TECHNIQUE TO DETERMINE DEPTH OF DEFECTS IN CONCRETE USING INFRARED THERMOGRAPHY – A SIMULATION STUDY

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The cracks and damages in concrete can occur during the construction, placement, curing or any time during the service life of the structure. Cracks and damages can indicate concrete deterioration. Structural engineers are interested in the identification of damage location and crack depth measurement. The crack and damage depth measurement can help contractor in evaluating the repair costs. There are different methods to measure the crack depth like Impact-Echo Method, Ultrasonic Pulse Velocity (UPV) which can be employed where location of the cracks and damages are accessible. However, sometimes location of crack and damage in the concrete is inaccessible and this requires non-contact measurement methods for identifying damages. Infrared thermography can be effectively used in identifying subsurface cracks and damages in such cases. The research work reported in this study is to identify depth of sub-surface defects located in concrete structures. The depth of damage is identified by taking infrared images of concrete surface. A pseudo experiment of thermal imaging was conducted on concrete surface using FEM simulations. A concrete slab model having defects inbuilt of known thicknesses and at known depths from the surface is used. The surface of slab is subjected to thermal excitation of varying amplitude and time period. The temperature contours on vertical sections passing through the defects is used to accurately determine the depth of damage. Using this technique depth of defect could be determined with a least amount of error up to 2% of actual depth. The results of simulation study are reported.

Keywords: Damages, Cracks, Temperature contours, Thermal camera, Pseudo experiment.

1 INTRODUCTION

The cracks and damages in concrete can occur during the construction, placement, curing or any time during the service life of the structure. Cracks and damages can indicate concrete deterioration. Structural engineers are needed for identification of damage location and crack depth measurement for repairs and retrofitting. The crack and damage depth measurement can help contractor in evaluating the repair costs. If location of crack and damage in the concrete structure are inaccessible, then non-contact measurement methods for identifying damages are required. Infrared thermography can be effectively used in identifying subsurface cracks and damages in such cases. Infrared Thermography (IRT), also known as thermal imaging, utilizes the infrared spectrum to show differences in heat dissipating from a structure using a thermal imaging camera. When a subject is heated by external sources such as the sun, ambient
temperatures, friction, or other thermal sources, it emits radiation in the long-infrared range of the electromagnetic spectrum which is detected by a thermographic camera. The IRT technique is becoming popular in the civil engineering domain for detecting defects in concrete structures such as buildings, bridges, dams and cooling towers owing to its simplicity in application. There is enough research reported on successful application of the IRT to detect damages in concrete structures.

Adeli and Sirca (2018) presented the state-of-the-art review about the application of Infrared thermography for detecting defects in concrete structures from the year 2007 to 2016. The IRT application in detecting the subsurface damages has been well established through many of the laboratory experiments conducted by the researchers Yehia et al. (2007), Maierhofer et al. (2006), Cheng et al. (2008), Aggelis et al. (2011). The IRT technique has been applied on real concrete structures for detecting damages by Naik et al. (1997), Sirieix et al. (2007), Vaghefi et al. (2011), Oh et al. (2013). In almost all above research presented it is well established that approximate size and shape of damages are detected. Masashi et al. (2012) have reported the study on detecting deeper defects in concrete using pulse phase thermography. The study concluded that detectable depth depends on phase image frequency, and analytical solutions were proposed to evaluate the phase data. The experimental results demonstrated that defects with up to 5–6 mm depth were detected, which is a significant improvement compared with the reported detectable defect depth of 3.5 mm earlier. There exists a necessity to explore IRT technique for damage detection in reinforced concrete members. In most of the cases the deterioration/damage start in reinforced concrete at the level of reinforcements when corrosion is initiated. Usually, concrete members have minimum of 30–50 mm cover to reinforcement. So, detecting damages using IRT at 30-50 mm deep will enable engineers to do early detection of corrosion in reinforcement bar too. The study reported by Masashi et al. (2012) demonstrated detection of defects of up to 5–6 mm depth in concrete using optimum frequency identification for different types of damages. The present study reported here is an effort to identify location and depth of damage which are located up to the depth of 20 - 30 mm in concrete members. To identify damages in concrete lock-in thermography as explained by Chatterjee (2011) is simulated on sample concrete slab modelled using FEM software. The surface of the concrete member is subjected to a controlled thermal excitation of varying amplitude and frequency. The thermal images of the concrete surface as shown in Figure 1 are obtained from simulated IRT experiments to detect damages which are 20 mm to 30 mm deep from the surface. The depth of damage from the surface is obtained from temperature contour of vertical section passing through the identified defected area. It is demonstrated that the technique of plotting thermal contour can be very well utilized to determine the depth of damage however the thickness of damage is not identified in this simulation study.

