NONDESTRUCTIVE TESTING IN A BRIDGE MAINTENANCE PROGRAM

Edward M. Beck, P. E.
Law Engineering Industrial Services
a division of
Law Engineering Testing Company

I. INTRODUCTION

The title of this paper may lead one to believe that nondestructive tests, as utilized in a maintenance program, will solve all problems. Nondestructive tests alone do not solve problems or prevent trouble. Nondestructive tests in fact may lend information which create problems rather than solve them. The intent of this paper is to offer suggestions to the bridge design and maintenance engineer that we consider essential in order to have nondestructive testing work effectively in any maintenance program.

II. TEST METHODS

Nondestructive testing has become an important tool in the overall maintenance scheme to lessen the risk due to failure of a system as well as eliminate unscheduled interruptions to the systems operation. In order to evaluate nondestructive test methods and their proper use in the maintenance program, it is essential to understand some of the basics of each of the test methods available. Basically, nondestructive testing is designed as its name implies to test or to detect within a product or system, any discontinuities which may be detrimental to the serviceability of the system. In this paper, we will limit our discussion to the following nondestructive test methods.

Liquid penetrant	(PT)
Magnetic particle	(MT)
Radiographic	(RT)
Ultrasonic	(UT)
Eddy Current	(ET)

Liquid Penetrant Testing

This NDT method is probably the oldest and simplest method presently being used. It is said to have begun in the early days of the railroad to detect cracks in train rail, wheels and other highly stressed parts of the system. The materials used were quite basic. The part to be tested would be coated with a light weight oil which was allowed to remain on the surface for a short period of time. The oil was then removed from the surface of the part and a liquid, commonly referred to as "whiting", then applied. The whiting was quick to dry and when it had done so, would leave a bright chalky white coat on the surface. If any surface cracks were present, the oil would have been trapped within and subsequently drawn from the crack by the whiting which acted as a blotter. The results: an oil streak following the zone of the crack on the background of a chalky white surface.

Although the modern day liquid penetration materials are much more sophisticated, the principal remains the same. The penetrant material which may be either fluorescent or dye is applied to the surface of the part to be tested. This highly viscous material will enter any discontinuity open to the surface. By capillary action, the penetrant is drawn into the discontinuity and held there under extremely high capillary forces. The penetrant is then removed from the surface of the part by a compatible solvent but remains confined in the discontinuity. The blotter effect of the whiting now is accomplished by the application of a developer which has as many different compositions as the penetrants that are now being used. The developer, when dry, draws the penetrant from the discontinuity and to the surface of the part. Assuming that the penetrant were a red dye the developer would be white; thus, a red image of the discontinuity would be displayed on a white background. If the penetrant were fluorescent, upon drawing the penetrant to the surface the indications would be viewed under black light conditions.

Liquid penetrant techniques can be extremely useful and accurate to detect fatigue or stress cracking on the surface of parts. It can detect shallow discontinuities that other more sophisticated techniques cannot.

Although not that it could be called a disadvantage, this technique is limited to detect only those discontinuities which are open to the surface.

No matter what surface is being tested by

PT it must be clean and relatively free from irregularities. If the penetrant material cannot be removed from areas such as weld ripples it may mask surface flaws that exist, thus resulting in an invalid test.

II. MAGNETIC PARTICLE TESTING

The theory behind magnetic particle testing is, as you may have already concluded, the theory of magnetism. We will briefly explain how magnetic fields behave, how they are produced and distribute themselves in feromagnetic material and how they can be used in the detection of defects.

Recall the high school experiment where a piece of paper was laid over a bar magnet. When iron particles were sprinkled over the paper they arranged themselves in what appeared to be lines. This pattern, called a magnetograph, is the cross section of the magnets force field.

The two ends at which most of the flux lines leaves and re-enter the bar are called poles. The lines are thought of as leaving the north pole of the bar and re-entering the bar at the south pole. Normally a bar magnet has only two poles; one north and one south located at opposite ends of the bar. However, it may have a number of poles called consequent poles.

