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Section 13
Advanced Inspection Techniques

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Section 13

Advanced Inspection Techniques

Topic 13.1 Timber

13.1.1 Introduction

Advanced inspection techniques 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 techniques 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 should have an understanding of the various advanced inspection techniques.

There are two main classifications of advanced inspection techniques. The first is labeled nondestructive testing or evaluation (NDT or NDE). This classification pertains to all advanced inspection techniques that do not impair the usefulness of the member being tested. Other testing, the second main classification, covers all advanced inspection techniques 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 techniques are becoming more popular for the routine inspection of all bridge members. Current and future studies have been, and will be focusing directly on relating results from advanced inspection techniques into Bridge Management Systems ratings.

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

13.1.2 Nondestructive Testing Methods

Pol-Tek

Pol-Tek is a sonic testing device that is used to detect rot or other low density regions in timber poles. 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 13.1.1).

Figure 13.1.1 Pol-Tek Sonic Testing Apparatus

This method eliminates the need for making holes in timber members. Members testing positive for rot are then drilled or cored to determine the nature of the defect. A dial reading that is low, compared with that of a good member of similar diameter, indicates rot or another low density region that delayed the sound wave within the member. However, several readings should be taken on the member since the readings are nearly instantaneous, and the Pol-Tek should be checked frequently for proper calibration.

Used by trained personnel, Pol-Tek 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 dimensions are known, the amount of time it takes for a stress wave to travel the known distance can indicate that defects 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 into a dynamic modulus of elasticity, which in turn, allows professionals 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 member is required.

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

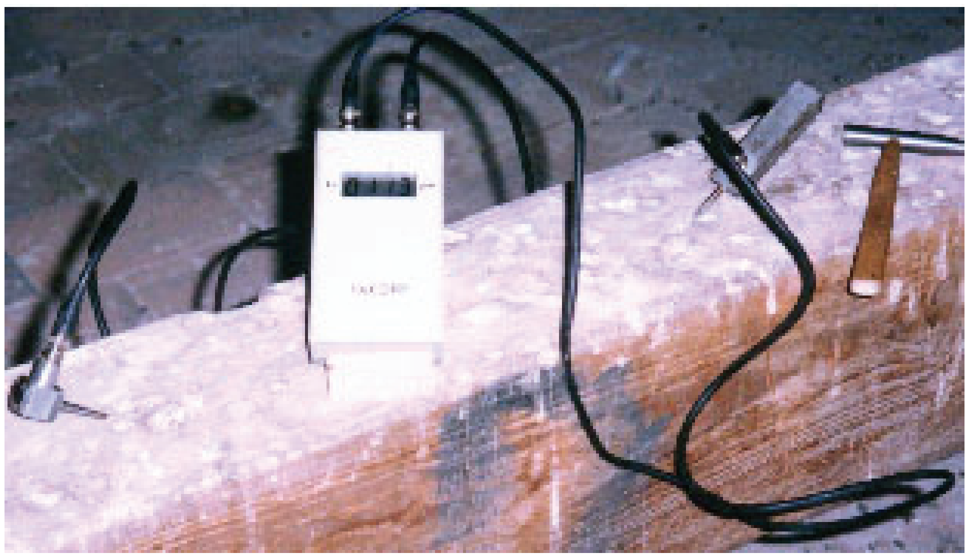

Figure 13.1.2 Stress Wave Timer

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 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 13.1.2).

Figure 13.1.3 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. This nondestructive testing method is based on the philosophy that all 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 defects 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.

13.1.3 Other Testing Methods

Boring or Drilling

Boring is the most dependable and widely used method for detecting internal decay in timber. Boring permits direct examination of an actual sample from a questionable member. An increment borer is used to extract wood cores for examination (see Figure 13.1.3).

Figure 13.1.4 Increment Borer

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. 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.

A decay detection device is a newer drilling technique. It operates upon the principle that a drill moving through sound wood will encounter more resistance that 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, because the record is marked in millimeters (mm) of penetration, can estimate the approximate location and size of the decayed area (see Figure 13.1.5).

Figure 13.1.5 Decay Detection Device

The use of increment cores for assessing the presence and damage due to bacterial and fungal decay requires special care. Cleaning of the increment borer is necessary after each core extraction to eliminate transfer of organisms; trichloroethane has been found to 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.

All bore holes can provide an entrance for bacterial and fungal decay to gain access to the member. As such, the holes must be treated with a preservative and must be plugged after testing.

Moisture Content

Moisture meters can be used to determine moisture content in a timber member. 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.

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. If the wood splinters, it is probably sound wood, and if it breaks abruptly, it is probably 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 should attach to the edge of a decay pocket, making it possible to determine the depth of the decay and the solid wood.

Shigometer

The Shigometer measures electrical resistance to detect decay in timber members. It should be used in wood with a moisture content of at least 27%, 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 3/32 inch in diameter. If the electrical resistance changes as the probe goes deeper, this indicates rot or a defect.

While this device effectively detects decay, it can also produce misleading readings on sound timber. Consequently, drilling or coring should be done on suspect members. Like the Pol-Tek, the Shigometer should be recalibrated frequently.

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Topic 13.2 Concrete

13.2.1 Introduction

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

13.2.2 Nondestructive Testing Methods

Acoustic Wave Sonic/Ultrasonic Velocity Measurements

A full evaluation of concrete decks can be accomplished with sonic˜ ultrasonic acoustic wave velocity measurements. This method delineates areas of internal cracking (including delaminations) and deteriorated concrete, including the quantification of strength characteristics (elastic moduli values). 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 13.2.1 and 13.2.2). 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 13.2.1 Portable Hand Held Sonic/Ultrasonic Testing Sensor Array System (http://www.ndtcorporation.com)

