Non-Destructive Evaluation Techologies for Concrete Bridge Inspections

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Abstract; Corrosion of the reinforcement steel (rebar) must be accurately measured to prevent failure of concrete bridges. Because the rebars are under concrete cover, non-visual evaluation techniques must be used to detect corrosion of rebars while keeping the bridge functioning. This paper discusses the underlying principles of five common types of non-destructive evaluation (NDE) techniques, their readiness as a technique, and their usefulness as they relate to corrosion of steel under concrete cover. The first technique, infrared thermography, detects infrared radiation based on the material's temperature to find temperature differences relating to discontinuities of the material. Ultrasonic testing sends a high-frequency acoustic pulse through a material, and detects the echo at a discontinuity boundary. Eddy current testing induces an electric field in a material and detects disturbances in the field. Magnetic flux leakage detects geometric perturbations in a material as the magnetic field begins to leak into the air to find the path of least resistance. A final technique measures the reflection of radar pulses and detects discontinuities within the material.

Keywords: Non-destructive evaluation, corrosion, rebars, infrared thermography, ultrasonic, eddy current, magnetic flux leakage, and radar.

Abstrak; Korosi yang terjadi pada tulangan baja harus diperiksa secara akurat untuk mencegah kegagalan pada jembatan beton. Teknik evaluasi non-visual harus digunakan untuk mendeteksi korosi pada tulangan baja karena material ini berada di bawah selimut beton. Tulisan ini membahas lima jenis teknologi evaluasi tak merusak (NDE) yang terdiri dari prinsip-prinsip dasar teknologi-teknologi tersebut, kesiapannya sebagai suatu teknik, dan kegunaannya yang berkaitan dengan pemeriksaan korosi baja di bawah penutup beton. Teknologi pertama, termografi inframerah dapat mendeteksi radiasi inframerah berdasarkan suhu material untuk menemukan perbedaan suhu yang berkaitan dengan diskontinuitas material. Pengujian ultrasonik dapat mengirimkan gelombang akustik frekuensi tinggi melalui material dan mendeteksi gema pada batas diskontinuitas material. Eddy current dapat menginduksi medan listrik dalam suatu material dan mendeteksi gangguan pada material tersebut. Magnetic flux leakage dapat mendeteksi gangguan geometris dalam suatu material sebagai medan magnet. Teknologi yang akan dibahas terakhir adalah radar. Teknologi ini dapat mengukur pantulan gelombang radar dan mendeteksi diskontinuitas dalam material.

***Kata-kata kunci**:* Uji tak merusak, korosi, tulangan baja, termografi inframerah, ultrasonic, eddy current, magnetic flux leakage, and radar

INTRODUCTION

Non-destructive evaluation (NDE) techniques are increasingly being considered for the condition assessment of aging infrastructures. NDE techniques are used for materials evaluation and defect detection in various structural components (such as beams, columns, slabs, etc) without impairing their future usefulness.

The most serious form of deterioration in concrete bridge problem is that caused by corrosion of embedded reinforcement steel. As the reinforcement steel corrodes, it expands and creates a crack or subsurface fracture plane in the concrete or just above the level of reinforcement. This subsurface fracture plane is sometimes refers to as delamination. Delamination is the separation of layers of concrete close to the surface. As the process continues, a rupture between the delaminated region and the main structural component can occur, which results in a spall [1].

The goal of this study is to obtain an accurate and reliable assessment of corrosion damage in concrete bridge. In order to achieve the goal, information from different corrosion evaluation techniques is needed. The objective of this paper is to explore the literature on possible NDE technologies for assessing the corrosion of the embedded reinforcement steel in concrete bridge. These techniques and methods will be discussed: Infrared (IR) Thermography, Ultrasonic Testing, Eddy Current Testing, Magnetic Flux Leakage (MFL), and Radar.

