A Heuristic Non Destructive Evaluation Technique For Rebar Corrosion of Marine structures based on the synergy of Infrared Thermography, Signal and Image Processing.

by G. Kannan*, N. Manoharan* and B. Venkataraman**

*AMET University, Chennai, India
** IGCAR, Kalpakkam, Chennai, India

Abstract

The marine structures predominantly make Rebar as the reinforcement steel as tension device mainly to strengthen and hold concrete intact. As these structures are in constant contact with sea water, they develop corrosion due to salinity of water. There are emerging challenges in exact quantification of these parameters. The present paper aims to dwell on corrosion mechanisms including rebar corrosion and reviews the various evaluation techniques on thermography by elaborating the methods. A simplistic heuristic infrared thermography method is described for collecting images of the specimens and applying digital signal & image processing techniques on them. Iterative data capturing is done for effective synergy of thermography and signal & image processing techniques.

Keywords: Rebar Corrosion, marine structures, infrared thermography, signal and image processing, synergy, iterative methods.

1. Introduction

1.1 Corrosion:
Corrosion is the deterioration of a metal as a result of chemical reactions between it and the surrounding environment. Both the type of metal and the environmental conditions, particularly what gases that are in contact with the metal, determine the form and rate of deterioration. There are a numerous ways of addressing the ‘corrosion’ and are described as 'General Attack corrosion', 'localised corrosion', Galvanic Corrosion, Environmental cracking, flow assisted corrosion, de-alloying, fretting corrosion, High-Temperature Corrosion.

Corrosion of steel in concrete Reinforced concrete structures perform well as long as the alkaline environment is intact [3]. The main reasons for depassivating concrete are carbonation of concrete and chloride penetration. Carbonation induced corrosion is a problem where concrete cover is small or the concrete of bad quality with well connected open pores and a low cement ratio with poor corrosion of reinforcement has been established as the predominant factor causing widespread premature deterioration of concrete construction worldwide, especially of the structures located in the coastal marine environment [10]. The most important causes of corrosion initiation of reinforcing steel are the ingress of chloride ions and carbon dioxide to the steel surface. After initiation of the corrosion process, the corrosion products (iron oxides and hydroxides) are usually deposited in the restricted space in the concrete around the steel. Their formation within this restricted space sets up expansive stresses, which crack and spall the concrete cover. This in turn results in progressive deterioration of the concrete. As a result, the repair costs nowadays constitute a major part of the current spending on for measurement of the corrosion rate of reinforcing steel in concrete, many electrochemical and non-destructive techniques are available for monitoring corrosion of steel in concrete structures. Rebar corrosion on existing structures can be assessed by different methods such as, Open circuit potential (OCP) measurements, galvanostatic pulse transient method, electrochemical spectroscopy, ultrasonic and X-ray measurements. In Open Circuit Potential (OCP) Measurements, the tendency of any metal to react with an environment is indicated by the potential it develops in contact with the environment.

1.2 Rebar Corrosion:
In reinforced concrete structures, concrete acts, as an electrolyte and manifestation of corrosion of steel in concrete Rebar is explained in the following manner. The rebar in marine concrete structures perform as desired provided the alkaline environment is not disturbed and is kept intact. When the passivating effect of the concrete with pH 10-12 is penetrated, corrosion of steel in concrete can occur. Chloride ion, present in marine breeze and seawater is considered the main external agent to damage reinforced concrete in marine environments. It affects the passivity of steel film and provokes the initiation of corrosion. Concrete is a very important construction material [4]. It is highly resistant to compression forces, but week under traction forces. To improve its properties, it is combined with steel bars, highly resistant to traction. Concrete offers corrosion protection to carbon steel. It acts like a physical barrier that partially isolates steel surface from the external environment and establishes an alkaline pH that facilitates steel passivity [5]. Durability of a reinforced concrete structure depends on the
environment in which it is exposed, as also on the time and properties of concrete. Permeability is an important property in determining sensibility of concrete to external factors. For high durability, concrete should have low permeability that is strongly linked to porosity of the concrete paste.

