Non-destructive Testing for Inspection of Bridges and Buildings

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LIST OF ABBREVIATIONS

Items	Description
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
AE	Acoustic Emission
AL	Alabama
AOI	Areas of Interest
ARA	Advanced Robotic and Automation
ASTM	American Society for Testing and Materials
AUT	Automated Ultrasonic Testing
BFRP	Basalt Fiber Reinforced Polymer
CAROS	Climbing Aerial Robot System
CATT	Computer Aided Tap Tester
CET	Chemical and Electrical Testing
CFRP	Carbon Fiber Reinforced Polymer
COMAC	Coordinate Modal Assurance Criterion
CT	Chemical Testing
DOL	Duration of Load
DPI	Dye Penetrant Inspection
DST	Damage Sequence Tree
DTT	Digital Tap Testing
EC	Eddy Current
ECT	Electrical Capacitance Tomography
EIS	Electrochemical Impedance Spectroscopy
E/M	Elasto-magnetic Method
EM	Electromagnetic
ETL	Equivalent Time Length
FHWA	Federal Highway Administration
FL	Florida
FRP	Fiber Reinforced Polymer
FT-DEDA	Fourier Transform-based Defect Detection Approach
FTA	Fault Tree Analysis
GA	Georgia
GFRP	Glass Fiber Reinforced Polymer
GHz	Gigahertz
GPR	Ground Penetrating Radar
GPS	Global Positioning System
GSR	Global Structural Response
HDPE	High-density Polyethylene
HW	Helically Wrapped
HWSC	Helically Wrapped Sand Coated
IE	Impact Echo
IR	Infrared Thermography
IRT	Impulse Response Testing

KHz	Kilohertz
LPI	Liquid Penetrant Inspection
LPR	Linear Polarization Resistance
LT	Laser Testing
MAC	Modal Assurance Criterion
MC	Moisture Content
MFL	Magnetic Flux Leakage
MHz	Megahertz
MOE	Modulus of Elasticity
MS	Magnetostatics
MSC	Mode Shape Curvature
MSCS	Mode Shape Curvature Square
MSE	Modal Strain Energy
MSS	Mode Shape Slope
MsS	Magnetostriction
MT	Magnetic Particle Testing
MW	Microwave Testing
NCHRP	National Cooperative Highway Research Program
NDE	Nondestructive Evaluation
NDT	Non-destructive Testing
NFRA	Neuro-Fuzzy Recognition Approach
NMR	Nuclear Magnetic Resonance
NSM	Near Surface Mounted
PAU	Phased-array Ultrasonic
PE	Polyethylene
PFD	Penetrant Flaw Detection
PT	Penetrant Testing, Post-tension
PTM	Precursor Transformation Method
QA/QC	Quality assurance/quality control
RC	Reinforced Concrete
RD^3	Rapid Damage Detection Device
RGB	Red, Green, and Blue
RH	Relative Humidity
RSC	Reinforced/Strengthened Concrete
RT	Radiographic Testing
RUDERM	Rust Defect Recognition Method
SC	Sand Coated
SHM	Structural Health Monitoring
SKMA	Simplified K-Means Approach
SMFL	Self-magnetic Flux Leakage
SPR	Surface Penetrating Radar
SuRE	Surface Response to Excitation Method
SwRI	Southwest Research Institute
TBM	Tunnel Boring Machine
TOF	Time-of-flight
TT	Tap Testing
UAV	Unmanned Aerial Vehicle
UPV	Ultrasonic Pulse Velocity

US	United States
USA	United States of America
UT	Ultrasonic Testing
UV	Ultraviolet
VT	Visual Testing
WDO	Wood-destroying Organisms

CHAPTER 1

INTRODUCTION

Abstract

Unchecked damages and the potential failure of civil structures could not only have a significant economic impact but also threaten public safety. As such, they should be inspected at short intervals to prevent the spread of damages and potential failure. These damages, after detection, should be repaired and the structure appropriately rehabilitated to prevent future catastrophic failures. It goes without saying that detecting the damages is the first step in this process.

Most of these damages in their advanced stage can be detected easily with a visual inspection. However, the detection of internal and subsurface defects requires inspection and testing techniques with capabilities above and beyond visual inspection. To address this, various NDT methods have been practiced over recent decades. The type of NDT method required for the inspection should incorporate the most practical and cost-effective technique to successfully assess the condition of the structural components and to determine the need for maintenance and repair action. In addition to a familiarity with and skill in the use of various available methods, the inspector needs to be aware of the environment in which the inspection takes place, as well as the section of the structure that is under survey, to determine the proper procedure.

REVIEW OF AVAILABLE NDT METHODS

Over the years, various techniques have been implemented for the inspection and structural health monitoring of the civil infrastructures. Among these techniques, non-destructive testing (NDT) methods incorporate testing of structural components and structural systems without causing any damage, changing their material composition or shape of the inspected components. These methods bring an innovative and rapid mode of inspection with which structural deficiencies such as cracks, fatigues, delamination, voids, and corrosion can be detected, analyzed, and diagnosed. The required type of NDT method differs from one structure to the next, depending on the structural type, the environment, and the preference of the owner. The selection of the methods also relies on their accuracy and cost of the operation.

This book presents the information regarding the application of NDT methods for building and bridges constructed using steel, reinforced concrete (RC), fiber reinforced polymers (FRP), and timber. Although both global and local damage detection methods are discussed, the focus of this book is on the methods applicable to local NDT methods. As such, the methodology, advantages, and disadvantages of each technique are thoroughly presented. Furthermore, recent innovations in this regard, including the application of drones, sensors, or robots for rapid and efficient assessment of damages on small and large scales are presented.

NDT methods are categorized in two major groups, those applicable to external or surface defects and others that are applicable to internal defects.

NDT METHODS FOR EXTERNAL OR SURFACE DEFECTS

NDT methods discussed in this section can be implemented to detect defects and damages occurring on the surface of test material. These methods can be considered as simple to apply and easy to interpret when compared to methods for internal defects. Despite the relative simplicity of these methods, the results are subject to human interpretation and the inspectors should be experienced and well trained. The following sections describe these methods.

Visual Testing (VT)

This technique is the most common form among all NDT methods due to its simplicity. Although most of visual inspection is performed with the naked eye, some cases may require visual aids such as magnifiers, binoculars, scopes, and borescopes. An inspector in this case needs to be experienced and familiar with the types and levels of damage in the material being inspected.

This is the most economical and fastest method of inspection [1]. However, because of the subjectivity of the visual inspection method, different results could be reported by different inspectors. Visual inspection limits the inspector to the surface defects that are sufficiently noticeable [2]. Different conditions can affect the inspector's judgment and focus, including traffic, working at a height, limited visual angle, lighting conditions, and multitasking with other tasks for bridge element rating [3]. These factors can be problematic for the inspectors to decide whether a flaw should be considered a defect and if it requires follow-up action. An example of challenging visual inspection is shown in Figure 1-1, where the lack of lighting and height can affect the inspector's ability for interpretation.

(a)

(b)

Figure 1-1 Challenges of visual inspection method: (a) Lack of lighting [3]**; (b) Visual inspection at heights can be dangerous and challenging** [1]

There are two ways in which a visual inspection can be conducted: 1) direct visual testing and 2) remote visual testing or visually aided inspection (see Figure 1-2) [4].