IR THERMOGRAPHY

IR thermography is a technique for examine abnormalities by observing radiant heat pattern emitted from the object. IR thermography for testing concrete bridge is based on two principles. The first principle is that all materials emit energy in the form of electromagnetic radiation at any temperature above absolute zero (-273°C). The rate of energy emitted per unit surface area depends on the temperature and emissivity of the material according to Stefan-Boltzmann Equation below:

$$Q = \varepsilon\sigma T^4$$

where Q is total radiant emission of the surface (W/m^2); ε is emissivity of the test object, which is defined as the ability of the test object to radiate energy compared to a perfect black body radiator (unitless); σ is Stefan-Boltzmann constant (5.67 x 10^{-8} W/m^2/K^4); and T is absolute temperature of the object (K) [2]. The second principle is that the heat transfer in any material is affected by presence of subsurface flaws or any other changes in thermal properties. Subsurface flaws, such as delaminations, interrupt the heat transfer through the concrete. Depending on the underlying cause, the flaw area may be warmer or colder than its surroundings. In periods of heating, the surface temperature of flaw areas is higher than the temperature of the surrounding concrete. In the other hand, in periods of cooling, the surface temperature of flaw areas is lower than the temperature of the surrounding concrete as shown in Figure 1 [3].

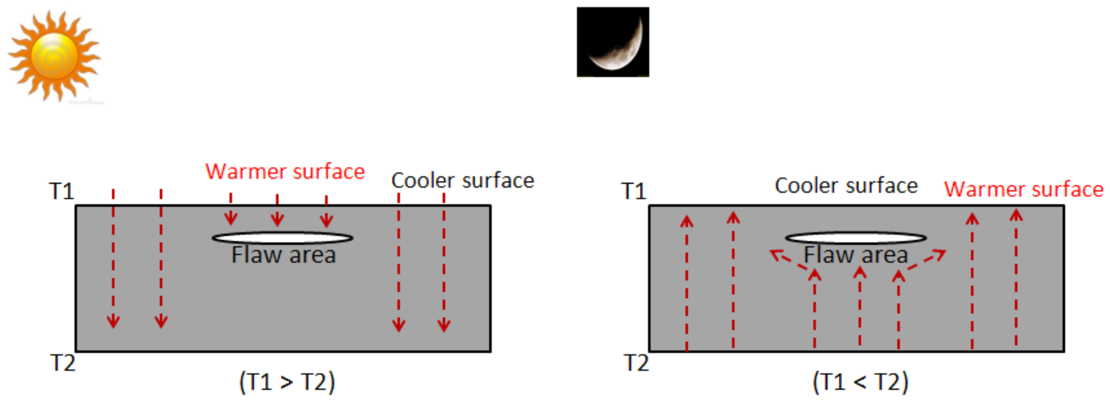

FIGURE 1 Effect of internal defect on surface temperature during heat flow.

Figures 2 presents a schematic of the infrared thermography method to detect presence of a flaw based on the surface temperature differences. A step thermal pulse of magnitude q and duration t is applied over the surface of the test object and then the surface temperatures above the flaw and in the background, where no internal flaw is present, are recorded. The quantities of interest include the maximum surface temperature and the thermal signal. The maximum surface temperature occurs above the flaw and at the end of the thermal pulse. The thermal signal is defined as

$$\Delta T = T_{defect} - T_{background}$$

where T_{defect} is surface temperature above the flaw; and $T_{background}$ is surface temperature at a point above the sound material and sufficiently distant from the flaw [4].