Carbonization and chloride penetration effect are the predominant contributing factors in corrosion\cite{1}. Innumerous structures are contaminated with chloride as a consequence of deicing during winter and chloride laden environment such as marine offshore and coastal structures. The marine structures are categorized, by one school of thought, into five major categories namely i) piled platforms ii) flexible bulk heads iii) gravity structures iv) rubble mounds and v) floating structures. These structures predominantly make Rebar as the reinforcement steel as tension device mainly to strengthen and hold the concrete intact. These structures are contact with sea water and hence are subjected to corrosion as described earlier and may be described as the deterioration of materials especially metals by chemical or electrochemical reaction with environment. Though it is simply stated, the exact quantification of the corrosion parameters, their measurements, and their characterization with time are all real challenging tasks \cite{8}. Various Non Destructive Evaluation techniques using conventional methods of radiography, ultrasonic, thermography and the like are deployed these purposes \cite{2}.

It is the endeavor of this paper to review various Non-destructive techniques and variants of thermography methods. Different methodology and signal processing techniques will be studied from the point of efficacy and merits and demerits on the existing conventional methods. The lock-in thermographic methods will be studied elaborately and how this method is best suited for defect characterization and quantification for rebar corrosion.

1.3 Various Evaluation techniques in thermography:

There exist several types of thermography approaches which can be classified based of the methodology for testing the materials, the origin of the source of thermal energy and the measured temperature differences arising from it. In general; the infrared thermography IRT techniques can be classified into two main types.

Passive, steady state or static thermography; this technique operates in two wavelength ranges, 3-5 μm (SWIR) and 8-12 μm (LWIR) \cite{6}. Where IR radiation energy depends on the chosen wavelength range. Passive thermography is essentially based on analysis where no external excitation is used to excite thermal gradients on the test specimen's surface\cite{11}. In this approach, the features of interest are naturally at a higher or lower temperature than the background. Passive thermography has many applications such as surveillance of people on a scene and medical diagnosis; specifically thermology\cite{12}.

Active or dynamic thermography; this technique is based on the detection and recording by an infrared camera of thermal IR radiations emitted by object surface. External energy source is required to be used in this approach in order to produce a thermal contrast between the examined specimen and the feature of interest (subsurface defects); where it is required to heat or cool the object being inspected in order to create the required thermal contrast\cite{11}. The active approach is necessary in many cases given that the parts being examined are usually in equilibrium with the surroundings\cite{12}.

Infrared Thermography (IRT) is one of the most attractive nondestructive inspection NDI methods because it is a non-contact technique, safe, clean, painless, and such a fast inspection method and is used as an NDT technique in variety of applications from medical to building inspections. That and is becoming a widely adopted technique to detect the presence of variety of internal flaws or defects; i.e. discontinuity or non-homogeneity inside materials.

IRT has many advantages like they are non-contact technique, can create 2D thermal maps (therogram), they are direct tests in real time and can reduce maintenance costs and finally with no harmful radiation effects.

To obtain maximum information about the corrosion state of rebar in a particular structure, a combination of measuring techniques is recommended. The electrochemical corrosion measurements are usually qualitative and also semi quantitative; significant benefits can be derived from them. The development of durable, embeddable sensors and inexpensive microprocessor control and communications, have encouraged the development of corrosion monitoring systems for new and existing reinforced concrete structures \cite{7}. The development of integrated monitoring systems for new and existing reinforced concrete structures could reduce costs by allowing a more rational approach to the assessment of concrete structures, the ability to continuously monitor the cover concrete and steel in real time could thus enable to provide more information of the current and future performance of the structure.

The minimum number of experiment components needed to perform infrared thermography are heat source and an infrared (IR) camera. The proper choice of heat source is paramount for a successful thermographic experiment. Such source must be chosen so as to maximize the thermal contrast between the defect and the surrounding material.

Any material can be inspected thermographically (such as metals, ceramics and composites) but the outcome of the inspection will depend on many factors such as sample geometry, sample thickness, amount of heat used, surface emissivity, specific heat, material density, thermal conductivity, defect depth and the size of the defect and other parameters.
The infrared temperature measurements are affected by many of the same factors including surface emittance, air temperature, background thermal radiation, and air humidity.

2. **Lock-in thermography technique (LT)**

Lock-in Thermography stands as an active thermography NDI technique which is established basing on using a periodic input energy waves (periodic excitation) to send periodic waves (sinusoids) at a given modulation frequency \( \omega \), in order to derive information from the observed phase and amplitude of the reflected thermal wave\[13\]. The halogen lamps represent the most common affordable stimulation heating source that is used in LT\[14\].