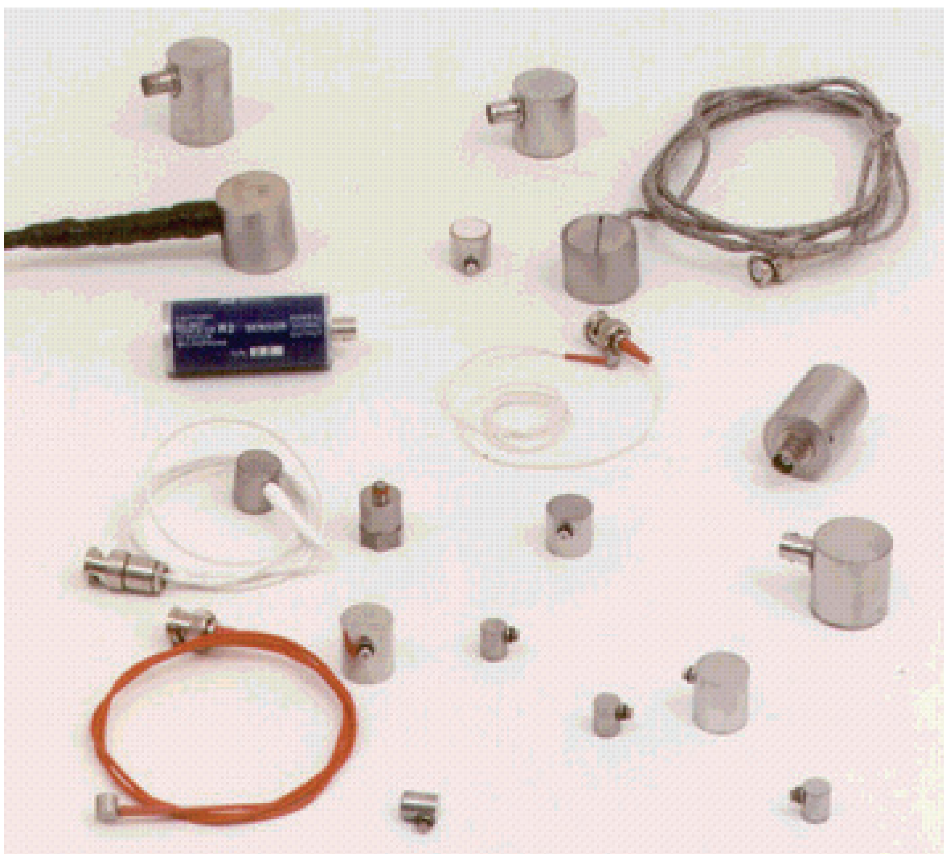

Figure 13.2.2 Acoustic Emission Sensors

Electrical Methods

Half Cell Potentials are used to evaluate the corrosion activity of reinforcing steel embedded in concrete. 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.

Delamination Detection Machinery

Delamination detection machinery is based on sonic responses and can be used to inspect concrete decks (see Figure 13.2.3). 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 13.2.3 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. As the wave spreads out and travels downward, if it hits a buried object or boundary with different electrical properties, then part of the wave energy is reflected or scattered back to the surface, while part of its energy continues to travel downward. 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 13.2.5). 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.

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/flaws in a reinforced concrete bridge, location of objects such as pipes, drums, tanks, cables, and boulders, mapping landfill and trench boundaries, mapping contaminants, and conducting archeological investigations. It has been used for concrete bridge deck and tunnel lining inspection.

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 75 mm (3 inches).

Electromagnetic Methods

Advancements in ground penetrating radar have lead 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 64 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 64 antenna modules or transceivers (see Figure 13.2.4). The system can inspect up to a 1.9 m (6'-3") width at a time with maximum speeds of up to 96 kilometer/hour (60 mph). At speeds of around 32 kilometer/hour (20 mph), the system can sample the concrete deck every 1.5 cm (9/16") 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. A 30 cm (11-13/16") penetration in concrete can be accomplished in about 6 nanoseconds. In the near future, a new system, called HERMES II, will update the original HERMES Bridge Inspector based on experience gained from the original.

Figure 13.2.4 The HERMES Bridge Inspector

Pulse Velocity

Pulse Velocity techniques 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 onto 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.

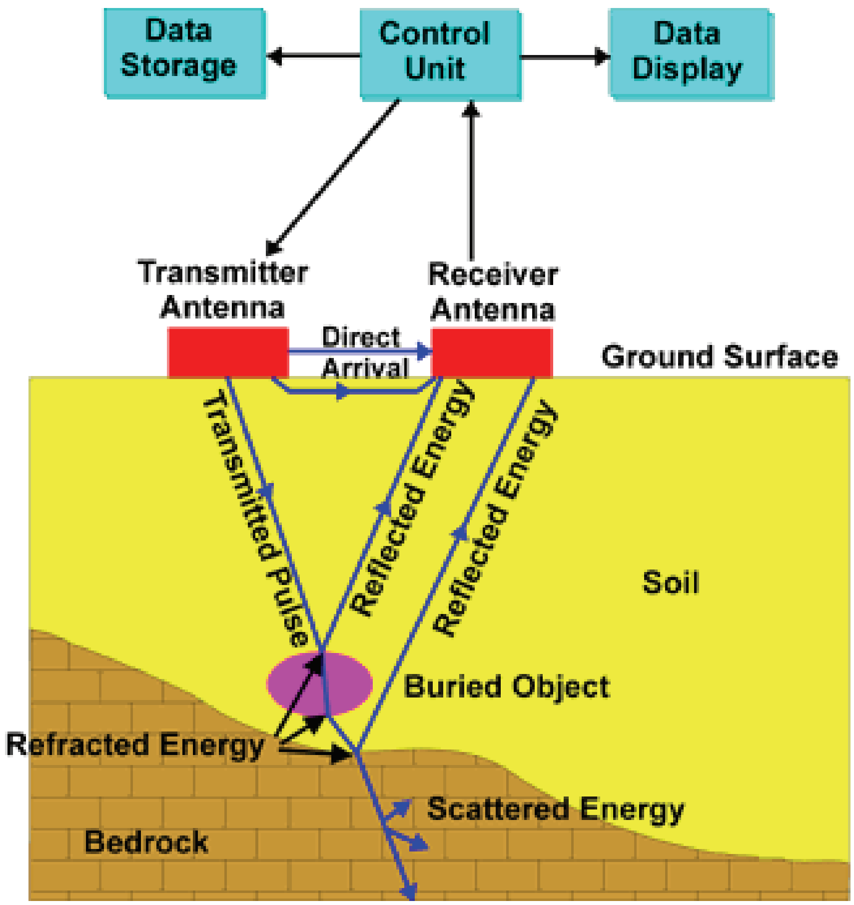

Figure 13.2.5 Schematic of Ground-Penetrating Radar

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 technique 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 13.2.6). 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 into 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.