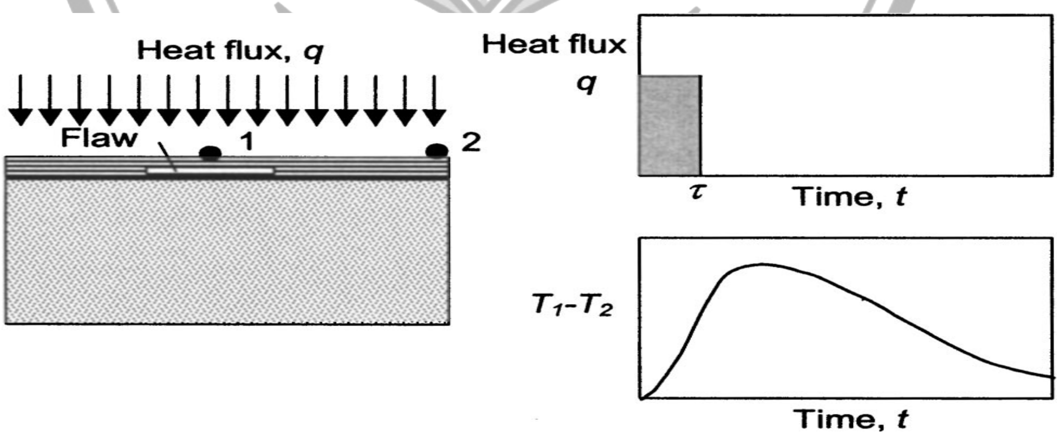

FIGURE 2 Schematic of the infrared thermography method to detect presence of a flaw based on the surface temperature differences [4].

IR thermography exploits heat transfer mechanisms: Conduction, Convection and Radiation. Conduction in a stationery media is the propagation of heat energy from one molecule to another, generally from higher temperature regions to lower temperature regions. The heat flow through a material is directly proportional to the temperature difference (between hot and cold regions) and the thermal conductivity of the medium. Convection is the heat transfer that takes place due to the motion of a fluid medium over the solid structural material. The main parameters that determine the convective heat transfer are: the temperature of the solid surface, temperature of the surrounding air and wind speed. Radiation is the heat transfer caused by the emission of electromagnetic waves. The energy transferred due to radiation is directly proportional to the fourth power of the temperature difference between the objects as shown by Stefan-Boltzmann Eq. [5].

IR thermography consists of radiometric detectors that are sensitive to electromagnetic radiation in the IR region. IR region is a light with a longer wavelength and lower frequency than visible light as shown in Figure 3. Radiative heat transfer takes place in the infrared portion of the spectrum, from 0.75μm to about 100μm, although most practical measurements can be made to about 20μm [5]. IR cameras use microbolometer focal plane array (FPA) technology, which is a type of thermal detector made of a material whose electrical conductivity varies with temperature change due to incident radiation. The electrical signal is then converted to single pixel containing temperature data by applying an appropriate calibration factor. The optical lenses for IR cameras are typically made of germanium, which is a convenient material due to the high index of refraction for wavelengths between 2 and 12 μm and opaque to wavelengths outside of the 2 to 20 μm band. This allows the lens to serve as a filter for visible and UV radiation that would otherwise be incident on the detector. The remaining wavelengths outside of the 2 to 20 μm band are removed using in-line spectral filters.

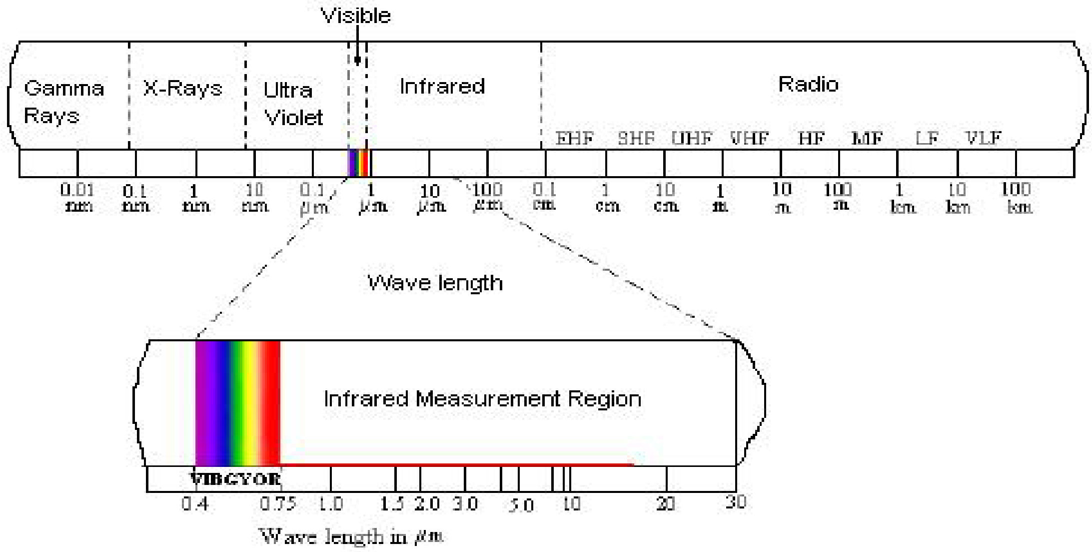

FIGURE 3 Electromagnetic spectrum showing the infrared measurement region [5].

