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NON-DESTRUCTIVE EVALUATION OF CONCRETE STRUCTURES BY NON-STATIONARY THERMAL WAVE IMAGING

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Abstract—Reinforced concrete structures (RCS) have potential application in civil engineering and with the advent of nuclear engineering RCS to be capable enough to withstanding a variety of adverse environmental conditions. However, failures/loss of durability of designed structures due to premature reinforcement corrosion of rebar is a major constrain. Growing concern of safety of structure due to pre-mature deterioration has led to a great demand for development of non-destructive and non-contact testing techniques for monitoring and assessing health of RCS. This paper presents an experimental investigation of rebar corrosion by non-stationary thermal wave imaging. Experimental results have been proven, proposed approach is an effective technique for identification of corrosion in rebar in the concrete samples.

1. INTRODUCTION

Reinforced concrete is one of the most versatile structural element being extensively used in various civil structures. High strength, durability, sustainability, flexibility in making complex shapes is the most preferred shapes of concrete structures. However, exposed to adverse physio chemical environmental conditions may lead to

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premature loss of strength due to corrosion of rebar. These defects can results catastrophic structural failure unless their presence is detected and their effects are assessed in time. Which makes the inspection of reinforced concrete structures is a crucial and challenging aspect in the area of damage prediction and health monitoring [1–7].

Present work highlights the applicability of Thermal Non-destructive Testing (TNDT) [1], for inspection of concrete specimens. Infrared TNDT involves mapping of surface temperatures as heat flows from and/or through a test sample, for detecting surface and subsurface features (voids, corrosion, cracks etc.). It is a fast, whole field, and non-contact method for defect detection. Since most solids conduct heat, TNDT has the potential for wide use in defect detection in a variety of solid materials [2–4]. It has numerous applications in the area of building, civil engineering, space, electrical, electronic and mechanical engineering industries. Of the various possibilities of TNDT implementations, InfraRed Thermography (IRT) has gained wide acceptance in non-destructive testing and evaluation (NDT & E) due to its remote detection capabilities. TNDT can be broadly divided into active and passive methods [1].

Passive thermography [1] involves mapping the temperature profile of a sample surface, in the absence of any external heat stimulus. The limitation of this approach is it's general inability to detect defects lying deep inside the test sample, for which it does not provide sufficient temperature contrast over defect and non-defective regions. In order to reveal these deep defects with a high contrast, active thermography is used. This requires an external thermal stimulus to the inspected specimen in order to obtain significant temperature differences witnessing the presence of subsurface anomalies. The present work is mainly focused on the active approach [8–18].

In active approach [2–18], external heat stimulus is provided to the test sample of whose thermal response is to be observed. Known characteristics of the external thermal stimulation applied onto the specimen (i.e., nature of excitation, its time duration and its band width etc), facilitates the qualitative and quantitative characterization of sub-surface defects. The present work is mainly focused on the active approach.

During the last two decades, intensive experimentation work is being carried by various researchers throughout the world to introduce new thermal non-destructive testing methods to overcome limitations in the existing methods. The most popular TNDT methods are: Pulsed Thermography (PT) [1, 2], Lock-in Thermography (LT) [3] and Pulsed Phase Thermography (PPT) [1, 2]. Choice of any of the above mentioned thermographic methods for NDT & E depends on the intended application, thermal properties of material to be tested, defect location and its thickness. Each method has its own advantages and limitations.