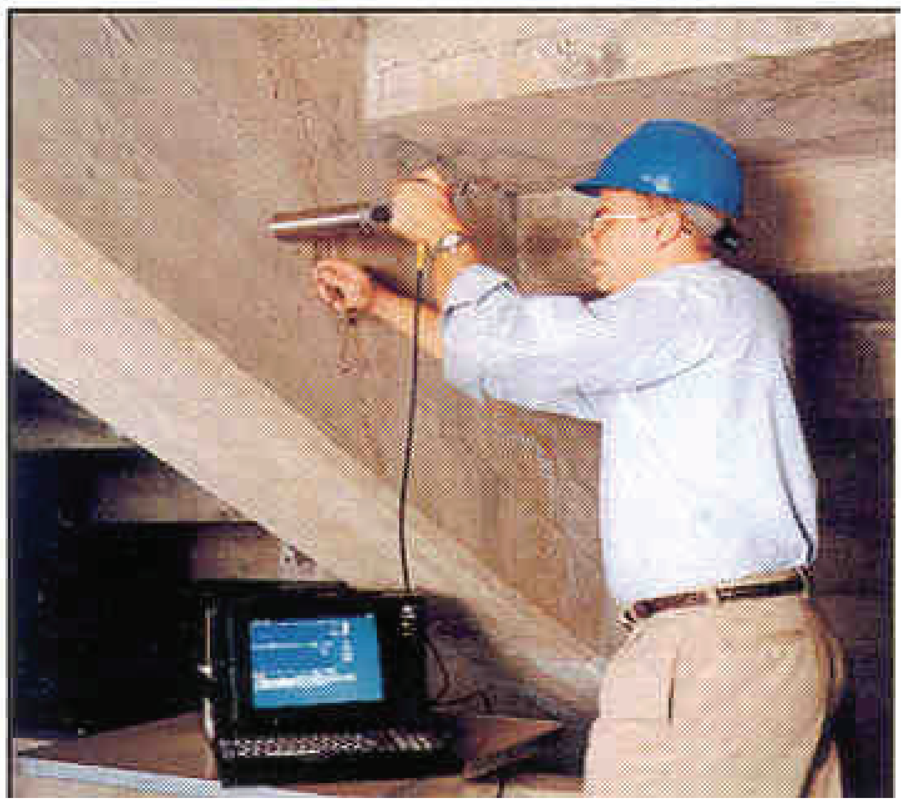

Figure 13.2.6 Impact-Echo Testing Equipment

Infrared Thermography

NDT inspection using thermography is based on imaging surface temperatures of a specimen in order to infer subsurface delaminations or defects. The basic theory is that heat conduction through a material will be altered if a delamination is present. Figure 13.2.7 graphically shows this concept. In this example the temperature of the deck is greater than the surrounding air. With no internal defect, heat flow through the deck will be relatively uniform. An image of the surface temperature of the deck will then produce an image that is relatively uniform. If a delamination is now present inside the specimen, the heat flow will be altered. In this example the surface of the deck above the delamination will appear to be lower in temperature than the remainder of the deck. The resulting image of the deck surface will show a corresponding area with a lower temperature.

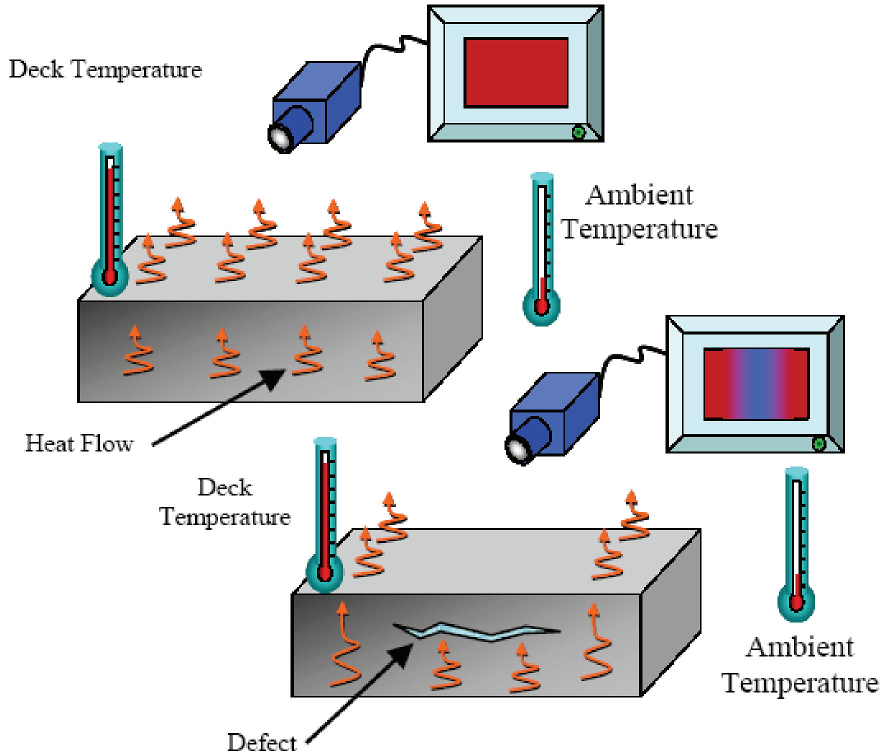

Figure 13.2.7 Schematic of Thermal Imaging

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 would 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, will alter results as well. Also, the technique is sensitive to material property differences on the specimen surface. Surface defects, such as oil stains, water, skid marks, will show up in the infrared data.

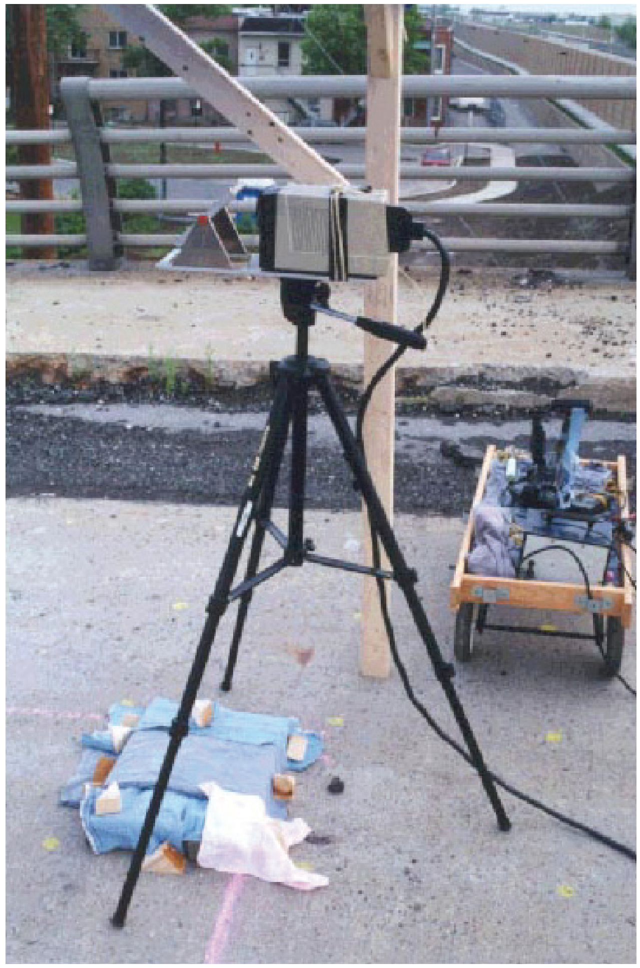

Figure 13.2.8 Infrared Thermography Testing Equipment

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 techniques 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. While the research has been encouraging for detecting fatigue-related damage due to the significantly different magnetic signals for corroded reinforcing, MFD has not yet been demonstrated for detecting in-service corrosion damage.