Most applications of IR thermography require a qualified person to interpret the data due to many variables that are often difficult to understand. In addition to the operator of the instrument, variables can be grouped into three categories. These relate to (1) the target, (2) ambient conditions of the system in which the target is operating, and (3) the instrument itself. Target variables include emissivity, spectral characteristics, temperature, heat transfer relationships in and around the target, thermal capacitance, and diffusivity characteristics. Among possible variables in ambient conditions are wind speed and direction, solar absorption, radiation cooling, precipitation, surface effects of evaporative cooling, ambient air temperature, background temperature, distance to object, relative humidity and the presence of emitting/absorbing gases. The other variables related to the infrared instrument are the precise waveband detected, thermal sensitivity, rate of data acquisition, dynamic range, field of view, spatial and measurement resolution and system calibration [6]. The American Society for Testing and Material (ASTM) developed standards used for determining the performance of infrared system. The standard testing method for detecting delaminations in bridge decks using infrared thermography is detailed in the ASTM Standard D 4788-03.

ULTRASONIC TESTING

Ultrasonic testing is a defect detecting technique which examines the behavior of a high frequency acoustic pulse as it travels through the material in question. As a brief background to the subject, recall that an acoustic pulse is a pressure wave whose wavelength corresponds to the distance between particle density peaks.

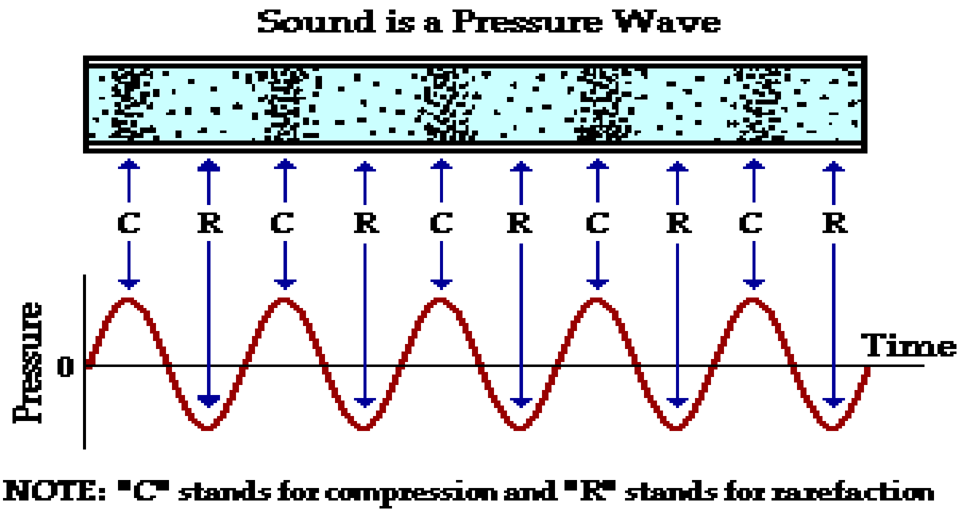

FIGURE 3 Pressure wave associated with acoustics.

Velocity of a propagating wave is a function of the density and elasticity of the material. A simple analogue of this relation is to visualize balls attached by springs, where the mass of each ball represents the density and the stiffness of the spring representing the elasticity. A low mass and a high spring constant will correspond to higher velocities. Similarly, a low density and high elasticity will correspond to higher velocities [6].

However, measurable changes happen in the acoustic wave at a boundary between media (such as a defect in the material). When an acoustic wave reaches a boundary, a portion of the wave will be transmitted into the second material while another portion is reflected. This is the principle which underlies echoes. The exchange is governed by the equation:

$$E = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right) X\ 100\%$$

where E is the reflected energy, and Z, called the acoustic impedance, is a material property which is a function of its density and velocity. It is noteworthy that a portion of the sound wave will always be reflected at a boundary, regardless of the relative densities. To return to the ball analogy, imagine the boundary between large balls joined by strong springs to small ones attached by weakly interacting springs. It is conceptually easy to imagine that a portion of the wave from either direction will be reflected [6].