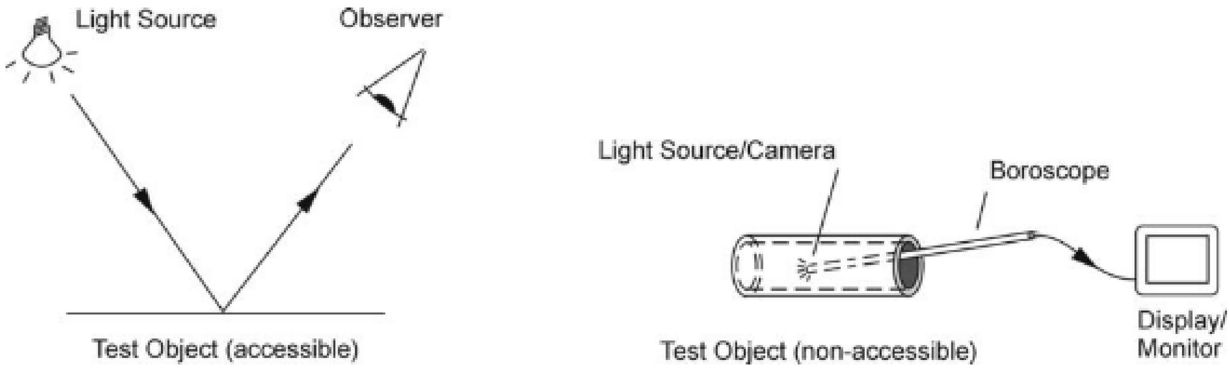


Figure 1-2 Direct and remote visual testing [4]

Direct Visual Testing

In direct visual testing, the inspection surface is directly accessible to the human eye however, instruments like cameras, mirrors, binoculars, magnifying lenses, flashlights, etc. may be used to enhance visibility. In addition, instruments like measuring tapes, calipers, gauges, micrometers and other measuring devices are used to take quantitative data of the observed defects.

Remote Visual Testing or Visually Aided Inspection

In remote visual testing, borescopes, fiberscopes and traditional video cameras are used to capture easily interpretable images of the surfaces that are not directly accessible to the human eye. Figure 1-3 shows the use of borescope for inspection of voids in PT ducts.

Figure 1-3 Use of borescope for inspection of voids in PT ducts

Penetrant Testing (PT)

Penetrant testing is also known as Dye Penetrant Inspection (DPI), Penetrant Flaw Detection (PFD), and Liquid Penetrant Inspection (LPI). The basic principle behind the dye penetrant testing is to increase the contrast between the defect and the surrounding material to detect the defects that may not be evident under normal visual inspection. The step-by-step process of the dye penetrant testing is shown in Figure 1-4 which involves spraying a high penetrating dye on the FRP composites, removing the excess, and applying a developer agent which reveals the defects either by color contrast under normal visible light or by fluorescence under UV light [5]. The penetrant dye is usually packed in a kit that contains the required chemicals in three aerosol spray cans, i.e., a cleaner, a penetrant, and a developer. Each of the cans is related to a specific step of the process [6].

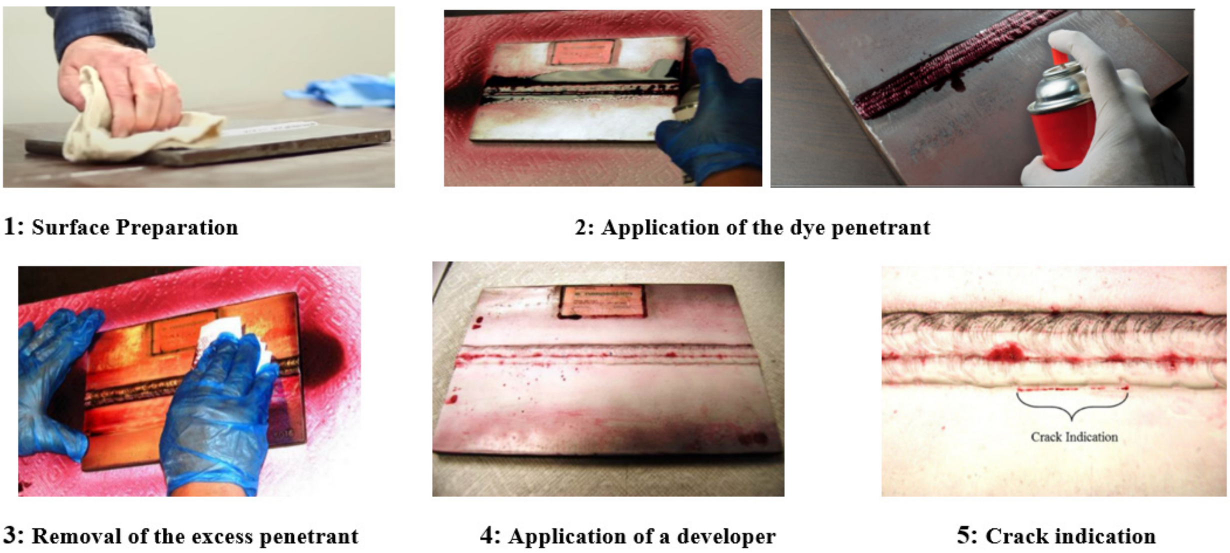


Figure 1-4 Steps for implementation of PT tests [7]

Flexibility of the method with respect to shape and size limitation of the elements to be tested, ease of use and interpretation, low-cost equipment, and high sensitivity are some of advantages of using this method. The dye penetrant method is highly sensitive, portable, and can detect even the smallest surface discontinuities. This method is inexpensive and simple and can be implemented for the confirmation of the visual inspection. It can be applied to a variety of base material and is suitable for complex shapes.

However, there are some disadvantages for this method: It is not suitable for inspecting the elements with a porous surface; it requires caution in pre-cleaning, chemical handling, and removal of the excess penetrant; and the inspector needs to access the tested components to safely conduct the whole inspection [8]. Its process is time-consuming and, as a result, may not be cost-effective where multiple locations need to be inspected. Temperature dependency, sensitivity to contamination, chemical compatibility issue, pre- and post-cleaning requirement and preparation of the surface, and inability of exanimating the sub-surface and internal discontinuities are some of the other drawbacks.

This method has been mostly used for steel material; however, it has some potential for detecting, or magnifying, FRP surface defects. It is used to detect and monitor surface cracks, welded details, and gusset plate connections in steel members. It is applicable to all types of material except for porous materials such as unglazed ceramic, wood, pottery, and cloth. Thus, the use of penetrants for detection of defects on concrete is questionable because of its porosity, however, there may be some application on detecting surface cracks at construction and closure joints.

Magnetic Particle Testing (MT)

Magnetic Particle Testing (MT) method (Figure 1-5) is used for detection of the surface and sub-surface defects in ferromagnetic materials. In this test, magnetic field magnetizes the element where discontinuities disrupt the magnetic flux (straight line of magnetic force which is existing in magnetic circuit). The sub-surface and surface defects are revealed by applying the ferromagnetic particles like iron powders [9].

Figure 1-5 An example of MT inspection [3]

In this method, after cleaning the surface of the test component from oil, grease, or any other contaminants, a magnetic yoke is placed on the surface, generating magnetic fields between the yoke probes. This creates magnetic flux lines which flow between the legs of the yoke. As such, any defect interrupting the magnetic flux lines produces a localized area of flux leakage, consequently changing the formation of iron particles that is spread on the suspect area.

There are two methods for applying this technique: implementation with dry iron particles or wet iron particles. For dry MT, iron powder is applied to the surface of the test area while the magnetic field is applied by the yoke. Then, the surface is lightly blown using a bulb applicator, removing additional iron particles. In response, the particles are absorbed and clustered at flawed sites (magnetic leakage areas), creating a clear indication.

For the wet MT application, the iron particles in a combination of water or oils are sprayed to the test areas. Other steps for the application of wet MT are the same as dry MT. Other relevant sources can be referred for more detailed procedures and practices[9], [10].