Each flux line must complete itself through a continuous loop. The line always leave the magnet at right angles to the surface and tend to seek the path of lowest reluctance.

If a bar magnet is partially cracked a north and south pole will form at opposite edges of the cracks. If iron particles are sprinkled on the bar magnet they will be drawn to this leakage field or north south pole.

It stands to reason that if a weld or any feromagnetic material were magnetized and if surface or slightly subsurface discontinuities were present, they would cause a leakage field. If iron particles were sprinkled on the surface, they would be drawn to this north-south pole and thus the discontinuity could be visually detected by the formation of the particles outlining the flaw.

There are a number of techniques used to magnetize test parts. We will discuss a few of the most widely used.

1. Use of electric current is probably the most commonly used method. The current is passed through the part by the use of prods in direct contact with the part or coils which surround the part.

The prod method causes a circular flux field to be passed through the part. Any discontinuity occurring at 45 to 90° to the flux pattern will attract the metallic particles.

A coil wrapped around a shaft will introduce a longitudinal field through its axis. Any discontinuity occurring at 45 to 90° to the axis of the shaft will attract the metallic particles.

2. Electromagnetic yokes are used to create longitudinal fields in the part being tested. They are composed of U-shaped cores of soft iron with a coil wound around the base of the U. The yoke method is becoming widely used in cases where surface discontinuities are likely to exist and portability is essential.

One advantage of MT over PT is that MT will detect not only surface defects, but slightly subsurface defects. As mentioned in penetrant inspection, if the surface is not properly prepared, flaws may be overlooked although preparation for MT inspection may not be as critical. For example, a MT test would be valid if the test object were cleaned by sand, shot blasting, mechanical grinding or brushing whereas these cleaning processes may mask or cover surface flaws disallowing penetrant to enter.

The metallic particles may be placed on the test object in either the dry or wet form. The most sensitive application is obtained using fluorescent particles suspended in a liquid. When used, the test area must be dark and the examination performed using "black" light. The wet fluorescent magnetic particle method may be one of the most effective and efficient tests available to detect fatigue and stress corrosion cracks on feromagnetic materials.

III. RADIOGRAPHY

The next two NDE techniques that will be discussed are considered as being volumetric tests in that they penetrate the entire volume of the object being tested.

Radiography employs highly penetrating x-rays, gamma rays, and other forms of radiation that do not damage the part itself. It provides a permanent visible film record of internal conditions, containing the basic information by which soundness can be determined. In the past decade alone, the evidence from millions of film records, or radiographs, has enabled industry to assure product reliability; has provided the informational means of preventing accidents and saving lives; and has been profitable for the user.

Industrial radiography is tremendously versatile. Objects radiographed range in size from microminiature electronic parts to mammoth missile components; in product composition from the lower through the higher elements of the periodic table; and in manufactured form over an enormously wide variety of castings, weldments and assemblies. Radiographic examination has been applied to organic and inorganic materials, and to solids, liquids, and even gases. An industry's production of radiographs may vary from the occasional examination of one or several pieces to the examination of hundreds of specimens per hour.

Probably the simplest way to describe how industrial radiography works is to compare its application to that of the medial profession's use of x-rays. Recall how chest x-rays are made. The technician positions your chest against an object (invariably cold) called a cassette or film holder. Behind you is a machine which produces x-rays. When the machine is activated, x-rays travel from the machine through your body and onto the film contained within the lightproof cassette. When the film is developed through a wet chemical process, images of the internal parts of your chest area appear on the film when viewed through high intensity light. These images are actually changes in the film density caused by the fact that more x-rays reached the film in the dark areas than in the light areas. The dark areas on the film are the meat and fatty tissues of your body and the light areas are of the ribs and spine or the more dense areas of the body. The x-rays are actually absorbed more by the denser areas of the body and are not reaching the film, thus some rays pass through and others are absorbed - the amount transmitted depending on the nature of the material and its thickness.

In industrial radiography, two basic types of penetrating radiation are used:

X-rays
Gamma rays

Nature of X-rays - X-rays are a form of radiant energy, as is light. Their distinguishing feature is their extremely short wave-length-only about 1/10,000 that of light, or even less. It is this characteristic that is responsible for the ability of x-rays to penetrate materials that absorb or reflect ordinary light.