To detect a defect, an ultrasonic emitting apparatus is placed against the material in question. In one method, the detector is placed on the same side as the emitter, to detect waves reflecting from the defect. In another, the detector is placed on the other side of the material and detects the wave fronts lost due to reflection at the defect [8].

EDDY CURRENT TESTING

An eddy current, in and of itself, is simply a circular electric field. This field passes through the material in question and a defect is measured by the disturbance of the field as shown in Figure 4. Note that the largest disturbance in the field (b) is perpendicular to the electric field lines. Thus eddy current testing is directionally dependent.

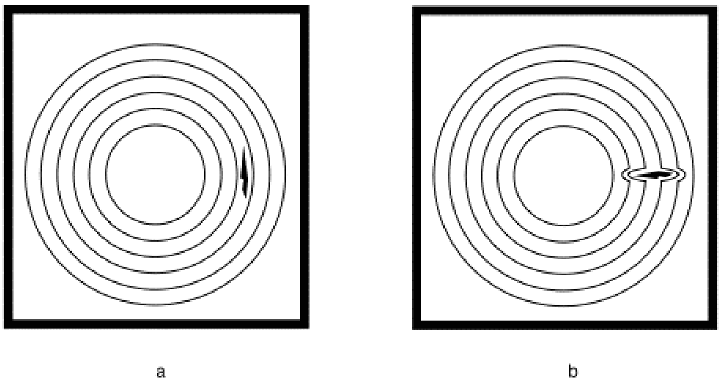

FIGURE 4 Defects among eddy currents [6].

More rigorously, an eddy current is a byproduct of a separate time-dependent, circular electric field. This time-dependent electric field is driven by what is called an electromotive force, simply the force that changes the field. In a similar fashion to Newton's third law, this force must have an equal and opposite force. The opposite force, called the counter-electromotive force, manifests itself in a magnetic field which opposes the right hand rule. This magnetic counter-electromotive force then itself produces an electric field, which is the eddy current in question.

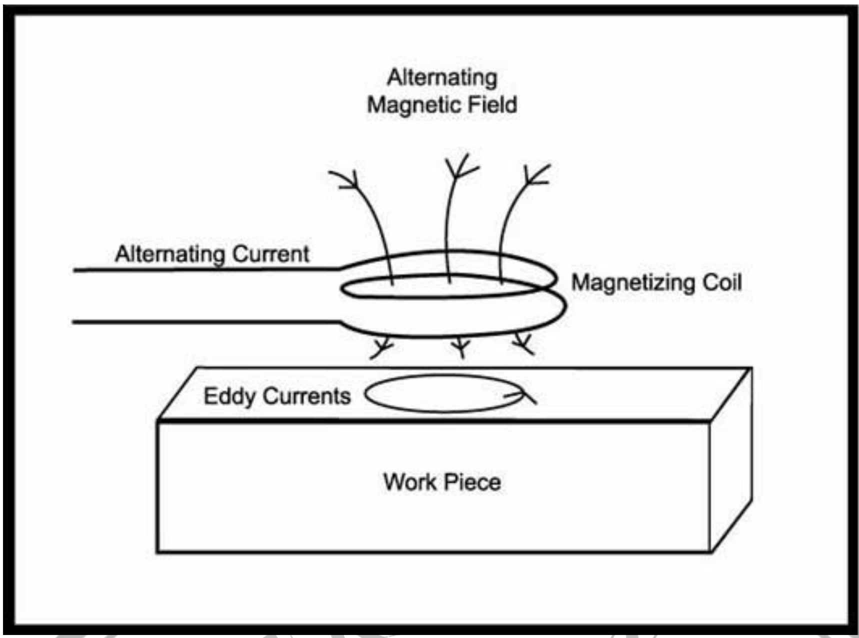

FIGURE 5 The production of an eddy current [?]