Compared to the PT method, the application of MT is faster and less costly, and requires less surface preparation. This method is simple and requires minimum training for inspectors. Recognizing the sub-surface and surface discontinuities, high speed test (in comparison with PT), no need for the surface cleaning and preparation (in comparison with PT), ability to test the elements which have a very thin coating, low-cost equipment, ease of use for testing and analyzing the element, and high sensitivity of testing are some of the important advantages for MT evaluation. MT can be implemented to detect surface and near-surface internal flaws in steel bridge elements.

However, this technique has some disadvantages, including issues for irregular surface finishes, the need for lane closure for performing the test, material type limitation (useful just for ferromagnetic materials), shape and size limitation, requiring two directions of measuring, inaccuracy for the element with coating, possible demagnetization needed after the test, and inability to detect deep internal defects [11]. The coating thicker than 2 mils should be removed before applying the tests [3].

Eddy Current Method (EC)

Eddy current (EC) method represents a non-destructive electromagnetic test that uses energized probes. This technology uses eddy coils placed side by side on the probe. When the probe is placed on the test piece, a dynamic magnetic field is created around the probe. This magnetic field produces eddy currents in the test piece centered on the probe. The currents induced on the test piece oscillate in a circular pattern and flow in a direction opposite to the current in the coil. Any cracks or discontinuities affect the magnitude and phase generated by the eddy current, therefore pointing to a defect. Figure 1-6 shows an example of EC practiced for the purpose of detecting a flaw on a steel element.

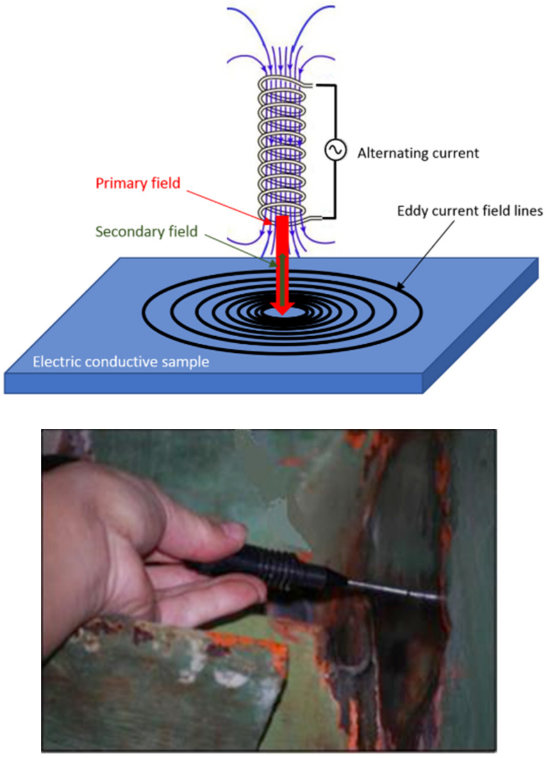


Figure 1-6 Example of the eddy current method for detection of flaws on a steel element [12]

The signals from the eddy current method can be affected and distorted by factors such as lift-off (distance between the test coil and the specimen), electrical conductivity, magnetic permeability, inhomogeneity of the material, or the thickness of the test piece [13]. Lift-off is one of the most common problems for EC tests, slowing down and limiting the growth of its applications. Further factors that can affect the received signals are the noise and low-level signals [14], [15]. To provide for the desired parameters and accurate readings, signal processing, signal analysis, and feature extraction and classification of the model must be performed.

Compared to MT and PT, the eddy current method is faster and requires less surface preparation. Accordingly, it is a time-efficient process and can be implemented where multiple inspection sites are present on a structure. Suitable sensitivity to surface defects, precise conductivity measurements, automated measuring, ability to detect defects through surface coatings (both non-conductive and conductive coatings), ease of use and portability, the ability to scan irregular shapes, not needing for surface contact and little pre-cleaning surface requirement are the advantages of using EC. On the other hand, inability to recognize internal defects, application being limited to conductive elements, high susceptibility to permeability changes, inability to detect defects parallel to surface (parallel to the probe coil winding direction), inability in using for large areas and complex geometry, and expensive equipment are disadvantages of application of EC [11].

The EC method was initially used in the aerospace and petrochemical industry for the non-destructive testing of non-ferromagnetic cylinders, metallic pipes, rods, bars, etc., to detect cracks, corrosion, and other material defects. The EC method has been expanded to civil engineering, specifically in the non-destructive testing of steel structural components [14].

Gros and Takahashi [16] demonstrated that eddy current testing can detect delamination at the interfaces between plies in carbon fiber laminates. Similarly, Mook, Lange, and Koeser [17] concluded that EC can detect fiber orientation, local imperfections like fiber fraction fluctuation, resin rich zones, and delamination and impact damages in carbon fiber reinforced polymer (CFRP) laminates. EC is not applicable for testing electrically nonconductive material like glass fiber reinforced polymers (GFRP) but it is applicable to CFRPs as they constitute of electrically conductive carbon fibers [18], [19]. However, the application of EC is only effective for high fiber density locations.

Tap Testing (TT)

The basic principle behind the tap testing method, also called impact testing or sounding, is that the local stiffness of a material within a defective area differs from that in sound areas [20]. The reduced local stiffness at the defective region causes a variation in the frequency of excitation upon impact [21]. Hence in the tap testing method, the defects (i.e., voids, debonding, delamination) are determined simply by tapping the test object with a coin or a hammer as shown in Figure 1-7 and then listening for a change in frequency of the sound produced. Sharp high pitch sound will denote that the test material is in good condition whereas a dull hollow sound will denote a defective area [22]–[24].

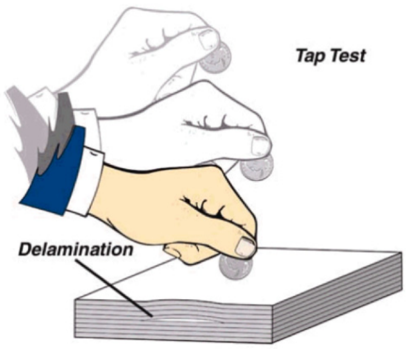


Figure 1-7 Coin tap testing and hammer tap testing

This method is applicable to medium to large near-surface defect detections in contrast to visual inspection which can only be used to detect surface deficiencies. Nevertheless, tap testing can be primarily considered as a surface inspection method due to its limitations of detecting defects within only few millimeters (5-10mm) [25]. It is a real-time inspection method and capable of providing immediate results in detecting near-surface discontinuities like delamination, debonding and voids in thin composites. Tap testing can cover large areas over less period of time [26] and the inspectors do not require intensive training to use this method which adds to its advantages [24].

The tap testing method has limited reliability due to its dependence on the hearing ability and the experience in signal interpretation of the inspector which makes the results subjective. This dependency on the human factor is one of the most significant drawbacks of the tap testing method [20]. The results also vary due to the inconsistencies in the force, angle and devices used for tapping [22]. Similarly, another drawback of this method is that the changes in frequencies due to geometric changes of the structure [24] and due to ambient noise [23] could be erroneously interpreted as defects. Tap testing cannot provide quantitative and objective information about the depth and width of the defects and finer defects like porosity or fiber breakage in composite material will not be detected due to low human audible sensitivity [26], [27].

Some of the drawbacks of the conventional tap testing methods have been eliminated by the availability of commercial digital tap testing (DTT) devices such as Woodpecker developed by Mitsui Industries, Rapid Damage Detection Device (RD^3) developed by WichiTech Industries and Computer Aided Tap Tester (CATT) by Iowa State University. A digital tap tester consists of a rubber-tipped instrumented hammer and a signal processor. A digital display quantifying the variation in the acoustic facilitates the interpretation of the results (Figure 1-8).

