3.15). Plastic deformation results in distortion of the member, which will provide a visual warning before the member would fracture. The reduced cross section is caused by plastic distortion rather than section loss. The fracture produces shear lips that are tilted at 45 degrees.

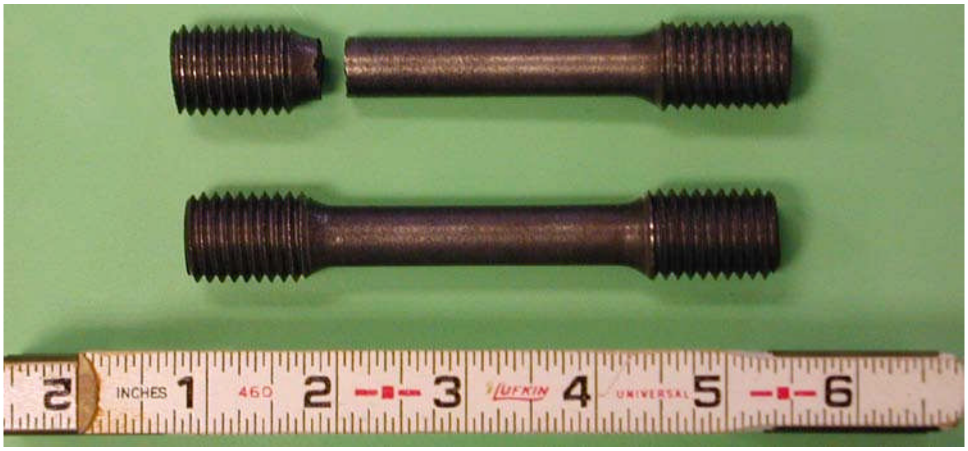

Figure 15.3.14 Brittle Failure of Cast Iron Specimen

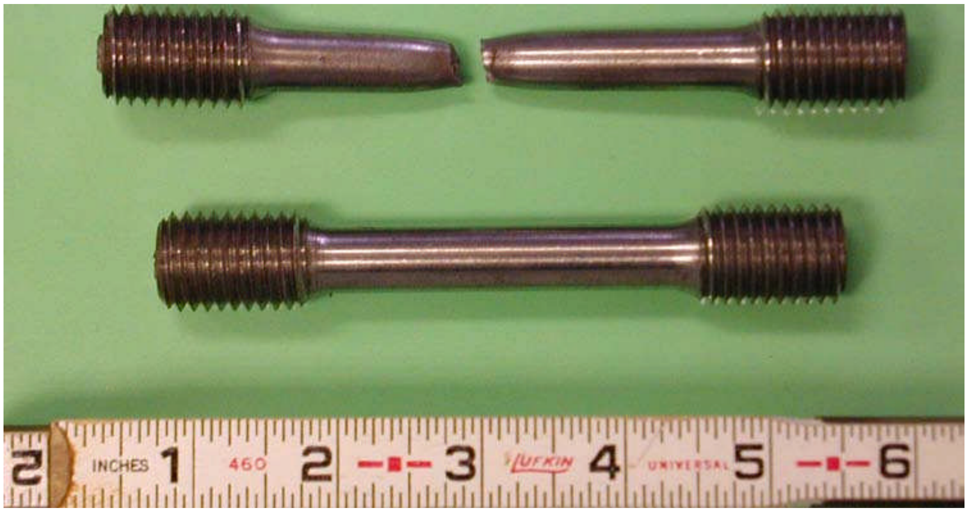

Figure 15.3.15 Ductile Failure of Cold Rolled Steel

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Topic 15.4 Advanced Bridge Evaluation

15.4.1 Introduction

Today's sensing devices capture and report highly accurate and objective data, which can be used to make "fact-based" evaluations for bridge condition and provide decision support for serviceability, repair or replacement actions, optimizing the owner's overall bridge management plan.