Simply put, an eddy current is produced by a changing electric field. The most practical way to sustain a changing circular electric field is to oscillate the electric field (AC current) [6].

The key to eddy current testing is in detecting discontinuities in the current which reflect defects in the material. This is either done through measuring irregularities in the current of the source wire, or using an external search device.

MAGNETIC FLUX LEAKAGE (MFL)

Magnetic fields can be used to interpret or inspect a material's properties. This allows for inspection techniques for bridges and other infrastructures. One kind of magnetic field phenomena that can be used on concrete structures is the direct current excitation resulting in magnetic flux leakage fields around defects in ferromagnetic materials. Magnetic flux leakage (MFL) non-destructive testing technique utilizes this magnetic field phenomenon. MFL testing incorporates a test article that is a ferromagnetic material being magnetized and its surface scanned with a flux-sensitive sensor for the magnetic leakage field [7]. The outer concrete surface of a concrete bridge is scanned and the tensioned or non-tensioned steel rebar or wire rope strands and cables are magnetized. Figure 6 shows the setup for magnetic flux leakage non-destructive testing including the power source, probe which has magnetic poles and the generation of the magnetic flux occurs through, and the interface equipment to view the magnetic flux leakage.

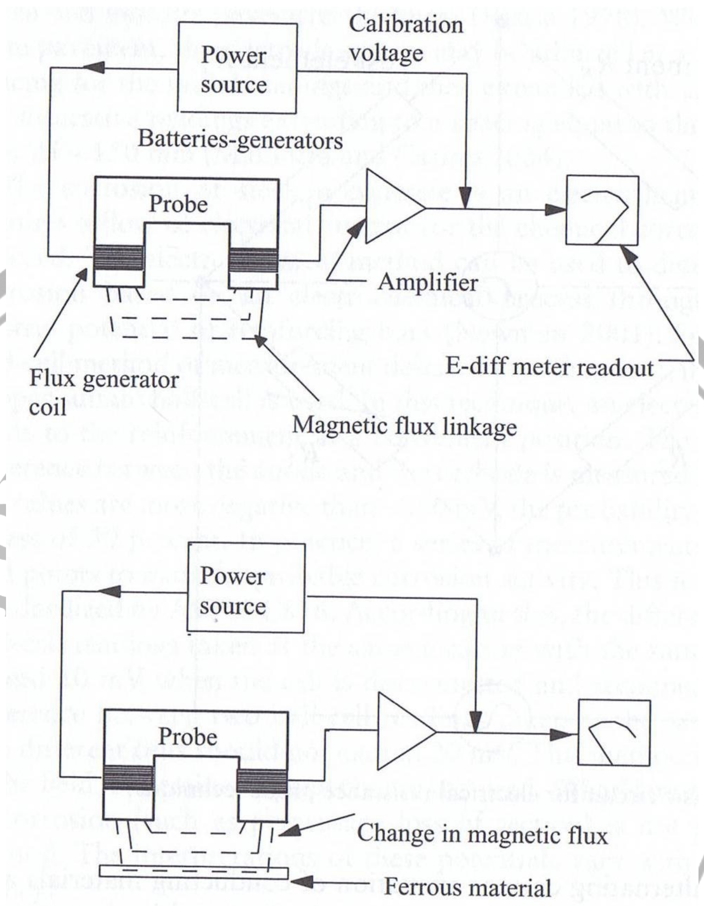

FIGURE 6 Magnetic Flux Leakage NDT Technique [7].

As the ferromagnetic materials are magnetized, a magnetic path between the poles of the probe is created when magnetic lines of forces, or flux, flow through the material. The magnetic flux increases from zero at the center of the material to increased density and strength near the outer surfaces of the material. Perturbations of the magnetic flux may occur if there is a crack or defect in the material. The magnetic permeability is drastically changed and the resulting leakage flux provides a way to identify defects or cracks with non-destructive testing. The geometry of the defect can affect the amount of flux produced. For example, a broad, shallow defect will not produce a large outward component of leakage [7]. The operator needs to be aware of this to help prevent discontinuities in the subject material from not being detected.