![Figure 1. Concrete slab surface thermal image (thermogram) heated with thermal excitation.](image-url)


2 METHODOLOGY

For simulation study a concrete slab of dimension 1 m x 1 m x 0.3 m is considered. The concrete slab having material properties as mentioned in Table 2 along with defects inbuilt is modelled in Finite element software. Linear elastic constitutive model was used to represent concrete in this study. For this study Plain Cement Concrete (P.C.C.) slab was considered. FEM Model of the slab with defects is shown in Figure 2a. FEM model is explained in detail in section 2.1.

2.1 FEM Model Development

The slab is discretized using free triangular 3D elements by adopting meshing methods. The discretization is done in such a way that finer elements are near the defects to ensure thermal excitation is more effective in heat conduction through concrete near defect region. Mesh sensitivity analysis was performed, and it was found that stable results were obtained with mesh sizes ranging from 2 cm to 15 cm. Maximum size of the mesh adopted was 15 cm and minimum size of 2.8 cm was adopted for discretization. The FEM model consists of 11008 domain elements, 1706 boundary elements and 349 edge elements. To simulate damage in the slab six rectangular defects are incorporated in slab at known depths from the surface with properties of air void as shown in Figure 2b. All six defects are of size 100 mm x 100 mm but with varying thickness and located at different depths from the surface. Details of defects are in Table 1. Defects along grid line AA are located 30 mm below the surface while defects along grid line BB are located 20 mm below the surface. Plan view of the defects is shown in Figure 2b.

![Figure 2](image)

Figure 2. (a) 3D view of discretized FEM model with inbuilt defects (b) Plan view of defects with gridlines.

<table>
<thead>
<tr>
<th>Label</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Thickness of defect (mm)</th>
<th>Depth from top surface (mm)</th>
<th>Location (x,y) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>100</td>
<td>100</td>
<td>10</td>
<td>30</td>
<td>(150,700)</td>
</tr>
<tr>
<td>A2</td>
<td>100</td>
<td>100</td>
<td>5</td>
<td>30</td>
<td>(150,450)</td>
</tr>
<tr>
<td>A3</td>
<td>100</td>
<td>100</td>
<td>2</td>
<td>30</td>
<td>(150,200)</td>
</tr>
<tr>
<td>B1</td>
<td>100</td>
<td>100</td>
<td>10</td>
<td>20</td>
<td>(550,700)</td>
</tr>
<tr>
<td>B2</td>
<td>100</td>
<td>100</td>
<td>5</td>
<td>20</td>
<td>(550,450)</td>
</tr>
<tr>
<td>B3</td>
<td>100</td>
<td>100</td>
<td>2</td>
<td>20</td>
<td>(550,200)</td>
</tr>
</tbody>
</table>

Concrete material property is assigned to the block and air property is assigned to the defects. Details of properties assigned are shown in Table 2.
Table 2. Details of material property used in FEM model.

<table>
<thead>
<tr>
<th>Property</th>
<th>Concrete</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>2500 kg/m$^3$</td>
<td>$\rho(pA,T)$ kg/m$^3$</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>1.8 W/m-K</td>
<td>$k(T)$ W/m-K</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>880 J/kg-K</td>
<td>$C_p(T)$ J/kg-K</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>25e09 Pa</td>
<td>NIL</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>10e-06 1/K</td>
<td>$\alpha_p(pA,T)$ 1/K</td>
</tr>
</tbody>
</table>

2.2 FE Simulation of Lock-in Infrared Thermography

To simulate lock-in active infrared thermography experiment, the surface of the slab is subjected to thermal excitation using heat flux as shown in Figure 3a. The typical setup for a lock in thermography experiment is shown in Fig 3b.