Advanced bridge evaluation technologies allow the owner to more objectively capture and evaluate known or suspect deficiencies found during a visual inspection. They may also be used to perform periodic or continuous inspections on members that are not readily accessible. Advanced bridge evaluation technologies usually require customized hardware and software, an experienced technician to install sensing devices or perform the testing, and an engineering professional that has expertise in interpreting the results (see Figure 15.4.1). Generally, bridge inspectors and engineers have a basic understanding of the advanced bridge evaluation technologies available. This basic knowledge allows them to participate in the selection and use of the appropriate technologies to better determine the bridge's condition.

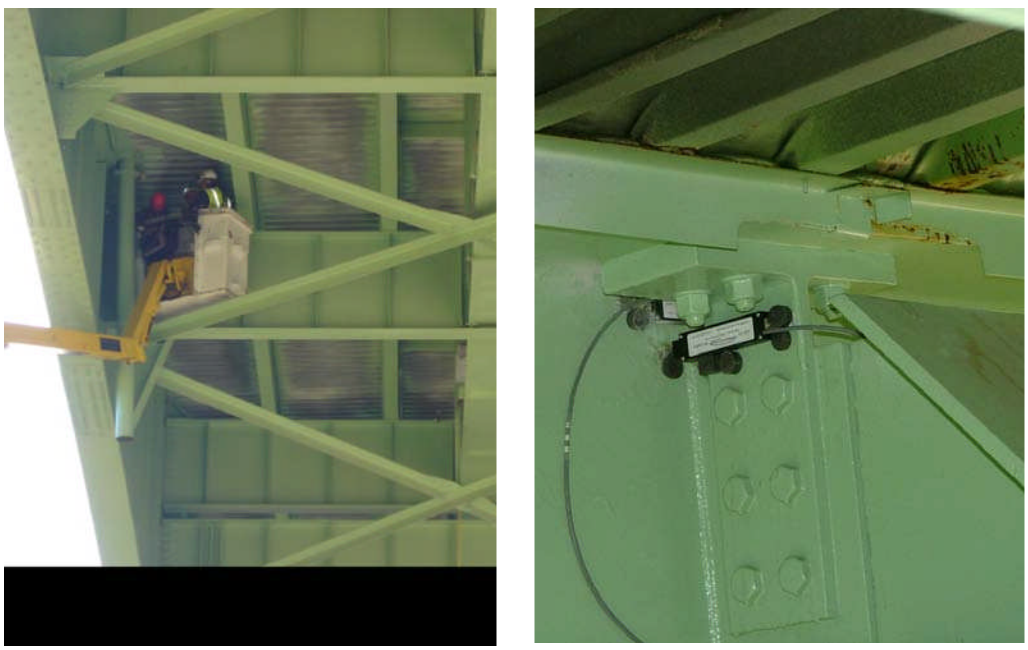

Figure 15.4.1 Installation of Sensors

There are two main classifications of advanced bridge evaluation technologies. The first is known as nondestructive evaluation (NDE). This classification pertains to technologies that do not impair the usefulness (short term or long term) of the member being tested. The other classification consists of advanced bridge evaluation technologies that negatively affect the member by reducing the structural integrity of the member being tested. For example, removing a part of a member for testing therefore reduces its capacity. Most practitioners and owners today prefer the nondestructive technologies for obvious reasons.

The proper use of these advanced bridge evaluation technologies can supplement routine bridge inspections and can be useful for optimizing an owner's bridge management program. Methods are being developed to transfer near real-time results from these technologies directly into Bridge Management Systems ratings and bridge management protocols (e.g. overload permitting.) (see Figure 15.4.2).

Near real-time solutions are made possible by the combination of a variety of sensing devices, wireless communication and internet technologies. The ability to capture data on member strains, relative movement between members, crack growth and propagation, and other relevant structural parameters are the result of digital technology being applied to structural bridge evaluations.