Lock-in thermography is a technique derived from photo-thermal radiometry (PTR)\[15\], in which, the thermal waves is delivered into specimen's surface in the form of periodic thermal waves (periodic stimulation), then the thermal response is recorded at the same time by using an IR camera\[12,16\]. In general in PTR, the examined specimen's surface is stimulated by a plane light beam and its thermal infrared emission is measured and recorded by an infrared IR detector. In one hand, if the infrared IR detector is made of a monolithic IR sensor, then the technique is known as photo-thermal radiometry (PTR), whereas if the detector is made of an array of IR sensors, the technique is known as lock-in thermography (LT)\[13,17\]. Using an un-cooled IR camera in LT is normally sufficient, and then it is an economical technique since the uncooled IR camera is cheaper.
2.1 Principle:

The principle of LT operation is based on applying periodic thermal waves into the specimen being inspected. The periodic wave propagates by radiation through the air until it reaches the examined object's surface where heat energy is generated and warms the specimen's surface up then propagates by diffusion through the material as thermal waves. Whenever these thermal waves reach any discontinuity (defect); such as inclusions, or delaminations, then these defect acts as a thermal barrier (thermal resistance) causing changes in amplitude and phase delay (shifting) of the response signal at the surface. The thermal response is recorded at the same time by using an IR camera\[16,18,19\]. LT technique has established basing on the fact that the thermal wave is very responded to any slight changes or interfaces between materials, where based on observed thermal images that obtained via IR camera, then any changes in amplitude or phase between defective areas and non-defective areas refer to the defect's presence. In LT technique, it is preferred to use halogen lamps to generate the periodic thermal waves, due to their relatively high efficiency, simplicity in use and possibility of control by amplitude modulation of conventional power units[13].

The most interesting thing as a NDI technique is these periodic thermal waves can be created and detected remotely. In general; lock-in thermography is convenient tool to be used for detecting subsurface defects, measuring thicknesses of coatings and determining material properties [9]. Basically, the lock-in terminology refers to the fact of being required to monitor the exact time dependence between the output signal and the original input signal.

Qualitatively, the phenomenon is as follows; in this technique the examined specimen's surface is periodically stimulated by one or several modulated heating sources, such as halogen lamps, to inject thermal waves perpendicularly into the inspected specimen. Where the periodic thermal waves transfer by radiation through the air (medium) until the sinusoidal heat wave's front being in phase with the inspected specimen's surface where the inspected specimen's surface is heating up then the thermal waves propagate by diffusion through the material. The temperature of each point in the inspected specimen will change over time, as it will be affected by the generated waves and those reflected in thermal barriers. Since the subsurface defect or any subsurface discontinuity or non-homogeneity act as barrier for heat propagation, then it will effect on the thermal waves and change its amplitude and phase as a result.

Simply, wherever these thermal waves being in face with any subsurface discontinuity or non-homogeneity in which there is a change of the thermal physical properties, causing a thermal effect change in terms of reducing the amplitude and its phase delay, then it will be partially reflected. The reflected part of the thermal wave interferes with the incoming input thermal wave creating at the stimulated surface of the examined specimen, causing an interference pattern in the local surface temperature and thus in the surface radiation as a result; which oscillates at the same frequency as the input thermal wave. The thermal response is recorded at the same time by using an IR camera, then evaluating the amplitude and the phase of the local surface temperature oneto earn information about the internal structure of test object. The IR camera can observe the whole or a large part of the inspected specimen's surface typically in a 320 x 256 or 640 x 512 pixel array configurations [20,12,21,16,22].

Any phase shift (delay) between the thermal evolution for a defective region and a non-defective region represents an abnormality (defect) which can be observed and revealed. For NDI testing purposes, the phase image (phasegram) is often more informative than the ampligram (amplitude image) one which strongly depends on the local IR emissivity; i.e. the phasegram is independent from the IR emissivity (\(\varepsilon\)) of the surface. In fact, the phasegram is a measure of the time delay of the surface temperature modulation referred to the power modulation, which is indeed independent of the magnitude of the heat source[23].

Mathematically, in the lock-in thermography technique the procedure as follow after observing the inspected specimen's surface via IR camera then the recorded temperature data is transformed into a frequency domain. In which in each pixel, the measured temporal evolution of the temperature represents a Fourier-transformed for all the recorded images sequence. Each pixel in the thermal image corresponds to atemperature at a given time, so that by using Fourier-Transform method for each pixel per cycle then an advanced new result is obtained. This new result is represented by a phase image and an amplitude image. Any fault (discontinuity or non-homogeneity) inside the object will be reflected in these images; hence they can show the internal structure of the inspected object and all possible defects.