Halabe, Joshi, and Gangarao [25] showed that DTT could detect debonding in fiber reinforced polymer (FRP) material of sizes as small as 1.5x0.75 in. (1.1 inch^2) although ACI 440.2R-17 [28] mentions that debond of sizes less than 2 inch^2 do not require special attention as long as the debond area is within 5% of the total bond area. In DTT, the test surface is tapped with an impact hammer and the contact time (impact duration) is measured. The defective area will show a wider force-time pulse or a longer contact time and a sound area will give lower reading. Thus, the limitations of manual tap testing which gives qualitative results are overcome by digital tap testing which gives quantitative results and hence subjectivity in data interpretation is no longer a concern.

Tap testing has been widely used to detect near-surface defects such as debonding, delamination and voids between FRP wraps and underlying concrete [25], [29], [30]. It is a fast and low cost NDT method which is very effective in inspecting structures strengthened with FRP composites [23], [31] and is mostly used to detect delamination [26], [27].

Tap testing is also carried out for inspections of PT tendons and stay cables to look for internal voids. This method is a simple and rapid way for finding moderate to large voids in PT and Stay ducts that indicate potential for corrosion. Digital tap tester that has been used widely in aerospace industry and finding its way in civil engineering for detection of voids and delamination, can be also applied for detection of defects and anomalies within the protective elements along the free length of the cables.

Another type of impact/sounding test is chain drag on bridge decks for finding delamination and voids.

Figure 1-8 Use of digital tap tester for inspection of stay cable

NDT METHODS FOR INTERNAL DEFECTS

The methods discussed in this section are normally implemented to detect internal/subsurface defects in test materials; however, these methods are also applicable in the detection of external/surface defects. Their application is mostly used for the sizing and characterizing of the defects previously indicated by external/surface NDT methods, the inspection of test sites in which a potential for internal damage exists, and the monitoring of the size of the subsurface defects to assess progressive fracture and determine the follow-up action These techniques are normally slow and require experienced operators, special training, and costly equipment.

Ultrasonic Testing (UT)

Ultrasonic waves are the stress waves or the sound waves with frequencies above the human audible range of 20 kHz. The ultrasonic testing (UT) is based on the principle that when the ultrasonic waves come across an interface between two materials with different acoustic impedances, a portion of the incident wave will be reflected. Acoustic impedances of defects, mostly filled with finite volume of air or water, are significantly different than that from the surrounding sound materials [4]. This contrast in the acoustic property at the interface between the defective and the sound area is the fundamental characteristics required for the detection of discontinuities in materials by ultrasonic testing. This method has been very successful in locating defects within concrete and composites as the coefficient of reflection (a measure of the percentage of acoustic energy that is reflected at an interface) is nearly 1 for both concrete-air interface [32] as well as for composite-air interface [4], which means that there is almost total reflection at the interface present due to defects.

Ultrasonic testing can be performed by either monitoring the waves transmitted through the test material or by analyzing the waves reflected due to defects within the material. The first approach is known as the ultrasonic through or direct transmission method, which is also referred as ultrasonic pulse velocity (UPV) method, and the latter is known as the ultrasonic-echo method (see Figure 1-9). UPV is based on measuring the time taken to travel by a pulse of ultrasonic compression waves over a known path length as they travel from one side of the member to the other. The speed of propagation of stress waves determined by dividing the member thickness by the measured travel time is then used to make inferences about the quality/uniformity of concrete i.e., it gives information about the presence of any defects in concrete. However, there are some limitations for the UPV method. It requires access to both sides of the member and only gives information about the presence of the defects but cannot determine the depth of the defect. Ultrasonic-echo method, on the other hand, addresses these limitations by using ultrasonic waves generated by a transducer that propagate through the member and reflect due to the presence of any discontinuities like flaws or interfaces.

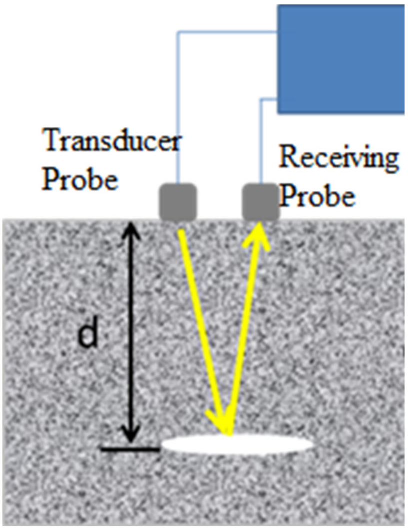


Figure 1-9 Ultrasonic echo method [33]

UT is a relatively quick nondestructive evaluation test and its cost is moderate [34]. It is well applicable to defect evaluation in different types of materials. Its accuracy in detecting defects, portability and high safety are other merits of this method [11]. Although UT method has the ability to specify depth and location of the defects [35], it is less effective for inspection of very thin elements, brittle materials and for components with complex geometry [36]. The application of UT may be limited for surfaces with considerable roughness. It should be mentioned that for UT evaluation, the operator needs to be experienced and adept at testing and analyzing the results, and extensive training is required for this type of nondestructive testing.

The application of Ultrasonic Testing (UT) to damage detection in steel bridges is widespread. Figure 1-10 shows the application of UT for steel bridges. For such applications, the frequency is typically between 2 and 5 MHz. It can be used to detect subsurface volumetric flaws, including slag inclusions and cluster porosity, surface-breaking flaws (e.g., cracks), and material thickness, to measure corrosion and construction errors. It is the most practical NDT method for detecting planar defects, including cracks, lack of fusion, and lack of penetration. It has also been implemented for wire break detection at anchorage zones for stay cables and tendons [3].

(a) Application of UT for uplift bearing anchor bolt

(b) Application of UT for inspection of weld area

(c) Application of UT for inspection of butt-weld

Figure 1-10 Applications of UT for steel bridges [3]

For concrete elements, the UT is limited to testing on smooth concrete surface [37]. The presence of air gaps between the contact of UT transducers and the surface of a tested piece may cause wave scattering. Therefore, this type of UT system uses transducers with gel-couplant applied on the material to strengthen the in-situ bonding [38], [39]. Air-coupled ultrasonic test without the use of couplant enables fast scanning of large structures [40]. Ongpeng et al. [38], [39] showed that the sensitivity of the noncontact ultrasonic test is higher for a concrete structure made using a higher water-cement ratio, whereas for the contact ultrasonic test, a lower water-cement ratio concrete structure provides a good sensitivity. The depth to which damage can be detected using UT depends on the level of the frequency. Ongpeng et al. [38], [39] showed that 100 kHz and 200 kHz are effective frequencies of the transmitting transducer and the receiving transducer, respectively, for detection of internal defects within plain concrete cubes of 150 mm thickness. UT is experimentally analyzed by Gucunski et al. [41] who evaluated the method to have good accuracy in crack detection.

UT can also detect discontinuities related to different FRP applications such as debonding, resin variations, broken fibers, impact damage, moisture, cracks, voids, and subsurface defects [24]. Ultrasonic testing can penetrate well into the materials and detect subsurface flaws both within composite materials and at the FRP-concrete interface. There have been several past studies conducted related to the use of ultrasonic testing for inspection of different FRP-concrete interfaces. Kundu et al. showed that both longitudinal waves (P waves) and Lamb waves can be used to detect delamination at the interface between the concrete and GFRP plates [42]. Bastianini, Tommaso, and Pascale [43] used ultrasonic-echo method to evaluate the bonding defects in external FRP strengthening applications by measuring the amplitude of reflected waves. La Malfa Ribolla et al. [44] presented an ultrasonic technique of evaluating the bond quality between the FRP-substrate interface by using Equivalent Time Length (ETL) which is a damage-sensitive feature that overcomes the limitation of requiring a coupling condition between the transducers and the material to be inspected. Concu and Trulli [45] studied the use of UPV for evaluating the quality of adhesion between FRP and its substrate and concluded that both the direct and semi direct modes of transmissions are effective in detecting the presence of adhesion defects.