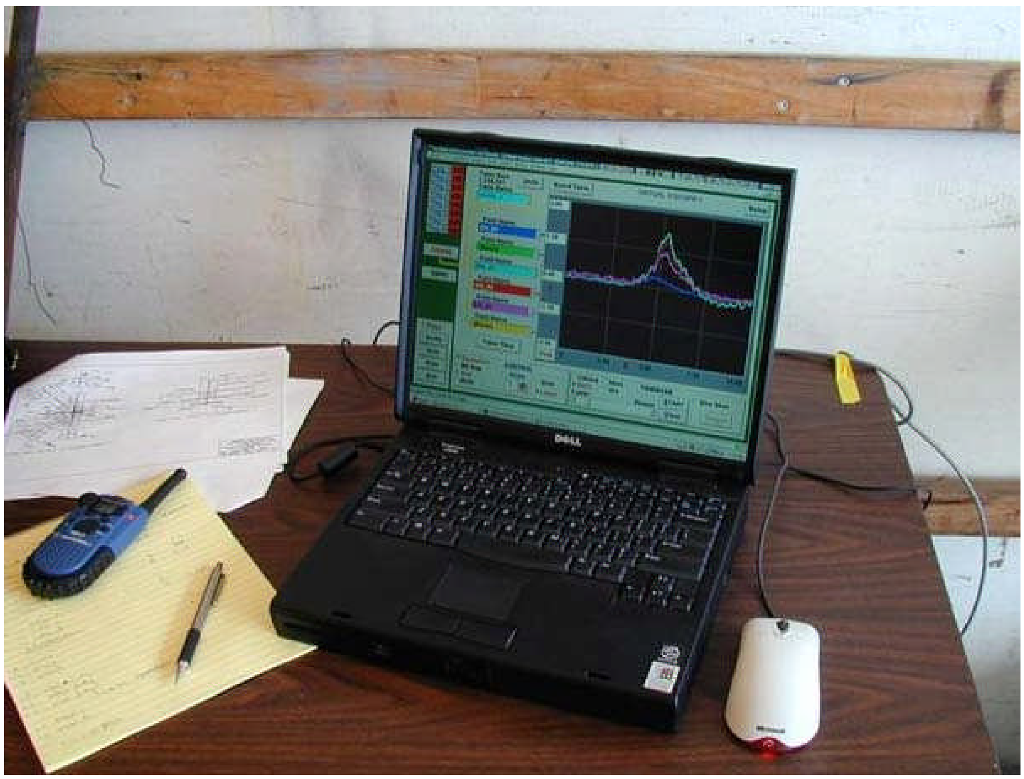

Figure 15.4.2 Viewing Real Time Data

15.4.2 Advanced Bridge Evaluation Methods

Strain or Displacement Sensors

Strain or displacement sensors can be used to monitor the response of a member to a live load and/or temperature changes. These type sensors are available and include foil type, vibrating wire, fiber optic, and a sensor that measures both current and peak strains in one device (see Figure 15.4.3). Foil-type sensors are only used in the axial direction of flat members. Single wire filament "vibrating wire" sensors can be used on flat members or cables. Portable strain reading instruments can be used to monitor sensors from a central location on or near the bridge in a manual data collection mode or fully automatic monitoring can be installed, allowing readings to be taken at user defined intervals and sent wirelessly to a central location for viewing over the internet.

Figure 15.4.3 Strain Gage Used on the Hoan Bridge, Milwaukee, Wisconsin

Locations for strain sensors are selected based on the condition of individual members, accessibility, and the objectives of the monitoring program. Strain/displacement sensors can provide valuable information about:

- The actual transverse load distribution through the structural member
- The load sharing between elements of a multi-element member
- The effectiveness of the various members of the primary structural system
- The influence of deteriorated or defective members
- The growth and/or propagation of cracks in steel or concrete members
- The relative movement of members to fixed points due to loss of section (chemical) or load-induced deterioration

The principal use of strain sensors today is to ascertain the actual condition of a member or series of members and use that information to infer the safe load-carrying capacity of the structure. In essence, sensors are used to provide data to allow additional decision making combined with a visual inspection. Strain sensor data can be used to ascertain the weight of vehicles crossing a bridge. This is known as a "weigh-in-motion" system.