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 techniques. 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 would be more useful to the bridge inspector, and this method is therefore more research oriented than operational in the field.

Pachometer

A pachometer is a magnetic device used in determining the position of reinforcement. 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 75 mm (0 to 3 inches) to an accuracy of about 6 mm (1/4 inch).

Rebound and Penetration Methods

Rebound and penetration methods measure the hardness of concrete and can be used to predict the strength of concrete. The Schmidt 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 technique 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 is called the Windsor probe. A pistol-like driving device 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 will travel 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 are 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.

13.2.3 Other Testing Methods

Core sampling is a destructive form of concrete advanced inspection techniques, and it can weaken a member. Cores can be used for many of the following destructive tests. Usable cores can normally be obtained only if the concrete is relatively sound. If possible, cores should have a diameter three times the maximum aggregate size. All core holes should be filled with non-shrink concrete grout.

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.

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 into 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 13.2.9). 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 posttensioning 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 13.2.9 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 13.2.2) or from concrete samples taken from the bridge and oven dried in a laboratory

Petrographic Examination

Petrographic examination is a laboratory technique for determining various characteristics of hardened concrete, which are useful in determining the existing condition and predicting future performance. This advanced inspection technique will 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 should be done only when such data is essential. See Topic 13.3.3. for the tensile strength test of steel.

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 60 volts DC 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 50-mm (2") long and 100 mm (4") 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 30 volts DC, 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 into the specimen.

Matrix Analysis

Additional Test

ASR Evaluation

The 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 80 °C (176° F) 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 80 °C (176° F), 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.

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Topic 13.3 Steel

13.3.1 Introduction

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13.3.2 Nondestructive Testing Methods

Acoustic Emissions Testing (American Society of Nondestructive Testing Designation (ASNT) - AE)

Acoustic emission (American Society of Nondestructive Testing Designation (ASNT) - AE) detection has been around for many years, but is now becoming more of a standardized, available procedure.

This inspection technique detects elastic waves generated within a test object by such mechanisms as plastic deformation, fatigue and fracture. Acoustic emission listens for sounds from active defects and is very sensitive to defect 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 and growth of fatigue cracks in steel structural members: the failure of bonds, fibers and filaments in composite materials and the appearance of potentially hazardous flaws in metal or synthetic pressure vessels.

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 the crack growth.

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: location, origin, energy, frequency, etc.

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 sent to be analyzed by an engineer.

A device known as Local Area Monitoring (LAM) can be used to monitor areas that already are cracked or cracked areas that have been retrofit. The device is a portable, modular eight-channel system that can be mounted close to the area being monitored (see Figure 13.3.1). The system can be directly connected to a computer or it can be accessed through wired or wireless modems for data collection.

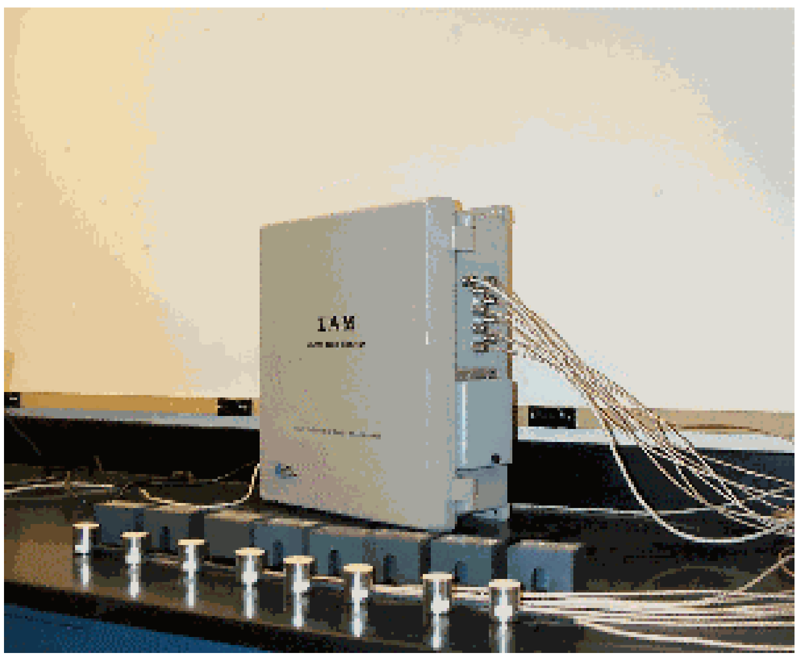

Figure 13.3.1 LAM System Showing Eight Sensors and Holding Magnet

Computer Programs

Computer programs have been developed to maximize the value of bridge inspections. In the pre-inspection routine, the inspector enters data on the bridge design and previously detected flaws. The computer responds with a customized checklist for the inspector, flagging critical areas of the structure. In the post-inspection routine, the inspector enters data about the flaws encountered in the field, and the computer responds with information about if the crack is likely to propagate and how to repair the crack. This procedure allows the inspector to detect flaws early and to judge which ones need immediate repair.

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 Paint 1

The National Science Foundation's ATLSS (Advanced Technology for Large Structural Systems) 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.