Phased-array ultrasonic technology (PAU)

Phased-array ultrasonic technology (PAU) is one of the advanced UT methods developed to detect cracks located at different depths, with random orientation probes at fixed conditions (Figure 1-11). The main property of PAU is its computer-controlled excitation of individual elements with a multi-element probe, which can generate an ultrasound focused beam with the capabilities of modifying the beam parameters [46] (Figure 1-12). These parameters include the beam angle, focal distance, and focal spot size, allowing this technique to detect cracks in various orientations located away from the beam axis [47]. PAU technique, usually, generates frequencies between 750 kHz to 100 MHz which is used for nondestructive evaluation in industrial applications.

Figure 1-11 Phased-array ultrasonic technology (PAU)

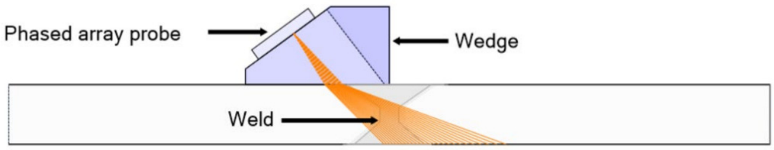


Figure 1-12 Schematic of Phased Array Ultrasonic testing [48]

PAU is known for its simplicity in implementing multiple transducers. This type of ultrasonic method is not only faster and more convenient than conventional monolithic technology, but it also possesses better accuracy. It provides better images due to multiple angles and frequencies which require less interpretation, higher resolution than UT, and capability of beam focusing, reliability, portability and mobility [49], [50]. Further capabilities include easier accessibility to out-of-reach components, shorter inspection time, and the detection and measurement of small stress cracks. Sometimes, the limitation in orientation for the path of the ultrasonic pulse makes it difficult for PAU to fully obtain an image of cracks and defects. It also requires costlier equipment compared to conventional UT. PAU is a relatively new technique as compared to the traditional NDTs and hence the limitations of portable units of PAU include the uncertainty in its application as it has yet to be completely proven [50].

Using PAU, two- or three-dimensional presentation can be produced for displaying the exact location and size of each potential defects such as manufacturing, service (like fatigue cracking and stress cross ion cracking), and parent material flaws (like inclusions), or erosion. Based on the experimental evaluation of concrete slab specimens, a quantitative numerical analysis for damage evaluation in concrete using phased array ultrasonic technology has been studied by Freeseman and Khazanovich [51].

Unlike conventional ultrasonic testing, phased array ultrasonic (PAU) testing allows signal focusing at desired locations and angles which is advantageous for testing of composite materials that have anisotropic structure creating challenges in signal evaluation [52], [53]. In a study by Boychuk, Generalov, and Stepanov [54], it is concluded that PAU testing can detect all the typical FRP defects as well as determine their size and location with high accuracy. Similarly, Meola et al. [55] conducted a study to detect defects and impact damage in CFRP composites and found that PAU can identify both its size and location. Taheri and Hassen [52] showed that the results of the PAU testing are better than that of conventional UT method with capability of detecting flaws as small as 0.8 mm and up to a penetration depth of 25 mm.

Acoustic Emission Testing (AE)

The primary basis for Acoustic Emission testing lies in the propagation of acoustic waves originated within a structure from external or internal sources. In general, onset of cracks, delamination, and similar anomalies releases stress and generates an elastic wave which goes from the sound source through the element. This wave is sensed by acoustic sensors attached to the element surface [56]. These events can be generated by applying a localized external force either as sudden mechanical load or a rapid temperature or pressure change to the element being investigated (Figure 1-13). The events can also be generated because of material deterioration such as cross-section loss in reinforcing bars and pre-stressing strands leading to fracture of steel or cracking of the concrete.

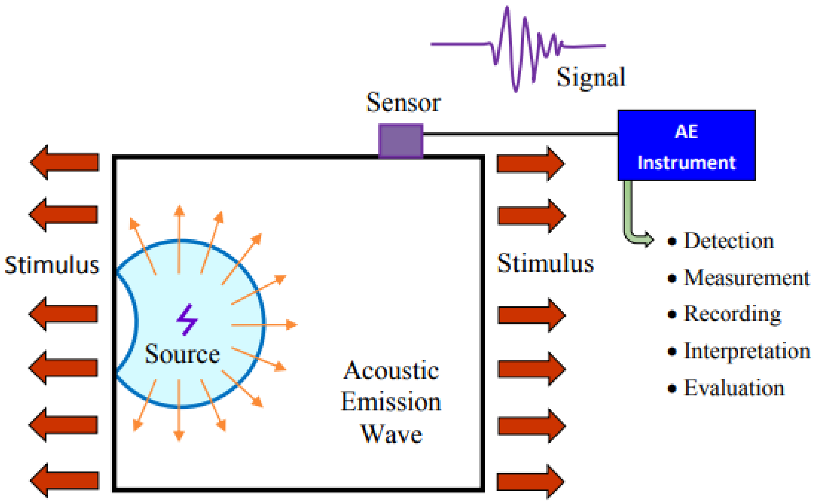


Figure 1-13 Schematic of Acoustic Emission Testing (AE) method [57]

AE method can sense the waves in a large area just by one sensor depending on the sensitivity of the sensor and extent of damages. However, for detecting the location of damage, more than one sensor is required. It can also be used as a continuous monitoring system for recording events within a specified timeframe [36], [58]. Severity assessment, source location and identification are the main aspects of damage for which AE is used as an applicable nondestructive testing method [59]. It allows fast and global inspections by using multiple AE sensors mounted permanently with process control that require no cleaning/disassembly of the specimens [23], [60]. Moreover, compared to other NDT techniques, after installation, it is not labor intensive and can be performed without stopping the service of the structure to be monitored [61].

Apparently, this method is not applicable for detection of damages prior to installation of the sensor, unless the activity at the damage creates sound waves. Therefore, it is categorized mostly as a structural health monitoring (SHM) method and can only be used to detect the onset of a defect or the progression of existing anomalies. It should be stated that this method requires special equipment and training for the inspectors. While there are several advantages of using an AE technique, its application is hindered due to difficulty in differentiating the stress waves from a specific damage source and that from other sources such as vehicular traffic [62]. Hence a drawback of using AE testing is that it requires high level of skill in correlating the AE data to respective damage sources [60]. Similarly, noisy environment may lead to false signals during data collection and hence filtering and reducing noise in signals are of great importance for AE testing [23]. Another drawback of AE is that the defects might go undetected if the loading is not sufficient enough to cause a considerable AE event [31]. And despite the fact that AE has capability to detect defects and determine its origin and approximate location, it cannot give information on their types and size which is why another NDT method such as ultrasonic testing may be required to give a full quantitative data on the defects [61].

The bridge evaluation application of Acoustic Emission testing is studied by Holford and Lark [63]. The AE has various applications for steel bridge elements including for rolled shapes, plates, welded connections, pins, and cable fittings. The AE method has been used successfully for detecting wire breaks in cable-stayed bridges and fatigue cracking in orthotropic bridge decks [64]. Figure 1-14 shows the sensors installed on a cable and anchorage. Before the installation of the transducers, coating should be removed at the attachment sites. In some cases, magnetic hold-downs are employed to couple the transducers to a test piece. For monitoring bridge components with the AE method, multiple transducers are typically used. To locate cracks and remove interference signals from noise sources, the transducers are to be placed on a test piece in geometric arrays. Figure 1-15 indicates the application of AE testing for the inspection of steel bridges [3]. It is implemented to monitor materials experiencing dynamic processes, including structural loading, corrosion, and weld heating and cooling.