In PT, the examined sample is warmed up with a short duration high peak power pulse and the resultant surface thermal response is recorded. The resultant sequence of images recorded contains information about defects in the material at different depths. In practice, this technique requires high peak power heat sources and has the inherent drawback of being sensitive to surface emissivity variations and non-uniform heating on the surface of test sample. In general, for the industry at present, pulsed thermography systems are perhaps the favourite choice. Though image processing techniques do help to improve the capability of the pulsed thermographic techniques for subsurface defect detection with improved resolution and sensitivity, the requirement of high peak power heat sources still remains a major drawback of PT. However, wave thermography does have some advantages over PT. In contrast to pulsed thermography, lock-in thermography (LT) is based on thermal waves generated inside the specimen under study. Mono-frequency sinusoidal thermal excitation at an angular frequency of ω, introduces highly attenuated, dispersive thermal waves of the same frequency ($\omega/2\pi$) inside the test specimen. The excitation frequency in LT is chosen depending on the sample's thermal characteristics and its geometrical dimensions. Smaller is the frequency of the thermal waves, lower is the velocity in the test specimen and deeper is its penetration into the test specimen. From the acquired image sequence, in the stationary regime of heat cycle, information about the phase and magnitude of the reflected thermal wave is derived. Phase images have several advantages including those of being less sensitive to non-uniform illumination of heat sources and variations of surface emissivity over the sample. Even though it requires a longer exposure time, another point in favour of LT is the relatively small increase in temperature of the object, which makes it preferable when the testing specimens are sensitive to temperature variations. Further, phase images are capable of probing deeper defects compared to the magnitude images. Due to its mono frequency excitation, the generated thermal wave length inside the test sample gets fixed, leading to a fixed depth resolution. Therefore, in order to get good resolution for various defects located at different depths inside the test specimen, it is necessary to repeat LT with different excitation frequencies [7, 8].

Insight of the above mentioned advantages and limitations of the widely used conventional methods, this paper focuses on an experimental investigation for detection of corrosion of rebar in reinforced concrete structures by frequency modulated non-stationary thermal wave imaging [7–18].

2. FREQUENCY MODULATED THERMAL WAVE IMAGING

In frequency modulated thermal wave imaging (FMTWI), frequency modulated heat flux deposited over the sample generates a modulated surface temperature distribution of the surface. These generated thermal waves diffuse to interior into the materials under test by producing similar time varying temperature distribution on the surface. Thermal diffusion in substances can be explained with 1D heat conduction equation given by [8],

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

where α the thermal diffusion coefficient and T is the instantaneous temperature and x is direction of heat flow (perpendicular to the surface). On solving the above equation for FMTWI under the following boundary conditions at $x = 0$ and $x \to \infty$, $T(x = 0, t) = T_0 e^{2\pi j\left(ft+\frac{Bt^2}{2\tau}\right)}$ and $\mathrm{Lim}_{x\to\infty} T(x,t) = T_\infty = 0$ with an assumption that ambient temperature $T_\infty = 0$ and consider only the dynamic variations in temperature, results in [8, 18]

$$T(x,t) = T_0 e^{-x\sqrt{\frac{\pi}{\alpha}\left(f+\frac{Bt}{\tau}\right)}} e^{-jx\sqrt{\frac{\pi}{\alpha}\left(f+\frac{Bt}{\tau}\right)}} e^{2\pi\left(ft+\frac{Bt^2}{2\tau}\right)} \tag{2}$$

where B/τ is the frequency sweep rate of the chirp and τ is duration of excitation.

Penetrating thermal waves gets attenuated as they travel through the substance. The depth at which energy of the wave attenuates to $1/e$ times of its surface value is called thermal diffusion length, which plays a vital role in thermography. Thermal diffusion length of this frequency modulated thermal wave is given by [8]

$$\mu_{fm} = \sqrt{\alpha/\pi\,(f + Bt/\tau)} \tag{3}$$

Dependence of thermal diffusion length on frequency and band width of the applied signal facilitates the depth resolution of probing of different depths simultaneously, within a single sweep using FMTWI. Thus analysis of inherent frequency components provides the details of the anomalies at different depths.

2.1. Post Processing Approaches

In IRNDT, anomaly detection and analysis has been performed using the thermogram sequence captured during or after the excitation of the object surface by known controlled heat stimulus. Detail of the subsurface anomalies can be extracted by contrast of thermal parameters obtained from any suitable and efficient processing algorithm applied over the temporal thermal profiles of each pixel.

2.1.1. Phase Based Analysis

As phase detail facilitates more depth analysis [3] than contrast based techniques, signatures of the anomalies have been identified by disintegrating the phase information of the inherent frequency components from thermal responses of captured thermogram sequence. Phase information is extracted using the one-dimensional Fast Fourier Transform (FFT) applied on temporal thermal responses of each pixel of the thermogram sequence and computing arctangent values from imaginary and real component values as [1, 2, 8, 18]

$$\varphi_n = \tan^{-1} \left(\mathrm{Im}_n / \mathrm{Re}_n\right) \tag{4}$$

where n is the nth component of the sequence and φ_n is the phase component.