![Thermal excitation as sinusoidal heat wave](image1)
![Typical setup for Lock-in thermography experiment](image2)

Figure 3. a) Thermal excitation as sinusoidal heat wave. The heat wave is having time period of 5 min, b) Typical setup for Lock-in thermography experiment (Chatterjee 2011).

Heat flux in the form of sinusoidal thermal wave is applied onto concrete surface. The Magnitude of the heat flux is given by Eq. (1) and Eq. (2).

$$\text{Excitation} = p_{source} \times wv1 \left( \frac{t}{\text{period}} \right)$$  \hspace{2cm} (1)

$$\text{Flux} = \text{Excitation} / (w_1 \times d_1)$$  \hspace{2cm} (2)

Where $w_1$ and $d_1$ are the plan dimensions of the slab, $wv1$ is sinusoidal waveform, $p_{source}$ is magnitude of heat source to simulate thermal excitation and period is time period of sinusoidal waveform. For this study two values of $p_{source}$ are considered i.e. 500 W and 1000 W and two values of time period 5 minute and 10 minute. The parameter optimization for stepped thermography was conducted on concrete slab model earlier by Naik et al. (2020) is referred to explore the optimum frequency of thermal excitation. The concrete slab is subjected to 60 minutes of thermal excitation. Initial temperature of the slab is taken as ambient temperature of 293.15 K.

A pseudo experiment of Lock-in Infrared Thermography is conducted on concrete slab. Thermal excitations of two different amplitudes with two different time periods is applied to the concrete surface in the form of a sinusoidal wave. A plot of surface temperature distribution in the form of thermal image is extracted after 60 minutes of thermal excitation as shown in Figure 1. The Temperature contour along the vertical sections passing through defect as shown in Figure...
4 is extracted to develop a technique to determine depth of damage. The technique is explained in the next section.

Figure 4. Temperature contour taken on a vertical section passing through center of a defect (depth of damage at 20 mm).

3 RESULTS AND DISCUSSIONS

The concrete slab as described in section 2.1 was subjected to thermal excitation in the form of sinusoidal heat flux. The magnitude of heat flux was calculated as per Equation 1 and 2. Heat flux was applied on the surface of the slab for a total of 60 minutes duration in four different simulations. Temperature variation on the vertical sections passing through defects as shown in Figure 4 were plotted in the form of a temperature contour. Such temperature contours are plotted on at least three vertical sections passing through each defect.

It is observed from Figure 4 that contour lines at the location of defects are changing from downward slope to upward slope after some height. The vertical distance from surface at which slope change noticed is recorded for all locations on the contour map and average value was considered. This depth is compared with actual known depth of defect from surface. Results were obtained for four different thermal excitations as mentioned earlier considered in this study i.e. 500 W amplitude and 5-minute time period (Wave Type 1), 500 W amplitude and 10-minute time period (Wave Type 2), 1000 W amplitude and 5-minute time period (Wave Type 3) and 1000 W amplitude and 10-minute time period (Wave Type 4). The depths of the defects are extracted from each temperature contour taken from vertical section as explained earlier. The percentage of error between actual depth of damage and depth extracted from the temperature contour map is calculated. The percentage of error in depth identification with thickness of defect and wave type is plotted as shown in Figure 5.

Figure 5. Percentage error between actual depth of defect and depth obtained from simulation with thickness of defect and wave type.
As observed from Figure 5, percentage error between actual depth of defect and depth obtained from temperature contour is about 2% which is fairly accurate. It is also observed that as thickness of defect increases the error between actual depth and depth obtained from temperature contour increases.

4 CONCLUSIONS

In this study a pseudo experiment of Lock-in Infrared Thermography was conducted on a concrete slab modelled in FEM software. Lock-in Infrared Thermography experiment is simulated by applying thermal excitation on the surface of the slab in the form of heat flux. FEM model is successfully utilized to simulate IRT to obtain thermal image. To find depth of defects, temperature contours were plotted on vertical sections passing through the defects and compared with the known depth. The comparative study showing error between actual depth and depth identified from thermal image is reported. It is found from the results that depth of defect could be determined from the thermal image of the vertical section with up to 2% error. Hence this is a fairly accurate method for determining depth of defect. Further study is being performed considering reinforcement in the slab and validating the data with simulation and IRT experiments.

References