Sensing devices, coupled with electronic control equipment, can be used to update owners and bridge inspectors about ongoing deterioration of the structure. Such configured solutions, which can be integrated into one system, generally include strain or displacement sensors, a system controller on the structure, wireless data transmission, customized software, and other features. This allows for secure data capture, data graphing, viewing over the internet and alerts (by e-mail, cell phone or other method) if strains or displacements exceed predetermined values.

Other Available Sensors

To complement strain or displacement sensors, newer sensors are being developed and deployed to enhance bridge evaluation. Typical sensing devices include tiltmeters (foundation movements), accelerometers (earthquake-induced movements), temperature and humidity sensors, and even global positioning satellite (or GPS) systems to monitor movement of piers, towers, and decks on long bridges to an accuracy of 3/16 of an inch. Other, more esoteric sensing devices include those to detect onset of fatigue cracking, actual stress in cables via electromagnetic fields, corrosion, and other member condition parameters.

Generally speaking, price and functionality are directly related. That is, sensors meant to be used in outdoor environments for long periods of time (years) are more expensive than those meant for controlled environments (laboratories) or short duration use (weeks). Sensing devices can be utilized individually or as part of a system that is configured to provide a total solution. Specialized personnel are required to integrate the variety of sensing devices with controller hardware and software for advanced bridge evaluations.

Dynamic Load Testing

In recent years, an increasing number of short-span bridges have been evaluated using measured response data from known loads. These bridge evaluations have provided useful information and, in some instances, have revealed bridges that required closure or restrictions and those that could be safely upgraded (load restrictions removed).

Use of this method involves a combination of strain sensors, on-site data capture, and response modeling. A known load (weighed dump truck) is driven across a short-span bridge with no other traffic (see Figure 15.4.4). GPS technology is used to precisely spot the truck's position while strain sensors capture member displacements/strains. Data capture typically occurs in one day or less. The data is then used to "build" a rudimentary structural model for evaluation of actual load-carrying capacity. The model is fitted to the actual structural response, allowing engineers to determine actual load-carrying capacity.

This technology gains advantage over current load capacity protocols in that it can consider composite action of the members and contributions to load-carrying capacity from other structural components (sidewalks and parapets) that are typically ignored with traditional analysis methods. Dynamic load testing has been used for over twenty years and has proven its ability to provide accurate load-carrying capacity determinations.

Figure 15.4.4 Dynamic Load Testing Vehicle

System Identification

Using actual structural response data, the properties of the structure (e.g., areas and moments of inertia of structural members) can be calculated. The process of building a structural model from response data is called system identification. The primary use of system identification in structural engineering has been for earthquake engineering research. The historical accuracy achieved in this advanced bridge evaluation methodology indicates that system identification can also provide a tool for detecting unseen structural flaws.

System identification can be performed using a variety of response data, such as modal and time history response. For modal response, the frequencies and mode shapes of the structure are obtained either from ambient vibration data or from the results of harmonic excitation. A time history response is the response (i.e., displacements or acceleration) of one or more points on the structure as a function of time due to a known loading function. For either type of response data, the results are used to determine structural parameters representing the structural integrity of the bridge.

Initially, system identification is used to create a structural model, which accurately represents the in-service condition of the structure (see Figure 15.4.5). Subsequent analyses are then performed to determine which parameters are changing. Since the parameters represent structural properties (e.g., areas and moments of inertia), the changes are indicative of structural deterioration.

Since bridge inspections focus on individual members and system identification considers the entire structure, they are complementary processes. Therefore, system identification can be used to define the structural integrity of the entire bridge structure.