2.1.2. Correlation Based Analysis

Pulse compression technique prevalent in RADAR allows the transmission of a medium peak power, long duration modulated wave to improve the target detection range and resolution comparable to that achieved with a short duration high peak power pulsed based techniques [11, 12, 14]. This can be achieved with a correlation based pulse compression technique by cross correlation of the temporal temperature distribution over the chosen reference pixel $s(t)$ over the sample, with the time delayed attenuated version of the pixel $h(t)$ for an imposed linear frequency modulated incident heat flux over the sample. Temporal temperature responses from defective and non-defective regions differ in their attenuation as well as delay, depending on the local thermal properties of the material underneath the surface [1]. Cross correlating the temporal thermal responses of the pixels with chosen reference, produces a pseudo pulsed response (compressed to a very narrow pulse) about a delayed time instant, with respect to the auto correlation of the reference thermal profile, corresponding to thermal property variations (i.e., diffusivity of material, effusivity of subsurface feature etc.). Pseudo pulsed response obtained from this correlation approach for captured temperature distribution to the imposed linear frequency modulated incident heat flux provides advantages similar to obtained with high peak power pulsed excitation.

Consider the thermal response from a pixel be $s\,(t)$ and its matched filter response be $h\,(t)$ then correlation can be computed from [11, 14]

$$g\,(\tau) = \int_{-\infty}^{\infty} s\,(t) h\,(\tau + t)\, dt \tag{5}$$

3. RESULTS AND DISCUSSIONS

Applicability of the proposed excitation method for IR non-destructive testing is experimentally tested on a reinforced concrete sample shown on Figure 1. Experiments have been carried out on a concrete specimen of 6.7 cm thickness and contain 4 cm thickness mild steel rebar of length 13.24 cm. In order to study the corrosion detection capabilities of the frequency modulated thermal wave imaging in rebar in concrete structures, an artificial corrosion has been simulated to the rebar as shown on Figure 1 by introducing four grove cuts of different widths (a, b, c and d) with a material loss of 5 mm from the surface of bar.

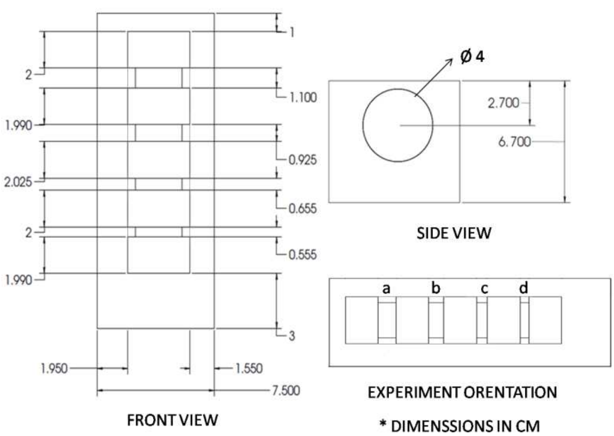

Figure 1. Layout of the experimental concrete sample with 40 mm mild steel rebar with groves of different widths located at same depth from the sample surface.

The rebar is placed in concrete sample by wounding a cotton cloth to fill the groves to avoid penetration of concrete into the grooved area. Experimental setup considered for carrying out 'FMTWI' is as shown in Figure 2. A frequency modulated signal whose frequencies varying linearly from 0.01 Hz to 0.1 Hz in a duration of 100 s is generated as shown on Figure 3(a) is used to control the halogen lamps (two halogen lamps of each 1 kW) via a control unit as shown in the schematic of experimental set of Figure 2. Temporal temperature distribution over the sample has been recorded by an infrared camera at a capturing rate of 25 frames/s during the active heating. Typical temperature rise over the sample for a given incident heat flux (Figure 3(a)) is as shown in Figure 3(b).