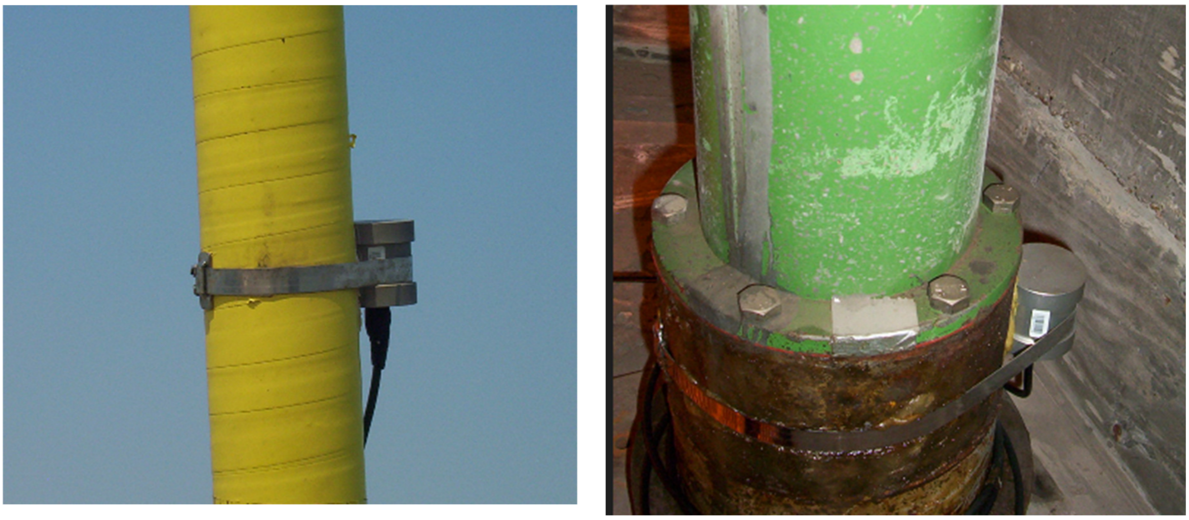


Figure 1-14 Application of AE for steel tension elements

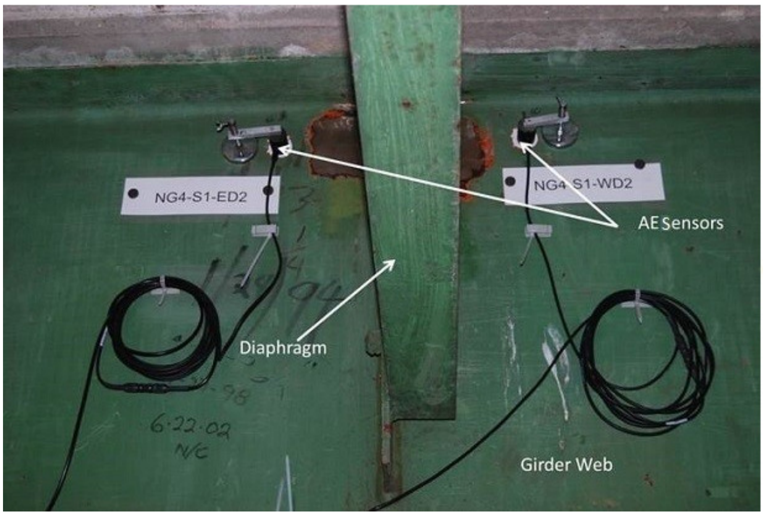


Figure 1-15 Application of AE for steel bridge [65]

Mirmiran et al. [66] assessed the feasibility of using acoustic emission technique as an NDT tool to inspect hybrid columns (CFRP tubes filled with concrete) and determined the correlation between the AE parameters and the stress states in the concrete. In another study, Gostautas et al. [67] used AE to determine the structural performance of several GFRP bridge deck panels with depths ranging from 6 to 30 inches. Carpinteriand et al. [68] used AE to detect and analyze the progression of crack leading to FRP debonding in a RC beam retrofitted with FRP sheets. Similarly, Degala et al. [69] performed AE tests on concrete slabs strengthened with CFRP strips and concluded that it is capable of identifying different sources of damage, in particular, differentiate between concrete cracking and CFRP debonding which were the two distinct failure modes for the several lab specimens tested in their work. The previous studies have reported promising results with respect to the use of AE technique for monitoring several FRP applications. AE technique also has an added advantage of being able to detect several defects due to fatigue loading such as fatigue cracks, fiber fractures, matrix micro-cracks, fiber-matrix debonding, and delamination [60].

Infrared Thermography Testing (IR)

Infrared thermography testing (IR) is based on emissivity of individual elements within the structural elements each of which absorbs or releases heat of emitted infrared radiation by distinctive rate due to the different rate of emissivity. Figure 1-16 presents the principle of IR technology, where a heating source is applied to both a non-defective and defective object. If the material is uniform, i.e., without any defects, the thermal signal propagates smoothly through the object, while, for the defective object, the thermal signal results in sudden changes in the surface temperature distribution [70].

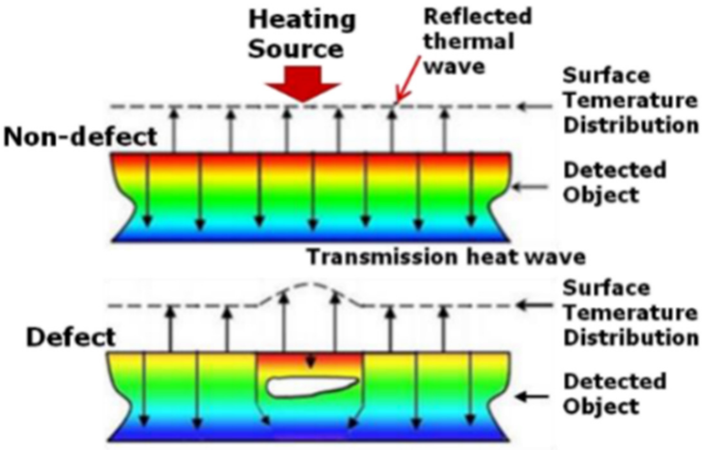


Figure 1-16 Principle of infrared thermography for uniform and nonuniform elements and their thermal wave propagation [70]

In this method an infrared camera is used for detection that measures the emitted infrared radiation from a structural member (Figure 1-17). IR method is categorized into two classes of passive and active thermography by Lee et al. [36]. In the former type, the IR is performed without any external cooling or heating source. However, for the active IR method, the heating or cooling source is needed to induce temperature differences [71].