Nature of Gamma Rays - Gamma rays are similar in their characteristics to x-rays, and show the similarities to, and differences from, visible light as do x-rays. They are distinguished from x-rays by their source, rather than by their nature. Gamma rays are emitted from the disintegrating nuclei of radioactive substances, and the quality (wavelength of penetration) and intensity of the radiation cannot be controlled by the user. Some gamma-ray-emitting radioactive isotopes, such as radium, occur naturally. Others, like iridium 192 and cobalt 60, are artifically produced. In industrial radiography, the artificial radioactive isotopes are used almost exclusively as sources of gamma radiation.

A radiograph is a photographic record produced by the passage of x-rays, or gamma rays, through an object onto a film. When film is exposed to x-rays, gamma rays, or light, an invisible change is produced in the film emulsion. The areas so exposed become dark when the film is immersed in a developing solution, the amount of darkening depending on the degree of exposure. After development, the film is rinsed, preferably in a special bath, to stop development. The film is next put into a fixing bath, which dissolves the undarkened portions of the sensitive salt. It is then washed to remove the fixer and dried so that it may be handled, interpreted and filed. The developing, fixing and washing of the exposed film may be done either manually or in automatic processing equipment.

Identification - If on the radiograph flaws are detected, the radiographer must be able to indicate their exact location on the part. Lead letters and numbers are used as station markers by placing them between the film and part. By absorbing more radiation than the surrounding area the letter images appear on the film. With their exact location marked on the part, the film or a tracing can be placed over the part lining up the markers, and the defect(s) may be outlined on the weld.

Other information such as the job name, part number, date etc., should also become a part of the radiograph. Quite often the radiograph will be kept on file for the life of the part, assembly or component.

Penetrameter - In order to determine the quality or sensitivity of a radiograph, a method of establishing this quality was developed through the use of a penetrameter. The penetrameter is a small rectangular piece of metal, containing several holes and in some cases slits and notches.

The penetrameter is placed on or near the area to be examined during the exposure. The image or outline of the penetrameter and the holes assure the interpreter that the radiographic quality is adequate.

In the inspection of weldments, radiography is an indispensible tool for the location of internal discontinuities. It is used to establish welding procedures, to qualify welders, and provide quality control of a welded part.

Most weld discontinuities can be detected by radiography since they consist of some change in material homogeneity.

Some of the most common weld defects detected by radiography are cracks, slag and tungsten inclusions, porosity, lack of fusion and inadequate penetration.

Although radiography is considered an excellent tool to detect internal discontinuities in materials, its effectiveness is greatly reduced when attempting to locate fine surface indications such as fatigue cracks. If such surface is accessible, either penetrant or magnetic particle examination is much more effective.

IV. ULTRASONIC EXAMINATION

The major limiting factor of radiography is the thickness of the part being examined. To radiograph metals over 7" in thickness requires extremely expensive equipment and even more expensive facilities to protect against radiation hazards.

In the 1930's it became apparent that another form of flaw detection which would overcome this thickness limitation was needed. During the 1930's German scientists developed a technique utilizing ultrasonic waves. During this early period efforts were made to employ reflected, as well as transmitted ultrasonic waves. The reflected technique was intended to overcome certain limitations found with the transmitted technique, primarily the necessity of requiring access to both surfaces of the specimen.

In the early 1940's Firestone invented an apparatus called the Supersonic Reflectoscope which utilized pulsed ultrasonic wave trains to obtain reflections from small defects. It was through the efforts of Firestone that ultrasonics found its way into production applications and was applied to critical quality control requirements.

To fully understand how ultrasound is used in the field of NDT we must first recall a few of the basic principals of sound and its reactions within solids. One way of describing these inter-reactions is to think of a solid as a series of balls, each interconnected, by springs. The balls represent the molecules, and the springs the inter-molecular forces within a solid.