2.2 Experimental Details:

The experimental configuration of lock-in thermography technique includes a periodic thermal stimulation source in order to deliver the thermal energy to the inspected specimen's surface in form of periodic thermal. The halogen lamps send periodic thermal waves to the inspected specimen's surface at a given modulation frequency \(\omega\), for at least one cycle; ideally until reaching a steady state which depends on the thermal physical properties of the examined specimen and the defect depth. The thermal response is recorded at the same time using an IR camera that is synchronized with the excitation signal and decomposed by a lock-in amplifier to extract the amplitude and phase of the modulation.

In LT, the object being examined is periodically excited by using a periodic thermal wave with a single frequency corresponding to a particular depth at which a particular defect can be detectable. However, this procedure (test) has to be repeated with other different frequencies to cover a wide range of depths (each single frequency to detect a defect presence at specific test depth).

The data acquisitions in LT technique are more accurate depending on the phasegram of the output signal. The lock-in thermography LT, allows the reconstruction of phaseimages that are less affected by the
characteristics mentioned above (non-uniform heating, emissivity variations, surface geometry, and environmental reflections); i.e. LT represents an insensitive technique [25].

An interesting thing of LT is in the fact that by the use of a periodic excitation-detailed examinations can be executed with a relatively low power thermal waves input into the object. This permits the examination of thermally sensitive components and the use of relatively simple heat sources.

2.3 Data Analysis

Preparing a building component specimen for thermography is somewhat similar to hotbox testing, with differences in flush mounting and emittance modifications. Large areas specimens can simply be located between the chambers with perimeter insulation distances can be measured for subsequent synchronization with the thermographic data. This step is critical to obtaining accurate spatial coordinates to pair with infrared temperature data.

The infrared imaging system should be positioned as close to the specimen as is practical, allowing the imager to view the desired portion of the specimen, the reference emitter, and at least two location markers, and also allowing the background mirror to be deployed. Each thermogram should include enough of the reference emitter to provide at least 10 horizontal and 10 vertical infrared elements or IFOVs. How much of the specimen is selected for viewing will vary depending on the specimen’s geometry and thermal contrast; small features and high surface temperature gradients require close viewing. The maximum viewing distance to resolve a given feature is determined by the IFOV of the infrared imaging system where three to five (or more) IFOVs are needed to resolve the temperature of a feature. The temperature span of the infrared imaging system should be the smallest possible value that includes all the features of interest. The reference emitter surface temperature should be set to within ±3°C of the temperature of a given feature of interest. Thermograms should be recorded by averaging data over time, usually by averaging multiple frames of data. For analog systems, 20 frames or more is recommended. Depending on the range of temperatures present it may be necessary to record several thermograms with smaller temperature spans and varying center temperatures. When multiple images with different spans and center temperatures are taken of the same view, good data alignment can be insured by including at the time of capture geometry overlays that will be used for postprocessing in all the related thermograms. Immediately before and/or after imaging a particular view of the specimen, deploy the reflective background mirror parallel to and in front of the test specimen and record the effective background radiation level (emittance set to 1.0). The imager viewing angle is usually at an offset from normal to prevent reflections of the cold scanner lens, which is an unavoidable nonuniformity in the background.

The specimens with introduction of various defects were manufactured and subjected to saline environment.

2.4 Merits and demerits of IRLT Techniques

Infrared Thermography is an attractive and powerful nondestructive testing and evaluating inspection technique that provides a safe remote (non-contact) inspection of components and structures without changing the integrity and properties of the examined specimens and without causing any damage, through a mapping of thermal patterns on the surface of the objects of interest. Defect detection fundamental in active thermography is based on the fact that the variations in temperature that exists between the reference area and a defective region based on its emitted infrared radiations, which can be used for defect detection and quantification purposes.

3. Conclusion:

The results of Lock-in thermographic data are acquired by preparing the experimental set up and also by conventional techniques. The initial interpretation of results are encouraging that the thermography methods for rebar corrosion specimens will turn out to be more effective and in-situ methods can be conceived for field applications.

References:
3. Alan D. Zdunek and David Prine “Early Detection of Steel Rebar Corrosion by Acoustic Emission Monitoring” Paper No. 547
4. T. Paul Teng “material and methods for corrosion control of reinforced and prestresses concrete structures in new construction" P.No 00-081, Aug 2000