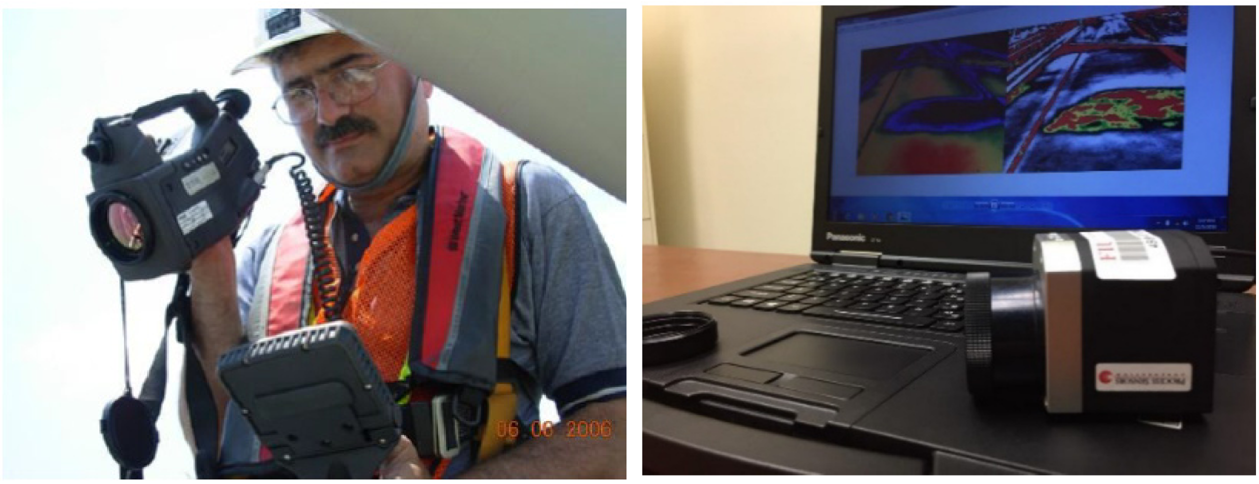


Figure 1-17 Infrared camera used for IR method [72]

There are two types of IR technology, which include a traditional approach known as pulse thermography and the more advanced lock-in thermography [73]. The traditional method uses a short-duration energy pulse and records the thermal response. In contrast, the lock-in method uses mono-frequency sinusoidal thermal excitation to find the phase and magnitude of the reflected thermal wave from the recorded thermal images. The lock-in method provides better accuracy and efficiency for noise rejection, but it takes a considerably longer time to measure frequencies [73], [74]. The pulse thermography method is known for its fast detection speed, large detection area, and ease of data access. This method can be implemented to detect cracks, rust, fatigue damage, and debonding in steel bridges [73]–[75]. Bridge deck with or without overlays can be also tested with this method.

According to the Non-destructive Evaluation Center of the Federal Highway Administration, compared to other NDT techniques, IR covers more areas for inspection, therefore it is a cost-effective method for inspection of steel bridges with large areas. Moreover, this method can indicate the percentage of deteriorated areas. However, there are some disadvantages to this technique, including the high cost of test equipment, being dependent on the proper temperature of the ambient, and the need for special training for the operators [76].

Infrared thermography testing (IR) has been used widely for detection of material variation based on variation of temperature. It was discussed by Seshu and Murthy [77] as a structural damage detection method including for detecting cracks, delamination, and voids.

Much research has been carried out on the application of IR for steel elements [78]–[80]. Sakagami et al. conducted an IR test on the steel deck of a steel bridge, with two types of cracks: weld-bead-penetrant-type)] and through-deck-type

[78]. They found this technique to be practical for identifying the cracks. Mehrabi employed IR for the non-destructive evaluation of cables in cable-stayed bridges with an ambient heat source [72].

Infrared thermography has been used to detect defects within externally boned FRP sheets and laminates that are used for strengthening concrete members [32]. A study conducted by Jackson et al. found that IR can effectively detect debonding, blisters, and shallow defects such as delamination in concrete columns with externally applied FRP [81]. Galietti et al. [82] investigated the possibility of using infrared thermography for detecting defects present between concrete-FRP interface and concluded that it is the most cheapest and a quick technique for the purpose. Yazdani et al. found that IR could clearly detect the four construction-related factors (surface voids, surface wetness, surface cleanliness, and upward vs downward CFRP application) that compromise the bond quality during the CFRP installation [83]. Similarly, research in quantitative assessment of defects in FRP bonded to concrete have also been conducted to determine the size and approximate depth of the defects in addition to just locating their presence [84], [85].

Radiographic Testing (RT)

In RT, the element is subjected to X-Ray radiation. Based on the material density, the radiation is transmitted at various rates. These variations in transmission can be detected by photographic films or fluorescent screens [86]. The radiographic testing equipment consists of a radiation source, film cassette or digital flat panel detector, penetrometer, and filmmakers.

Little or no surface preparation is needed for the application of RT. The most effective application for RT is for the detection of subsurface defects hidden from the naked eye. This method is very effective for detecting the internal defects and specifying an accurate image of the defects or discontinuities. Radiographic testing functions with an X-ray sensitivity of 2%, meaning that if the smallest dimension of a component is 20 mm, the smallest void that can be detected is 0.4 mm [87], [88].

The disadvantages of the RT method for steel bridges include its slow operation and high cost, serious safety issues and health hazards, improper use for thick sections, and the need for expensive equipment and special training for the inspectors [89]. Moreover, this method has another drawback of requiring access to both sides of the test object for placing the source and receiver in opposite sides.

Radiography has significant use in structural engineering. For steel bridges, it is more commonly used for testing the welded joints. Cracks in welded joints under dynamic loading can propagate further and reduce the cross-section until the fracture of the welded part occurs. Although this type of NDT can be very slow and expensive, it has the capabilities and accuracy to detect porosity, cracks, inclusions, and defects in weld interiors. Figure 1-18 shows an inspection of a steel beam using the radiographic method [90]. RT has also been used at an experimental level for detection of wire breaks in stay cables [91].

RT method can have application in a variety of material types. It is also applicable in detecting voids and defects in concrete [77].

Figure 1-18 Inspection of a steel element using RT Method [3]

RT can clearly detect the defects like delaminations in FRP as there would be variations in the absorption of the radiations between the sound and defective regions [92]. However, if the orientation of the delamination is perpendicular to the radiations, these defects will not be detected in a 2D scan [60]. Defects that cause significant density variations such as excess density of fiber or matrix, resin variations, impact damage, delamination, debonding, foreign contamination, cracks and voids can be easily detected by radiography [93]. It is also useful in detecting non-uniform fiber distribution, broken fiber, poor fiber weaving and misorientation in fibers such as fiber wrinkles. It can be used for both quality control of composites before service and for inspections for defects during service [93].

Laser Testing Method (LT)

This method is in the experimental stage and information on its applicability is very limited. This method employs Lamb wave initiation by pulsed laser that generates a laser impact on the component [36]. The flaw is detected by a standing Lamb wave produced by the impact and recorded by the photorefractive interferometer.

In particular, Laser Testing method is comprised of three main techniques; Profilometry, Shearography (Figure 1-19), and Holography all of which use laser for inspection [94]. These three techniques have almost the same methodology but require different processing. When using any of these methods the surface defects can be detected in the elements subjected to stress developed by heat, pressure, or mechanical load [94]. This method can detect cracks, splits, delamination, and voids by scanning across the surface of the elements, and comparing the test outputs with an undamaged reference element [94].

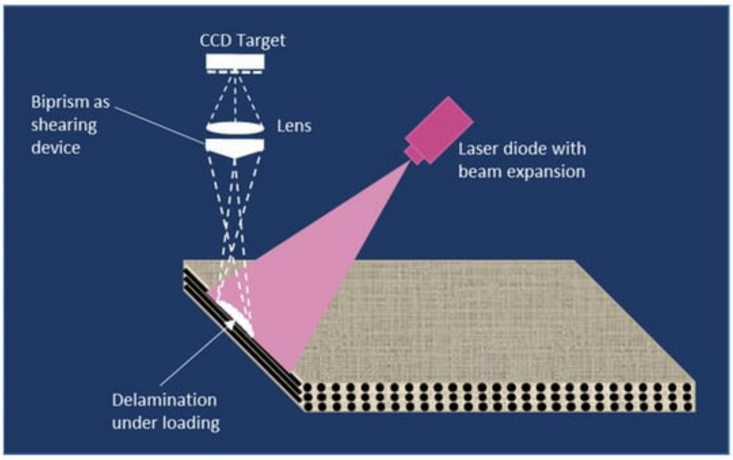


Figure 1-19 Principle of shearography [95]

Laser-based nondestructive testing methods provide the advantages of non-contact, high sensitivity and high detection rate [96]. These methods do not add mass to the test object in contrast to conventional contact sensors and hence the measurements are free from any influence due to added mass of the testing device or procedure [97]. However, they require laborious analysis of results and expensive devices.