If we were to apply a force normal to the plane of the molecules, the energy would be transmitted through the assembly of balls and springs in a manner of a series of compressive and expansive forces. This form of force transmission is called a compressive or longitudinal wave through matter.

If we apply the force at an angle to this plane we create a different wave form or wave mode. Now instead of pure compression and relaxation, we have the force being transmitted through a series of up and down motions or, as you would suspect, in a shear motion. The shear or transverse wave mode is similar to that of the longitudinal wave in that it too has a wave length, frequency and velocity.

Two other wave forms which will only be mentioned are the Rayleigh or Surface and the Lamb or plate wave. As they indicate, they are primarily used for surface flaw detection or for scanning very thin plate material.

Both the compression and shear waves are utilized to detect internal and external discontinuities which may be impossible to detect by any of the previous testing methods mentioned. The primary benefit of using ultrasonics is the extremely large material thickness ranges that can be evaluated. Practically every metal and non-metal product such as bars, tubes, sheets, plate, forging and castings can be evaluated both when being produced as well as while in service.

Certainly one of the most highly used ultrasonic test methods is ultrasonic thickness measurements. Material thinning due to corrosion, erosion and other in-service conditions can readily be performed using ultrasonic thickness techniques. Shear waves can be utilized to locate and size fatigue cracks, heat cracks, stress corrosion cracks, etc.

One of the most essential ingredients of ultrasonic examination as opposed to the previous test methods mentioned, are calibration standards. It is impossible to perform even the most basic ultrasonic thickness test without a calibration standard of the known material type and thickness. Standards are also essential when searching for anomalies which are of an unknown size and distance from the surface being examined. Without a proper standard, the evaluation of such anomalies would be impossible.

V. EDDY CURRENT

In 1832 Faraday reported the discovery of the law of electromagnetic induction which forms the basis of eddy current testing.

Eddy-current testing involves the use of a varying magnetic field produced by a test coil to induce small circulating currents called eddy currents into electrically conductive materials. Certain properties within the material have an effect on the eddy current induced. The eddy currents themselves set up a magnetic field of the coil in such a way that the impedance of the test coil is changed. Any change of the eddy currents is reflected by a change in test coil impedance. Since the impedance of the test coil can be monitored by instruments, any factor existing in the material under test that affects the eddy currents can be detected.

There are three properties of materials that affect the eddy currents induced in test materials. These are:

A. Conductivity: which is the ability of the material to conduct electrical current. Factors that affect conductivity are: alloy composition, hardness temperature and residual stress, and conductive coatings.

B. Permeability: which is the ability of a material to become magnetized.

C. Dimensional variations such as material thickness changes and discontinuities cause impedance changes in the eddy current coil used in the examination. Lift off, or in the case of internal coils, fill factor are the terms used to describe any space that occurs between the article under test and the inspection coil.

There are three coil types which are used in ET examinations. These are the surface coil, the external or feedthrough coil and the internal or bobbin coil.

Eddy currents decrease in strength with increase in distance from the test coil. So discontinuities whose major axis lies parallel to the current flow will not be detected as those whose major axis cuts across the current flow.

The two methods utilized in eddy current testing are differential and absolute methods. In the differential method, an alternating voltage is impressed across two test coils. The coil voltage is sinusodial and can be described with a single vector having magnitude and phase. The absolute method uses only one test coil.

Selecting the right frequency is a critical part of ET testing. The frequency is a function of both material conductivity and thickness. The higher the frequency the less the penetration and vice versa. Also increasing frequency will increase phase discrimination.

Like ultrasonic testing without a proper calibration standard, it is impossible to perform a proper test. The calibration standard performs three functions; it allows to balance the coils to the material being examined, developes a defect depth versus signal phase relationship and allows the operator to qualify the procedure.

Eddy current method is the predominant test used in tube analysis of heat exchangers. Also, eddy current can be used for thickness measurements of conductive and non-conductive coatings and cladding thickness plus crack detection utilizing the surface probe techniques.