Smart Paint 2

Japanese scientists have developed a new 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 can be used to define the extent and size of surface flaws in steel members (see Figure 13.3.2). The test area is cleaned to bare metal, a dye is applied and allowed to penetrate the defect, and excess penetrant is removed. A developer is then 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

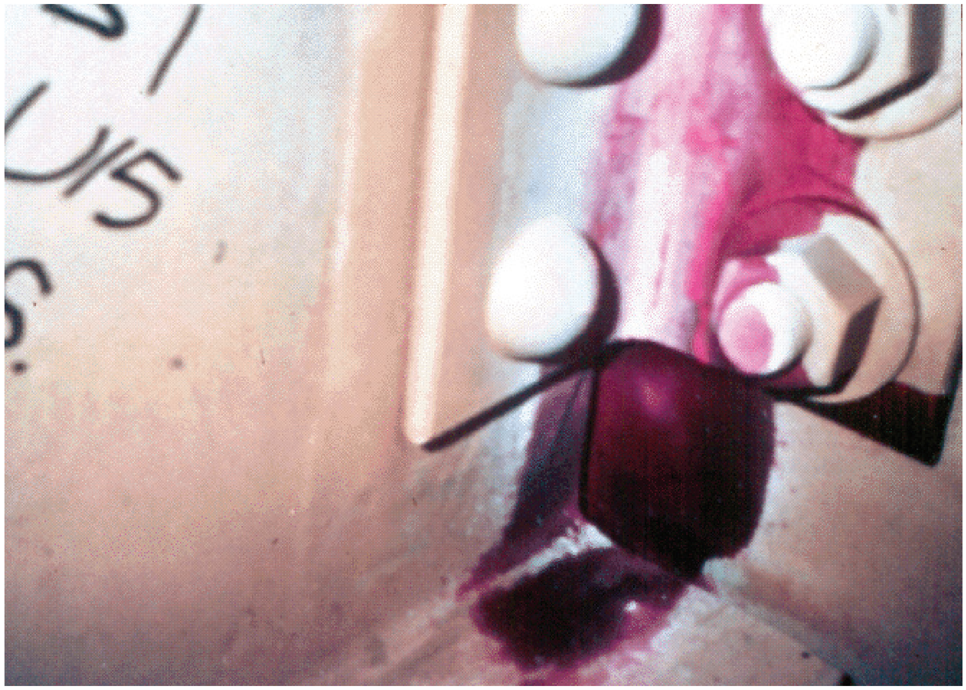

Figure 13.3.2 Detection of a Crack Using Dye Penetrant

Magnetic Particle

Magnetic particle or magnetic flux leakage testing is useful in detecting surface gouges, cracks, and holes in ferromagnetic materials. It can also detect subsurface defects, such as voids, inclusions, and cracks, which lie near the surface. 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 13.3.3). This technique is also referred to as magnetic field disturbance.

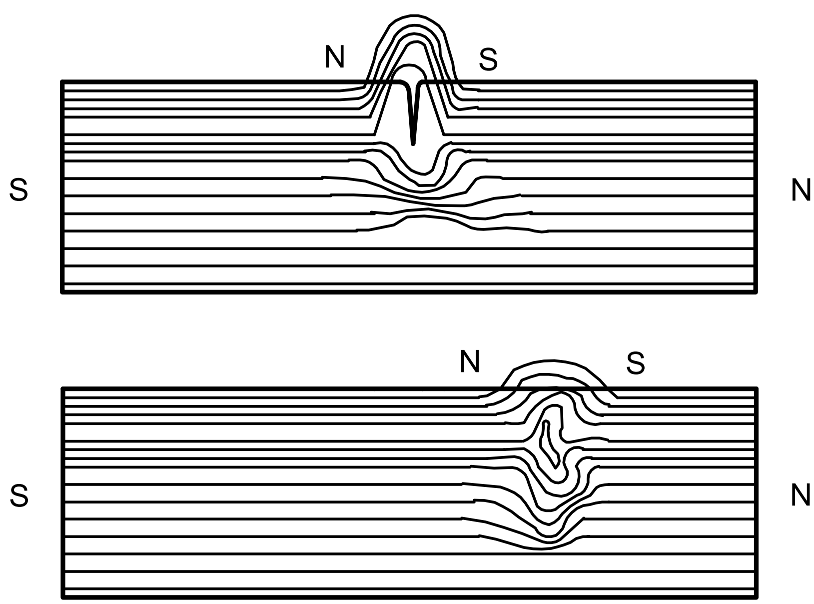

Figure 13.3.3 Schematic of Magnetic Field Disturbance

Radiographic Testing

Radiographic testing is used to detect and locate subsurface defects such as cracks, voids, and inclusions. X-rays or gamma rays are passed through the member and are absorbed differently by the various flaws. When a piece of film is exposed to the rays, the defects appear as shadows on the film. This type of advanced inspection is typically used for full penetration groove welds during fabrication and construction.

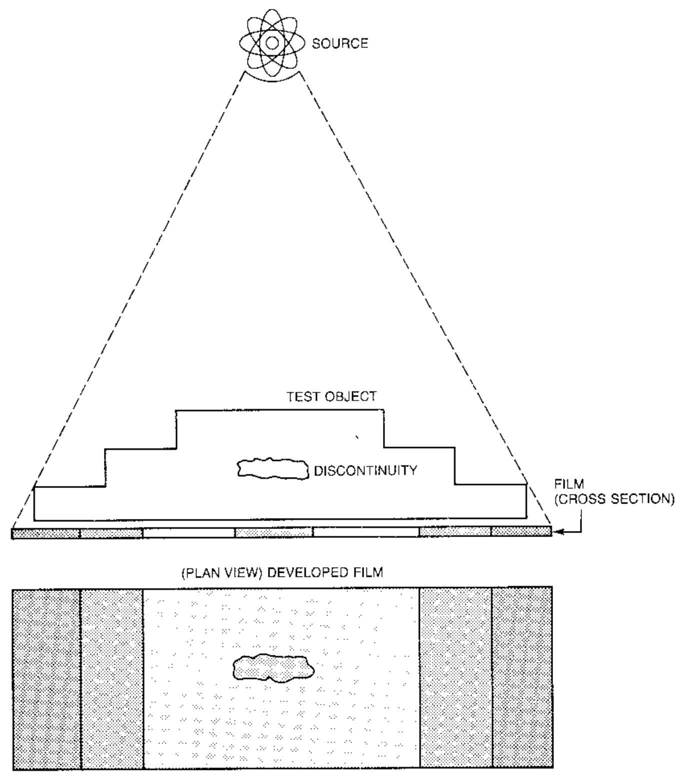

Figure 13.3.4 Radiographic Testing

Computer Tomography

Computer tomography uses X-ray and gamma radiation to visualize the interior defects 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 a system which uses 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 (see Figure 13.3.5). 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 (30 m) 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.

Figure 13.3.5 Robotic Inspection

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 (see Figure 13.3.6). 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. Refer to Topic 13.1 for further details about the principles of ultrasonic testing.

Figure 13.3.6 Ultrasonic Testing of a Pin in a Moveable Bridge

Eddy Current

This type of electromagnetic technique uses AC currents. Eddy current testing can only be performed on conductive materials and is capable of detecting cracks and flaws as well as member dimensions and variations. 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. Defects in the member disturb the eddy currents, which, in turn, effect the induced current. The effected induced current is monitored through the voltage across the coil. Eddy current testing devices can be hand held devices (see Figure 13.3.7).