Further processing on the experimental data has been carried to

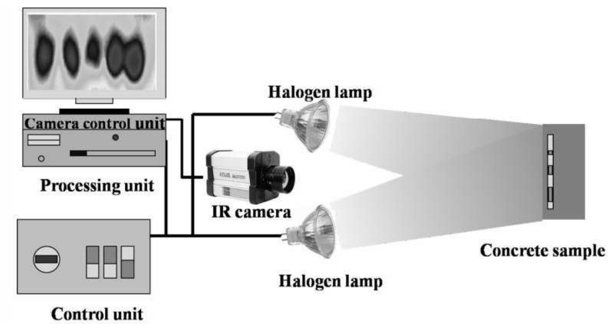

Figure 2. Experimental setup for FMTWI.

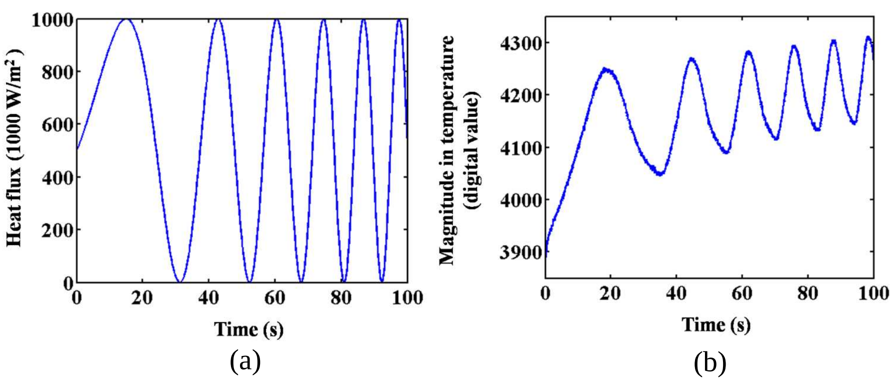

Figure 3. (a) Experimental signal used for FMTWI. (b) Temperature response over the sample during the experimentation.

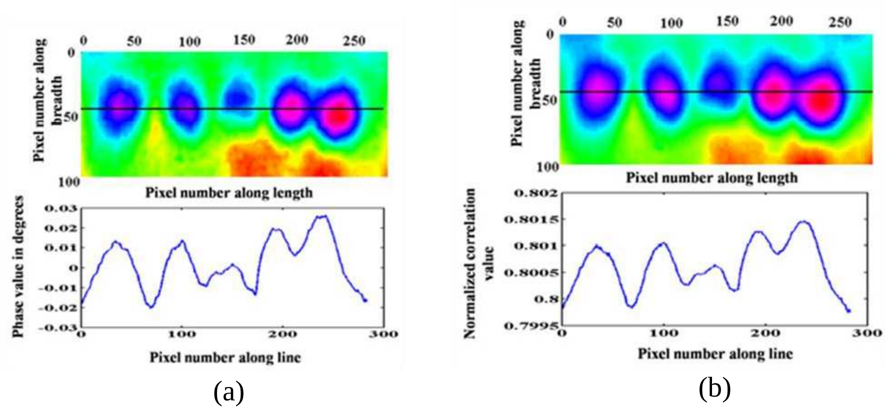

Figure 4. (a) Experimentally obtained phase image obtained at 0.012 Hz. (b) Experimentally obtained correlation image obtained at 20.8 s.

reveal subsurface features using phase based approach (Figure 4(a)) and compared with the proposed correlation based matched filter approach (Figure 4(b)). The obtained line profiles clearly indicate the amount of corrosion of the rebar in concrete specimen with phase and correlation based approaches in Figures 4(a) and 4(b) respectively. In phase based analysis, Fast Fourier Transform (FFT) is applied over to the temporal thermal profile of each pixel and phase information has been extracted. Further phase images are constructed by the obtained phase information. Whereas correlation based approach, a temporal thermal profile of each pixel is cross correlated with the chosen reference pixel.

Figure 4 illustrate the detectability of FMTWI for concrete sample using phase and correlation based processing approaches. The profiles along the line in the images clearly shows that the detection capabilities of the proposed approach to distinguish corroded areas a, b, c and d.

4. CONCLUSION

Frequency modulated thermal wave imaging has been implemented experimentally to detect the corrosion in rebar in concrete specimens. Results highlight the detection capabilities of the proposed FMTWI with phase and correlation based approaches for detection of hidden corrosion and a qualitative study on the amount of corrosion.

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