Combination of Thermal and Elastic Wave Imaging Techniques for Detection of Subsurface Defects in Concrete

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Abstract

Near surface cracks in concrete structures affect the strength and durability of the structure. Early detection of such cracks using non-destructive techniques can be beneficial with regard to timely maintenance which would prevent further deterioration of the structural element. A combination of two independent techniques, thermal imaging and ultrasonic wave based imaging is explored in this study for detection of near surface defects in concrete slabs. Thermal imaging is found to be effective in detection of fine surface breaking cracks developed as a result of accelerated corrosion of a rebar embedded in laboratory scale concrete slab. The ultrasonic technique is further applied to develop images of horizontal slices at various depths through the slab. The thermographic and ultrasonic approaches are found to be complementary in terms of the detection of surface breaking corrosion cracks and assessment of the extent of corrosion induced damage in the subsurface.

Keywords: Non-destructive test, Thermography, Ultrasonic imaging, Tied-together approach

1. Introduction

Sub-surface cracks are generated in a concrete structures due to extreme exposure conditions such as high temperature, aggressive sea water, heavy loads, etc. These cracks are sometimes generated due to reinforcement corrosion. These are detrimental to concrete and reduces the life of concrete structure. In many instances, the cracks are not visible at their initial stages. Therefore, development of Non-Destructive-Evaluation (NDE) techniques is required to probe the sub-surface, without damaging the structure. Subsurface imaging is a NDE technique, which is a visual tool for detection of defects or anomalies inside a material. The Infrared Imaging Technique (IRT) is one such NDE method which can be used to assess shallow depths of the inspected material. This technique is commonly used for the inspection of materials ranging from composites to masonry and concrete. The thermal contrast across various regions indicates the presence of shallow defects within the material. The response of the specimen to a thermal excitation is recorded using a thermal camera which creates a pixelated image, the color intensity of which represents the distribution of surface temperature. The major advantage of thermography is the non-contact nature of the technique. The imaging depth controls the modulation frequency to be adopted in thermography. The advantages of Phase Sensitive Thermography (PST) have been described by some of the researchers [1]. Pulsed Phase Infrared Thermography (PPT) is a technique which combines the strengths of both Modulated Infrared Thermography (MT) and Pulse Infrared Thermography (PT). It is associated with launching a broad band thermal excitation of the specimen and disentangling the group of frequencies by performing the Fourier transform of temperature response. It also provides better resolution of the shape of the defect [2]. A uniform heating of the surface of the specimen is a prerequisite for suppressing artifacts and this is ensured by placing the sample at a suitable distance from the heating source. The efficiency of thermal imaging is also dependent on the cooling time. While a
lower cooling time is needed to obtain a good contrast image of a shallow defect, a deeper defect reveals itself only on providing a higher cooling time [3-4]. A longer wavelength has poor resolution for the surface defects and vice-versa. The ratio of depth of the defect to its lateral dimension should also be less than two for effective detecting of the defects [6-7]. In reinforced concrete structures, the presence of reinforcement deteriorates the effectiveness of thermal imaging, as it affects the process of heat propagation. Consequently, some defects may go unnoticed in presence of rebars [8]. Another technique is ultrasonic imaging which has the ability to penetrate much deeper depths as compared to thermal imaging. The ultrasonic waves emanating from a contact based or air coupled piezoelectric source transducer is transmitted through the sample under inspection and the reflected waveform is recorded by using a similar receiving transducer. The captured data can be used to imaging of concrete subsurface using different algorithms such as the Synthetic Aperture Focusing Technique (SAFT). This technique has been applied successfully to materials which are more or less homogeneous and isotropic [9]. Two dimensional (2D) and three dimensional (3D) SAFT reconstruction algorithms have also been presented in [10, 11] imaging of concrete structures. Different variations of the SAFT algorithm have been developed especially for the detection of rebar and embedded defects in concrete [12-14], by adopting a Full Matrix Capture (FMC) data collection procedure. The FMC based technique is time consuming and there is a need to develop a faster data collection strategy. Thermography and ultrasonic imaging can be combined in order to assess concrete structures [15]. Firstly, thermography can be utilized to quickly ascertain the probable location of the defect. The location and depth information, can be obtained using ultrasonic imaging at different depth. Therefore, both these techniques provide promising results when imaging defects within concrete.