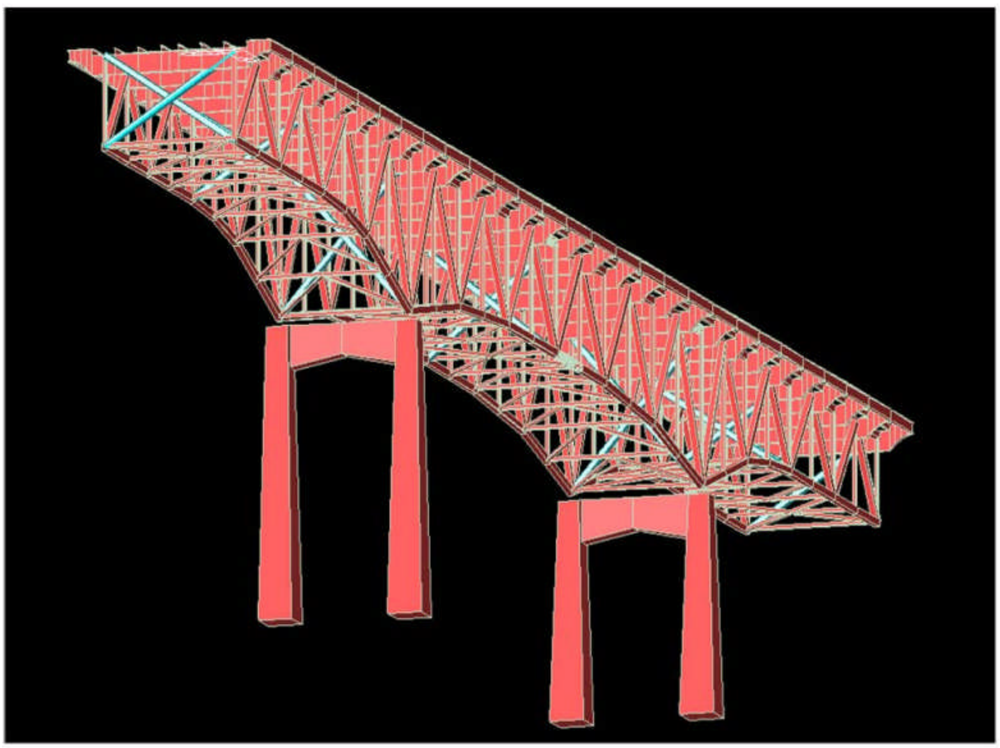

Figure 15.4.5 Structural Model

Practical Considerations for Selection and Use of Advanced Bridge Evaluation Technologies

Any advanced bridge evaluation technology typically provides a reasonable return on investment. There is no reason to pay for technology unless that technology can provide a sufficient return for the Bridge Owner. Over the past several years, significant research has been conducted to demonstrate new advanced bridge evaluation technologies. Some worked well; others did not. But given the current advanced bridge evaluation technologies, owners can typically expect adequate returns on projects. Returns can be calculated using a variety of financial metrics, but some of the more useful are provided below:

- Safe extension of bridge life span, lowering life cycle cost of ownership
- Safe deferral of bridge maintenance or repair programs
- Safe deferral of bridge replacement programs
- Improved prioritization of limited funds
- Removal of unnecessary load restrictions to support commercial traffic and reduce detours, congestion and air pollution
- Identification of bridges that are to be replaced or repaired immediately, thereby lowering liability exposure and increasing safety

Other issues to consider before utilizing an advanced bridge technology:

- Is the advanced bridge evaluation technology being used for a few bridges or across the entire system?
- Is the advanced bridge evaluation technology capturing the “right” information to aid decision making and not a lot of extraneous information?
- Can the advanced bridge evaluation solution be expanded easily and cost effectively if it is later decided to capture more data?
- Should a solution provider be used, capable of system configuration and installation, or integrate the hardware and software internally?
- Should the captured information be able to integrate with the existing information system?
- How long is the technology expected to be deployed – what is the reliability and durability of the hardware and software?
- Can the confidentiality of captured data, both on-site and for later viewing and downloading, be assured?
- Who has the responsibility for conversion of the structural data into useful information and subsequent analysis of that information?
- Can the hardware be used on other structures after project completion?

In summary, the use of advanced bridge evaluation technologies can provide owners with information that promotes “fact-based” decisions. Care and judgment are utilized when specifying and purchasing improved technologies, as well as use in the field. To obtain the best return on investment, defer to those with experience and earned reputation to provide alternative solutions for consideration

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