Taillade et al. [98], [99] demonstrated the feasibility of using shearography in the evaluation of bond defects between externally applied CFRP and concrete substrate through a case study on a bridge in France over the Doubs River. Yang [100] used digital shearography to assess defects and delamination in a CFRP specimen subjected to tensile stressing, a GFRP plate subjected to thermal stressing, and a GFRP honeycomb panel subjected to partial vacuum stressing. Similarly, Qiu and Lau [101], [102] experimentally validated the feasibility of the acoustic-laser technique for the detection of defects in FRP-bonded concrete and also concluded that it is able to quantify the size of defect. Chen et al. [103] found that acoustic-laser vibrometry was also capable of detecting a shallow crack in concrete under externally applied FRP. The feasibility of acoustic-laser technique for remote detection of debonding was experimentally validated on GFRP-confined concrete specimens by Büyüköztürk [104].

Impact Echo Testing (IE)

Impact echo testing uses stress waves or mechanical waves generated by an impact (by a hammer or a steel sphere) that propagate through the member and reflect due to variation in acoustic impedances caused by the presence of discontinuities (Figure 1-20). The reflected waves are recorded by a transducer placed near the impact point in the form of a time-domain signal (voltage versus time signal) which can be transformed into a frequency-domain signal (amplitude versus frequency spectrum) as a preferred approach for easy signal analysis [23], [32], [61], [105]. These recorded signals are analyzed to provide information about the extent and location of the subsurface defects.

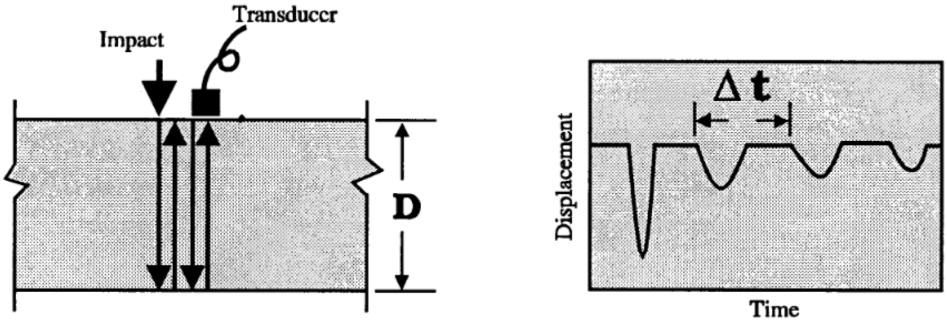


Figure 1-20 Schematic representation of impact-echo testing [106]

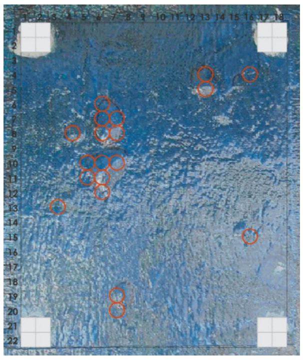
The IE method allows faster inspection rate for locating the defects which can later be inspected in detail using other comprehensive NDTs. Unlike ultrasonic testing, that uses high frequency stress/sound waves with high signal attenuation and noise issues, the impact from the hammer or steel ball generates high-energy low frequency (typically 2 to 20 kHz) stress waves that can penetrate deep into the test material [30], [61], [107]. The use of impact to generate stress pulse also has an additional advantage of eliminating the need for a bulky transmitting transducer that would be required for ultrasonic testing [32], [108]. This method is effective in detecting cracks, voids, and delamination present in plate-like structures where discontinuities are usually parallel to the test surface [61]. Hence this method has great potential for detecting discontinuities in external FRP applications. Detections using IE can be performed from just one side of the test structure and it eliminates the hassle of accessing the structure from both sides for inspection [26]. Further, it provides benefits of considerable accuracy, repeatability and speed in measurements for crack detection [109], [110].

However, there are some limitations in the use of impact echo testing. As this method use stress waves of low frequencies, smaller cracks and discontinuities cannot be detected easily which is a serious issue regarding the resolution of the method [61]. Moreover, the current IE instruments are only capable of testing members with thickness up to 40 inch (1 m) and require experienced personnel for its operation [32]. In IE method, evaluation process is associated with a relatively sparse grid and normally requires a lane closure for the case of bridge deck inspection. This method also has some limitations for crack detection for elements in which there is a gap between the element and an overlay similar to concrete bridge deck covered by asphalt wearing surface [41]. The ability of IE for void detection in reinforced-concrete is somehow limited because of the interfering effect of steel embedment in distribution and reflection of the waves [37].

Impact Echo Testing (IE), owing to its mechanical wave generation and deep penetrating ability into the concrete, has a great potential for detecting discontinuity and delamination in concrete elements [37], [77], [111]. IE was, experimentally, studied by Gucunski et al. [41] for estimating bridge deck defects. They pointed out that IE is the most reliable method for detection of delamination, and that the interpretation of results can be automated and directly presented for effective data collection. Accordingly, IE shows promising for evaluation of large delamination and cracks, voids, and discontinuities. They also noted that for crack detection, IE has high level of accuracy, repeatability of measurements, and speed of data collecting and analyzing, however, the cost of testing and the ease of use for this technique was rated by them as moderate. Other advantage of IE in concrete is that it is capable of determining deck and slab thickness [77], [111]. Figure 1-21 shows IE being used for determining pavement thickness in a bridge structure [112]. Hurlebaus et al. [37] investigated the accuracy of this NDT method in defect evaluation and detection. IE has shown moderate accuracy for void detection in post-tensioning tendon ducts, and requires multiple impact points for higher accuracy [36], [37].

Figure 1-21 Void detection in concrete by using IE method [112]

IE can be used for quality control and detection of defects in FRP composite applications [62]. Maerz, Galecki and Nanni [113], [114] performed impact echo testing with an air coupled receiver to detect delamination on externally applied FRP sheets on a bridge abutment as shown in Figure 1-22. The test was carried out in a 1x1 in. grid, and they found that IE was very successful in detecting delamination in FRP application.



A. Olson Instruments impact echo tester B. Measurement results (red circles indicate delamination)

C. Impact echo measurements

Figure 1-22 Impact echo testing [113]

Microwave Testing (MW)

Microwave Testing is a single side scanning technique for detecting internal discontinuities, voids, and cracks within materials. MW method is sensitive to dielectric variation [115]. It can be divided in two main technique of Ground Penetrating Radar (GPR) and Surface Penetrating Radar (SPR) [116]. The dominant methodology in this method is that the electromagnetic microwave energy travels at different velocity through different materials. In Microwave Testing, radar antenna will detect any internal anomaly in the depth of the elements by sending and receiving the electromagnetic signals. In this technique, considering the wave velocity, the system can determine the characteristics of each defect based on the depth and time of the signal reflection [116].

In the last decade, software developments have helped mechanical and civil engineers to improve outputs of their non-destructive evaluation and plot high quality and more accurate defect model for elements. Two-dimensional image by stacking the single scanned signals next to each other, and three dimensional images by combination of multiple scans of the elements in different directions are two possible outputs for the result of Microwave Testing method [116].

Microwave testing technique has been used to detect defects in FRP composites and the FRP-concrete interface [117]–[120]. It can be used to determine the depth, location, geometry and dimensional information of flaws in FRP applications [23], [61]. Li and Liu [121] used microwaves to detect air voids between FRP and concrete substrates.