Figure 13.3.7 Hand Held Eddy Current Instrument

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

13.3.3 Other Testing Methods

Strength tests are normally considered destructive tests since they usually involve tests conducted on pieces of steel removed from the bridge. Small steel pieces cut out of steel members are called test "coupons." The removal technique and coupon size must 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 should not remove a coupon from the web area over a bearing. An inspector also should not remove a coupon from the bottom flange at midspan. Destructive 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 technique 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 a 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 13.3.8). 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. This test can be performed at different temperatures to determine if the steel is susceptible to brittle failure.

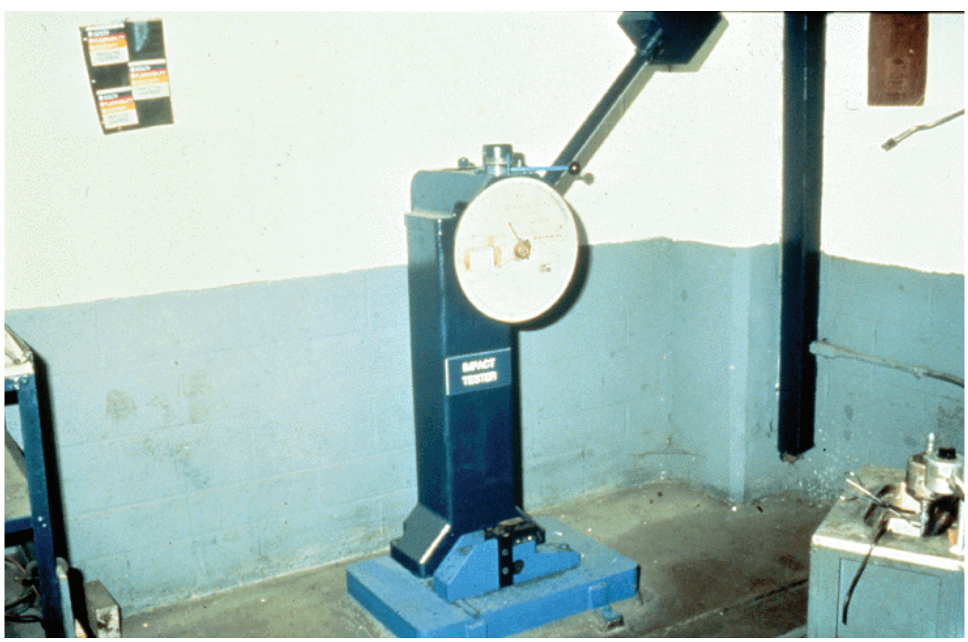

Figure 13.3.8 Charpy V-Notch Test

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:

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

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 ruptures. Once the yield strength has been exceeded, the coupon begins to elongate or "neck down" and eventually breaks if the load is not removed. The tensile strength of the steel can be easily determined. See Section P.2, 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 ruptures. This load and the cross-sectional area of the coupon determine the tensile strength of the steel (See Figures 13.3.9 and 13.3.10).

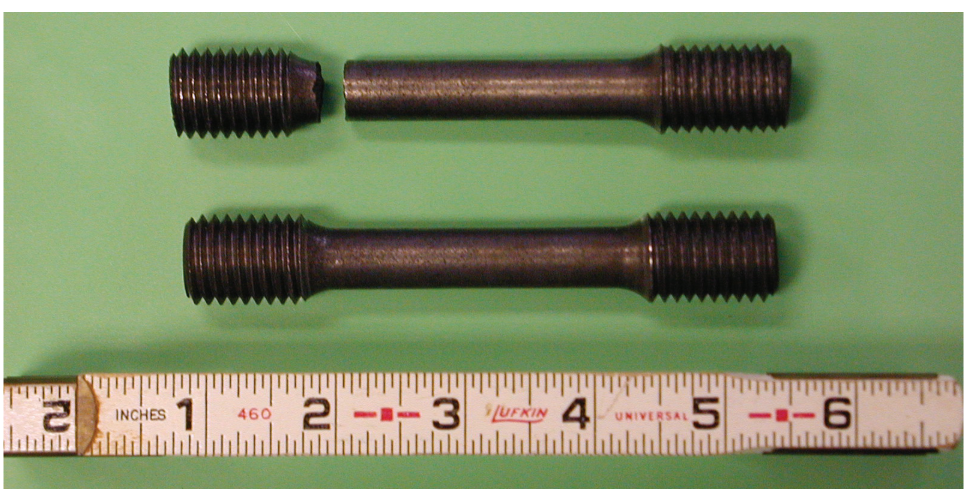

Figure 13.3.9 Brittle Failure of Cast Iron Specimen

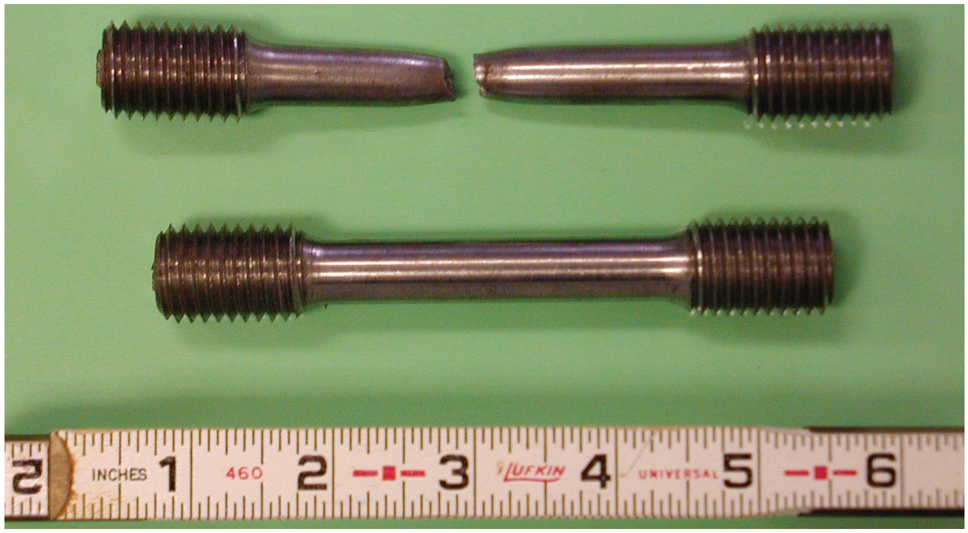

Figure 13.3.10 Ductile Failure of Cold Rolled Steel

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Topic 13.4 Advanced Asset Assessment

13.4.1 Introduction

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

Advanced asset assessment technologies allow the owner to more objectively capture and evaluate known or suspect defects found during a visual inspection. Also, they may be used to perform periodic or continuous inspections on members that are not readily accessible. Advanced asset assessment 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 advanced asset assessment results (see Figure 13.4.1). However, bridge inspectors should have a basic understanding of the various available advanced asset assessment technologies to allow them to participate in selection and use of appropriate asset assessment technology to further enhance rating determinations.