A combination of thermal and ultrasonic technique is developed in the current study for imaging of corrosion induced crack, in a concrete slab. The efficiency of thermography for detection of this hairline crack is demonstrated. Further the ultrasonic array based imaging is explored to produce horizontal slice images of the medium at various depths. The combination of the two techniques shows potential for efficient detection of corrosion crack in concrete.

2. Methodology

A slab of M30 grade concrete (compressive strength 30 MPa) was cast with the following proportions by weight as tabulated in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Cement</th>
<th>Coarse aggregate</th>
<th>Sand</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>1</td>
<td>2.772</td>
<td>1.7</td>
<td>0.45</td>
</tr>
</tbody>
</table>

The dimension of the slab is 400 mm x 400 mm x 100 mm. The sample was cured in water for 28 days and prepared for thermographic and ultrasonic inspection. The reinforcement of the sample is subjected to accelerated corrosion for 7 days. The experimental setup for reinforcement corrosion is shown in Figure 1. The ultrasonic and thermographic inspection is carried out after that.
2.1 Thermal Imaging

After the 7 days of accelerated corrosion of the rebar, the slab is placed in front of Infrared (IR) camera for the thermal wave inspection. Active thermography technique is applied for the inspection of uncorroded and corroded concrete slab. Thermal imaging is carried out based on the radiation of heat from the specimen surfaces. Infrared (IR) camera records only the temperature intensity radiation from the specimen. As a result, a 2-D array of numbers is stored as image representing temperature values of the specimen. The pictographic representation of this array is termed as a thermogram / thermal image. Theory of thermal radiation shown below.

**Stefan’s law of radiation:**

A black body is the one which emits heat proportional to fourth power of its absolute temperature, as given by Stefan’s law.

\[ H = \sigma T^4 \]  

where \( H \): Heat radiated per unit area per unit time, \( \sigma \): Stefan’s constant, \( T \): Absolute temperature of the body. From Equation 1, it is clear that a body at higher temperature will radiate more heat than the one at lower temperature. Diffusion length \( \mu \) denotes the distance up to which the amplitude of the wave is significant, and beyond which the chosen thermal wave attenuates to such a value, that it cannot detect any defect.

\[ \mu = \frac{2K}{\omega \rho c} \]  

where \( K = \) thermal conductivity (W m\(^{-1}\)°C\(^{-1}\)), \( \rho = \) density (kg m\(^{-3}\)), \( c = \) specific heat (J kg\(^{-1}\)°C\(^{-1}\)), \( \omega \): modulation frequency\(= 2\pi f \) (rad s\(^{-1}\)), \( f = \) the frequency (Hz). The values of these parameters used for concrete are given in Table 2.

Table 2

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity (K)</td>
<td>1.5 W m(^{-1})°C(^{-1})</td>
</tr>
<tr>
<td>Density ((\rho))</td>
<td>2450 kg/m(^3)</td>
</tr>
<tr>
<td>Specific heat (c)</td>
<td>800 Jkg(^{-1})°C(^{-1})</td>
</tr>
</tbody>
</table>

Pulsed Thermography (PT) is used in the experiments. The sample is subjected to thermal excitation for absorbing heat energy and it radiates energy in the form of IR waves which are
being captured by the IR camera. Experimental setup for thermal imaging is shown in Figure 2. The computer generates the required heating waveform through the arbitrary waveform generator. The two 1000 Watt tungsten-halogen lamps are modulated through the power amplifier. The sample is kept at a distance greater than 1 meter from the heat sources to avoid heating non-uniformity. The IR camera is focused and the required parameters are adjusted in the recording software (Altair®). The camera digitizes the surface temperature of the specimen as shown in Figure 2. The reason for choosing PT lies in the fact that it has a superposition of waves of all frequencies. The sample is heated for a specified duration as per the required diffusion length or effective depth of penetration based on Equation 2.

The Fast Fourier transform (FFT) of the raw images, captured by the camera at different time instances, are performed (Figure 3). Therefore, for each pixels of the images, FFT operation is carried out using MATLAB® Software. Amplitude and phase images for a particular frequency are plotted after the FFT operation.
2.2 Ultrasonic Imaging:

Ultrasonic inspection is carried on the surface of the slab before and after the corrosion (Figure 4). A grid of lines is marked on the slab. The lines were spaced at an interval of 10 mm along both the directions. In the Tied-Together Approach (TTA), a pair of transducers (source + receive) are placed next to each other and shifted in steps of 10 mm along the aperture after a reading is taken, until all the grid points are covered. A 200 Volts square wave signal originating from a pulser-receiver circuit is used as the input for the source and the received signals are digitized (by performing 128 averages) in an oscilloscope with sampling frequency of 5 MHz for a time window of 500 µs. A pair of 250 kHz frequency transducers is used as the excitation source and reception. A petroleum jelly based coupling agent is applied to the surface to enable efficient transfer of energy from source to the sample.
Synthetic Aperture Focusing Technique (SAFT):