III. PROGRAM IMPLEMENTATION

Now that we have discussed some of the basic details of nondestructive test methods available to you as a bridge desigh and maintenance engineer, let's now discuss how nondestructive tests can work most effectively in a maintenance environment. First and foremost, there must be a systematic approach to the overall maintenance scheme. Components of the bridge must be subdivided into various categories and systems. When these decisions have been made and a preliminary program devised, it is then time to invite engineers who are familiar with nondestructive evaluation to discuss the systematic approach proposed by the maintenance engineering staff.

Although this paper's primary intent is to discuss how nondestructive examinations can be utilized in a maintenance environment, I feel that we must go back one step prior to the bridge being placed in service. In many instances, bridges and bridge components have been improperly fabricated, and/or manufactured. It is essential that bridge engineering have control over the purchase of new equipment, which includes both the design for service as well as the manufacturing of that component. A weak set of specifications and poorly assembled equipment, can be a real headache and greatly reduce the equipment's reliability when put into service. All of this creates a tremendous additional maintenance cost. Money spent up-front prior to putting equipment into service is money well-spent; eliminating costly maintenance problems and perhaps saving lives.

When the bridge engineer has categorized the equipment the nondestructive testing engineer should be invited to participate in the development of a nondestructive examination program. This individual may be a private consultant or may be associated with an engineering-testing organization. A detailed review of the systems proposed for the maintenance program should be performed at this time. A historical review of each individual piece of equipment needs to be performed to determine what tests and evaluations have been performed in the past and the anticipated present condition. This step is essential to establish a baseline for each individual piece of equipment. Once this baseline review has been performed, the nondestructive testing engineer should prepare a recommended test procedure for each piece of equipment. This may involve nothing more than a visual examination, or a combination of several nondestructive tests. In addition to the recommended type of nondestructive examination, the nondestructive examination engineer and bridge engineer should agree on the frequency of inspection.

At this point, one of the most important steps must be taken. What are acceptable conditions; what are rejectable conditions? As we stated earlier in this paper, no one nondestructive examination solves problems. If the bridge engineer, design engineer, and nondestructive examination engineer have not decided on acceptable standards for each piece of equipment, then more than likely serious problems will occur when discontinuities are found during the evaluation stage. When does a discontinuity become a defect? This question must be answered before the evaluation begins.

When the type, frequency, and degree of inspection has been determined, then the nondestructive examination engineer should provide the bridge engineer with information regarding the amount of time to perform the agreed-upon examinations. This information being provided, the bridge engineer may now summarize the time and involvement to perform the agreed-upon examinations. This is essential in establishing an orderly and timely maintenance program.

Prior to the examinations and the work being performed, it should be agreed upon as to the type of reporting that will result from the examinations. It is essential to have reports which are easy to read, and point out anomalies quite rapidly. When large volumes of data are produced by nondestructive examination, it is essential to have an information management system which can answer questions raised by the bridge engineer accurately and quickly. This is not to say that the system must be so complicated and exotic that it is both too expensive as well as ineffective.

Quite often in the past, and to a lessor degree presently, subcontracted nondestructive examination services have done more to cause problems than to solve problems in a bridge maintenance program. Quite often, the only consideration given to the nondestructive examination is to look at last year's budget and see what the NDE costs were, realize that not all of the work got done, then increasing the budget to compensate during the next campaign. Adding more people and money for testing very seldom solves the real problem, and that is, lack of a systematic approach of obtaining data that is meaningful to the overall integrity of the bridge process. When the basic steps addressed by this paper are accomplished, then, and only then, will nondestructive testing and monitoring prevent trouble.

BIOGRAPHICAL SKETCH

Edward M. Beck is Chief Engineer and Corporate Consultant with Law Engineering Industrial Services, a Division of Law Engineering Testing Company located in Charlotte, North Carolina. Mr. Beck received a BCE degree from Auburn University and is a Registered Professional Engineer in North Carolina and New York. He is a member of ASNT, ASME, AISC and AWS. Mr. Beck presently serves on the AWS Qualification and Certification committee and is vice chairman of the AWS Structural Welding Code D1.1 Committee. He presently serves as a D1.1 representative on the subcommittee on AASHTO/AWS Bridge Welding Committee.