Figure 13.4.1 Installation of Sensors

There are two main classifications of advanced asset assessment technologies. The first is labeled nondestructive testing or evaluation (NDT or NDE). This classification pertains to all advanced asset assessment technologies that do not impair the usefulness (short term or long term) of the member being tested. The other classification consists of asset assessment technologies that affect or destroy the structural integrity of the member being tested. Most practitioners and owners today prefer the nondestructive technologies for obvious reasons.

Objective asset assessment solutions can support routine bridge inspection. As a result, advanced asset assessment solutions can be useful for the purpose of optimizing an owner's asset management program. Methods are being developed to transfer results from near real-time advanced asset assessment technologies directly into Bridge Management Systems ratings and bridge management protocols (e.g. permitting) (see Figure 13.4.2).

Near real-time advanced asset assessment 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 asset assessments.

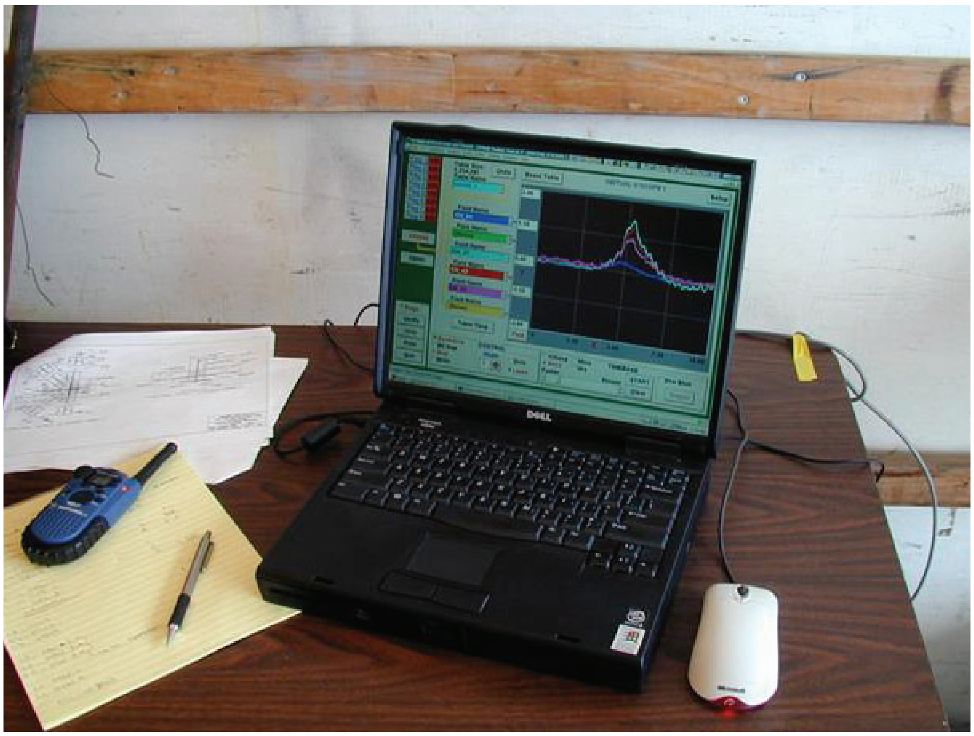

Figure 13.4.2 Viewing Real Time Data

13.4.2 Overview of Major Asset Assessment Technologies

Strain or Displacement Sensors

Strain or displacement sensors can be used to monitor the response of a member to a live load and/or thermal excursions (temperature changes). These type sensors are available and include foil type, vibrating wire, fiber optic, and even a sensor that measures current and peak strains (without power) in one device (see Figure 13.4.3). Foil type sensors must be used in the axial direction of flat members, and 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.

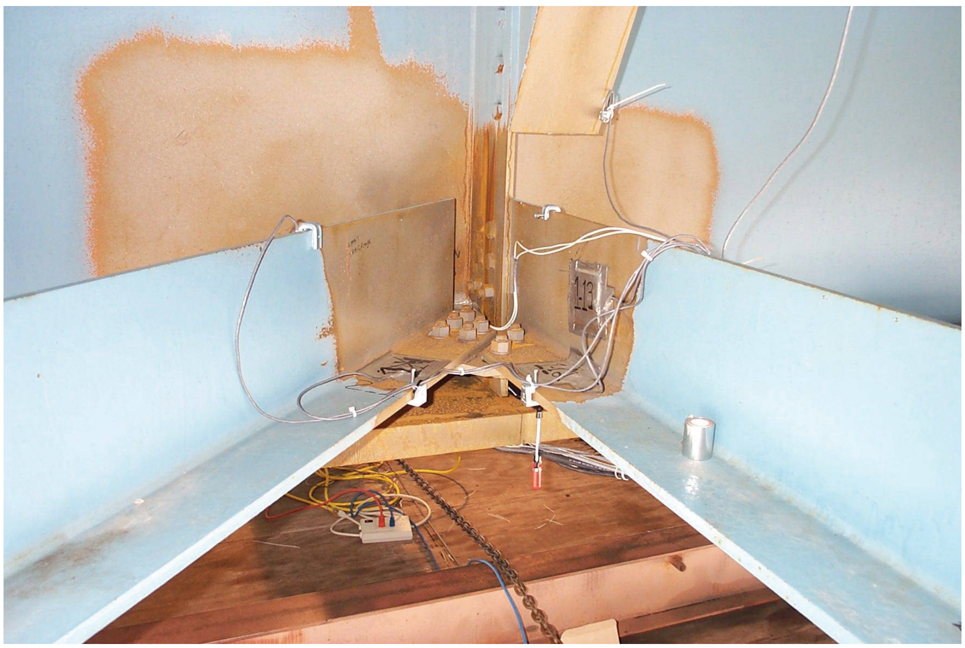

Figure 13.4.3 Strain Gage Used on Hoan Bridge

Locations for strain sensors should be 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, allowing secure data capture, data graphing, viewing over the Internet and even electronic alerts (e-mails) 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 asset assessment. Typical sensing devices include tiltmeters (foundation movements), accelerometers (earthquake induced movements), temperature and humidity sensors, and even GPS systems to monitor movement of piers, towers, and decks on long bridges to 5 mm (3/16") accuracy. 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 personal is required to integrate the variety of sensing devices with controller hardware and software for advanced asset assessment.