After the data acquisition, the planar SAFT imaging is carried out. In this technique, an imaging plane for the slab is chosen, which could be oriented along any of the three directions (Figure 6). It is assumed that \( A_{i+1}^{i+1}(t) \) is the signal received at receiver position \( R_{i+1} \) when source is at \( R_i \), where \( R_{i+1} \) and \( R_i \) correspond to the vector positions of the receiver and the source. The image value at any pixel \((m,n)\) is given by:

\[
S_{m,n}^{i,i+1} = A_{i+1}^{i+1}(T)
\]  

where,

\[
T = \frac{|R_i - r|}{V_c} + \frac{|R_{i+1} - r|}{V_c}
\]

with \( r \) denoting the vector between the origin and the center of the pixel \((m,n)\) and \( V_c \) denoting the compressional wave velocity in the concrete sample. The image values in Eq. (3) can be added up for all the possible locations of source-receiver pair in TTA to obtain the final image value \( C_{m,n} \) at the cell \((m,n)\) on the selected plane of the sample:

\[
C_{m,n} = \sum_{i=1}^{N} A_{i}^{i+1}(T)
\]
3. Experimental Results

Thermal imaging:

After capturing the thermal images at different time instances, amplitude and phase images are prepared using FFT. It is evident from Fig. 7a), that the crack is not visible in a photograph of the sample. However, in the thermal amplitude and phase images the crack is clearly visible, with the phase image showing a better contrast.

![Figure 7. Thermal Imaging: a) normal image b) amplitude image c) phase image](image)

**Ultrasonic Imaging:**

**Before corrosion:**

SAFT images in plane 2 and at a depth of 35mm in plane 3 of slab are shown in Figure 8. It can be seen that, before the corrosion, there is a dark red mark along the length of the rebar. White dotted lines are added to emphasize the rebar location.

![Ultrasonic Imaging](image)
**Figure 8.** Results obtained using SAFT algorithm for slab with uncorroded rebar at depth = 35 mm and Y= 160 mm

(dotted white line indicates location of rebar)

Similarly, at 40 mm depth, continuous red patch is observed. This is the situation when there

![SAFT Image](image.png)

before the corrosion experiment.

**Figure 9.** Results obtained using SAFT algorithm for slab with uncorroded rebar at depth = 40 mm and Y= 160 mm

(dotted white line indicates location of rebar)

**After corrosion:**

After 7 days of corrosion, same experiment is again performed and SAFT images are prepared. At section 3 of 35mm depth, the continuous red patch line at the rebar location become discontinuous.
Figure 10. Results obtained using SAFT algorithm for slab with corroded rebar at depth = 35 mm and $Y = 160$ mm

At 40 mm depth, red patch line is almost absent except certain locations and become discontinuous. This implies some activity happened at rebar location which scattered the wave energy. Therefore, receivers are not getting the same signal like pristine condition.

Figure 11 Results obtained using SAFT algorithm for slab with corroded rebar at depth = 40 mm and $Y = 160$ mm
It is observed that after the corrosion, the red patches in the SAFT images become discontinuous. It may be due to the scattering of the compressional wave by the corrosion cracks and other corrosion products. Therefore, rebar corrosion crack have been localized using combination of thermal and ultrasonic technique.

4. Conclusions

The following conclusions may be drawn from the above study:

1) Artificially accelerated corrosion has been created in concrete structure to simulate near surface defects.
2) Thermal imaging provides non-contact based diagnostics of near surface defects in concrete specimen viz. very fine surface breaking corrosion cracks. The phase and amplitude images provide the exact location of the crack. The phase images provide a better contrast in comparison to amplitude based IR imaging.
3) Ultrasonic images identify the corrosion event in the slab. The developed planar SAFT imaging need only Tied-Together data collection which is much lesser than the existing SAFT using Full Matrix Capture data acquisition.
4) From the study, it can be concluded that a preliminary survey by thermal imaging would generate information regarding presence of very fine corrosion cracks that are otherwise not visible. Once such defects are located, a more detailed investigation may be performed with ultrasonic imaging to assess the status of rebars in the concrete. More investigation will be part of future work.

REFERENCES