The change in area in steel reinforcement and cables, and the breakage of strands of prestressing cables in reinforced concrete bridges can be identified by magnetic flux leakage testing. Corrosion can cause this change in area but MFL cannot identify corrosion, it can only identify the effects of corrosion that have been mentioned, such as change in area and breakage of tendon. It is the engineers or technicians judgment to determine whether corrosion is occurring. MFL techniques do not require mechanical contact with the test article and they allow for automatic signal recognition schemes.

RADAR

Radar is an electromagnetic wave technique that can be used in non-destructive testing of concrete. Microwaves, which are lower frequency waves in the RF to S-band frequency, are used by radar. These microwaves are in reflection mode for the radar technique testing. The radar technique testing system consists of a control unit, two antennas (one for transmitting and one for receiving pulses), an oscillographic recorder, and a power converter for DC operation. When used in testing concrete and concrete structures, a radar antenna with relatively high resolution is preferred so that small layers of a concrete member can be detected [7].

A radar system transmits pulses through an antenna and during the propagation of the pulses; the pulses are partially reflected and refracted at any interface where there are distinct changes in the dielectric characteristics, such as the location of an internal void. Reflected pulses are received through a receiving antenna and processed by the radar equipment. The equipment provides an evaluation of the properties and geometry of the testing object. Impulse radar is one approach of radar that transmits a series of discrete sinusoidal pulses within a specific broad of frequency band. This radar approach is used in field testing of concrete structures and many commercial radar systems are of this type.

A radar signal can be attenuated as it passes through the structure or specimen of interest. The amount of attenuation is dependent on the frequency of the signal used and the conductivity of the materials. In conductive materials, attenuation increases which results in a decrease in the penetration depth by radar pulse. Low frequency radiation may penetrate further than high frequency radiation, but there exists a loss in resolution because the increase in wavelength. The moisture content of the concrete and steel reinforcement can also skew the results [7].

CONCLUSION

Many different NDE inspections methods can be used to evaluate and identify flaws and weaknesses in a bridge. Infrared imaging provides the inspector a technology to examine delamination, cracks, and other structural defects in a bridge from a distance away through examination of the thermal effects on the bridge. Another technique utilizes the use of ultrasonic waves to identify cracks and defects in the concrete. As the bridge is being inspected, Acoustic pulses are sent through the material and discontinuities are observed. Eddy current testing identifies a defect in the bridge through release of an electric circular current that will be disturbed when it interfaces with a defect. These techniques vary in the time, complexity, cost, and whether the inspection can be performed from a distance or must be performed while actually being on the bridge. Magnetic flux leakage sends a magnetic field through the material and detects leakage into the air based on changes in the cross sectional area of the material. Finally, radar techniques measure discontinuities in the reflection of the wave.

REFERENCES

Rens, K. L., Nogueira, C. L, Transue, D. J., Bridge management and nondestructive evaluation. *Journal of Performance of constructed facilities*. ASCE/ February 2005.

ACI Committee 228, "Nondestructive Test Methods for Evaluation of Concrete in Structures (ACI 228.2R-98)," *American Concrete Institute*, Farmington Hills, Mich., 1998.

Manning, D. G. and Holt, F. B. (1980) “Detecting Delaminations in Concrete Bridge Decks”, *Concrete International*, November 1980, pp.34-41.

Starnes, M. A., Carino, N. J., and Kausel, E. A., "Preliminary Thermography Studies for Quality Control of Concrete Structures Strengthened with Fiber-Reinforced Polymer Composites," *Journal of Materials in Civil Engineering*, V. 15, No. 3, pp. 266-273, 2003.

Kaplan, H. (1999). Practical Applications of Infrared Thermal Sensors and Imaging Equipment, SPIE *–The International Society for Optical Engineering*, Belling-ham, Washington, U.S.A.

Hellier, C. J. *Handbook of nondestructive evaluation*. McGraw-Hill, 2001

Li, Z., Leung, C., and Xi, Y. Structural renovation in concrete. Taylor & Francis, 2009.

Szilard, J., Ultrasonic Testing, John Wiley & Sons, Binghamton, N.Y., 1982.

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