Dynamic Load Testing

In recent years, an increasing number of short-span bridges have been assessed using measured response data from known loads. These assessments have provided useful information and, in some instances, have revealed bridges which need to be closed or restricted and those that can be safely upgraded (load restrictions removed).

Use of this technique involves a novel 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. 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 (see Figure 13.4.4).

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 traditionally ignored with traditional analysis methods. Dynamic load testing has been used for over fifteen years and has proven its ability to provide accurate load carrying capacity determinations.

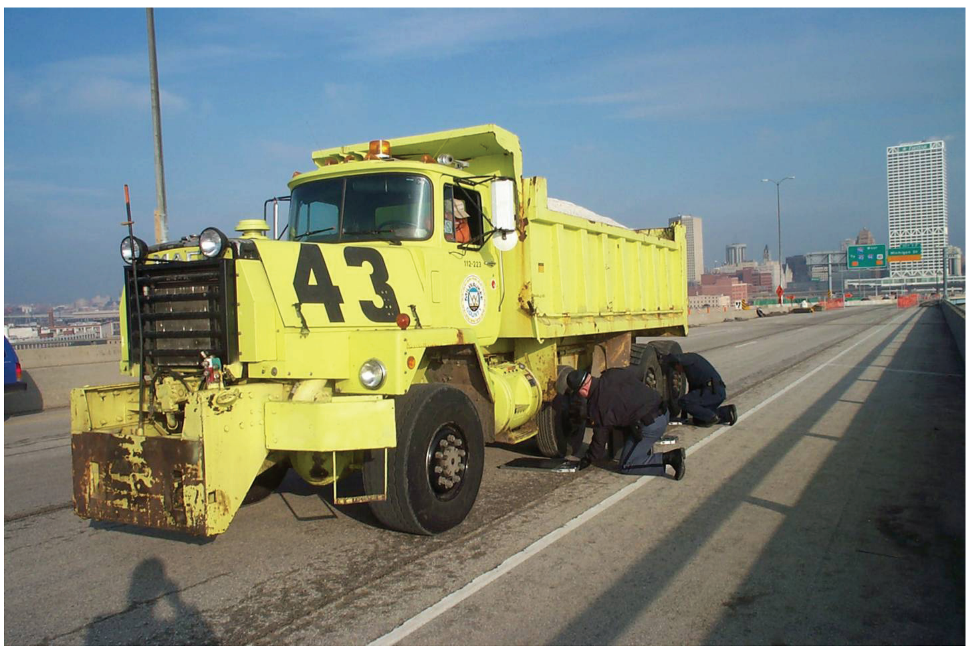

Figure 13.4.4 Dynamic Load Testing Vehicle

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 assessment 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 13.4.5). Subsequent analyses are then performed to determine which parameters are changing. Since the parameters represent structural properties (e.g., areas and moments of a 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.

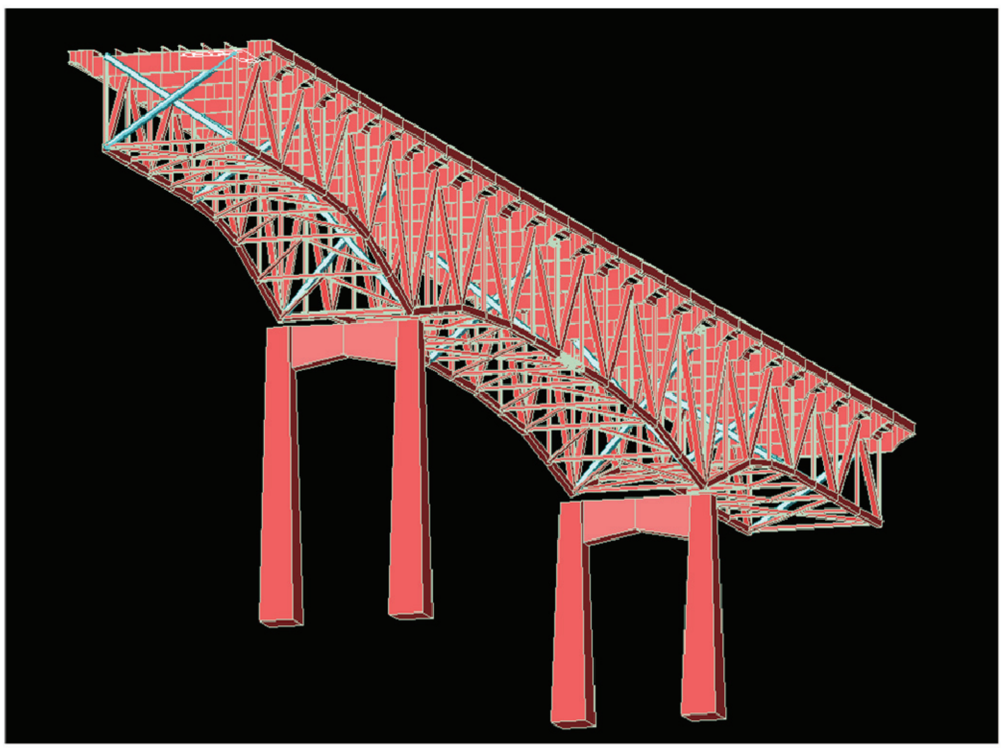

Figure 13.4.5 Structural Model

Practical Considerations for Selection and Use of Advanced Asset Assessment Technologies

Any advanced asset assessment technology should provide a reasonable return on investment. There is no reason to pay for technology unless that technology can provide a sufficient return for the asset owner. Over the past several years, significant research has been conducted to demonstrate new asset assessment technologies. Some worked well; others didn't. But given the current asset assessment technologies, owners should 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 asset life span, lowering life cycle cost of ownership
- Safe deferral of asset maintenance or repair programs
- Safe deferral of asset 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 dangerous assets that must be replaced or repaired immediately, thereby lowering liability exposure and increasing safety

Other considerations include the following issues that should be evaluated and decided upon before utilizing advanced asset assessment technologies:

- Is the asset assessment technology being used for a few bridges or across the entire system?
- Is the asset assessment technology capturing the "right" information to aid decision making and not a lot of extraneous information?
- Can the asset assessment 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 solution (hardware) be used on other structures after project completion?

In summary, the use of advanced asset assessment technologies can provide owners with information that promotes "fact-based" decisions. Care and judgment must be utilized when specifying and purchasing improved technologies, as well as use in the field. Always defer to those who have the experience and earned reputation to provide alternatives for consideration to drive best available returns on investment.