# Evaluation of Rebar Corrosion in Concrete by Active Thermal Sensing

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#### ABSTRACT

Active thermal (infrared) sensing has been used to locate simulated areas of corrosion in uncoated rebar test specimens embedded in concrete slabs. Varying amounts of rebar corrosion were simulated experimentally by milling notches into steel bars and then filling the notches with an iron oxide paste. The rebars were embedded in concrete and then resistively heated using DC current. Images of the heated rebars (in concrete) were acquired using an infrared focal plane array camera. Infrared images, illustrating the ability to detect non-destructively a reduction in rebar cross-sectional area of only 10 percent, are presented. In addition, results are presented demonstrating the dependence of the resulting thermal images on the orientation of the defect.

# **INTRODUCTION**

In recent years the sensitivity of infrared cameras has increased considerably. This increase in sensitivity has led to new investigations to determine their usefulness in a variety of testing and diagnostic applications. Among these are locating corrosion in aluminum aircraft components (1) and delaminations in composite materials (2), evaluation of coatings (3), and a wide variety of predictive/preventative maintenance applications. Infrared imaging has also been used in the last 10–15 years to identify delaminations in concrete (4,5). The sensitivity of the cameras in these early studies was on the order of 0.1°C. Due to advances in infrared focal plane technology, today's cameras have a greater temperature resolution than those used just a few years ago. The infrared focal plane array (IR-FPA) camera used in this investigation measures the intensity of radiation in the 3–5  $\mu$ m range, and has a relative temperature sensitivity of less than 0.01°C for an object at room temperature and emissivity of 0.95. This increased sensitivity allows less significant flaws to be detected through their previously undetectable surface temperature change.

Subsurface structures, with at least slightly differing thermal properties, can be viewed by observing variations in the surface temperature profile during transient heat flow through the material. For example, air has a thermal conductivity seventy times less than that of concrete. Thus, concrete containing a pocket of air will conduct much less heat than a neighboring region of solid concrete. The heat flux required to produce an observable surface temperature variation in a bridge deck or similarly large concrete structure is significant. A readily available source for a large transient heat flux occurs during the rising and setting of the sun. The diurnal cycle has been used effectively in

many infrared imaging applications. However, "passive" thermal heating by the sun has two drawbacks: (a) use is limited to specific times of day and is subject to climate conditions, and (b) the length of time over which the thermal transients occur is relatively long, such that thermal diffusion results in image "blurring" and a loss of resolution. As an alternative, "active" heating can be used to produce large thermal transients in many applications. Flashlamps have been used successfully to produce microsecond transients in materials with high thermal conductivity, such as sheet metals and composite materials. Carbon dioxide lasers have also been used in locating simulated landmines in sand and soil (6). By reducing the time span of the thermal impulse, thermal diffusion effects are minimized, resulting in more detailed image resolution.

The active heating technique in this work uses an electrical current to resistively heat a section of rebar embedded in concrete. Resistive heating was chosen because of the ability to uniformly heat a rebar, overall simplicity of the components, and cost effectiveness. Results are presented on the ability of the thermal imaging system to evaluate rebar containing simulated regions of corrosion. The degree of cross-section reduction and orientation of corroded regions relative to the imaging plane have been investigated.

# **EXPERIMENTAL SETUP**

Contained in Figure 1 is a diagram of the rebar assessment system. Infrared images were obtained in this work by an infrared focal plane array (IR-FPA) camera (Inframetrics,



Figure 1: Block diagram of the EchoTherm hardware used to acquire infrared images from the Inframetrics camera.

Model SC1000 ThermaCam). The IR-FPA is a platinum silicide (PtSi) CMOS 256×256 array, sensitive in the 3.4–5.0  $\mu$ m spectral range and has variable integration time. Interchangeable zinc selenide lenses provide either a 16° or 32° field of view. The temperature sensitivity of the camera is ~0.01°C. The camera can be operated manually through a keypad or remotely through a serial RS-232 interface.

Two automotive car batteries (Sears Diehard Gold), each rated at 1000 A, were used to resistively heat the rebar. Voltage measurements across a calibrated 50  $\mu\Omega$  resistor connected in series with the rebar were used to accurately measure the current passing through the circuit. Stranded copper wire (4 AWG) was used to make the circuit connections.

Concrete test samples were prepared with a commercially available "Redimix" small aggregate mixture. The dimensions of the samples were  $57 \times 20 \times 6$  cm ( $22 \times 8 \times 2.5$  in.). A single uncoated rebar was placed along the centerline of each sample. For test controls, a rebar, 1.9 cm (0.75 in.) diameter, was inserted in one sample. The typical depth of the rebar below the sample surface is 2.0 cm. Simulated defects were produced in two different rebars, shown in Figure 2. In the first sample, three degrees of cross-sectional area reduction due to corrosion were produced. Notches were milled into the bar, at 10 cm increments along the length, to depths such that the cross-sectional area of the bar was reduced to 60%, 75% and 90% of normal. The notched areas were filled with a paste composed of iron oxide powder and acetone and allowed to dry. The second test specimen contained four "v-shaped" notches, each representing a 50% reduction in cross-sectional area. The notches were oriented in  $90^{\circ}$  increments around the circumference of the rebar, as shown in Figure 2.



(a) Rebar with three reduced cross-sectional areas.



(b) Rebar with four defect orientations.

Figure 2: Schematic diagrams of two rebars with simulated defect regions. In (a), Sample 1 contains three defects, A, B, and C representing 60%, 75% and 90% of the normal crosssectional area of the rebar, respectively. In (b), Sample 2 contains four defects, A, B, C and D, each representing approximately 50% of the normal cross-sectional area, but oriented in 90° increments. In each case, the defect is back-filled with iron oxide paste or putty to simulate the thermal properties of corrosion products that would be present in the defect.

The data acquisition system (Thermal Wave Imaging Inc., EchoTherm) consists of a program interface and three main hardware components: ISC-PCI interface card, Intelligent System Controller (ISC), and camera bus interface. The IR-FPA camera outputs image data at the rate of 60 frames per second. The bus interface converts the voltage levels of the IR-FPA data to the voltage used by the ISC data bus. The ISC transmits acquired data to the computer through the PCI interface, and transmits commands from the computer to the IR-FPA. If it is desired to collect data at less than 60 frames per second, the ISC can select every n<sup>th</sup> frame by specifying an index n. The stored data can be combined through software into a series of gates. Each gate consists of a prescribed number of frames averaged together. Up to 20 gates can be selected from a set of data. By averaging multiple frames together, the signal to noise ratio (SNR) can be reduced to provide clearer images. The infrared data acquisition system was originally designed with an emphasis on imaging relatively fast thermal variations, such as those associated with sheet metal and composite plates. With large concrete masses the characteristic time of the thermal processes is much slower. To increase the capabilities of the system to investigate much longer time frames, a manual data acquisition box was constructed. The box increases the length of time over which data can be acquired and permits a greater number of frames to be averaged together to reduce the SNR.

# RESULTS

## **IR-FPA** Calibration

The IR-FPA was first calibrated so that digital numbers (DN) from the camera could be converted to temperatures. Since the camera measures the temperature through the intensity of the infrared light reaching the detector, the approximate emissivity of the surface to be imaged should be known (7). A calibration was done for both copper ( $\varepsilon = 0.38$ ) (8) and black electrical tape ( $\varepsilon = 0.95$ ) (9). The experimental data was taken at an ambient temperature of 24°C. The temperature resolution of the IR-FPA for copper and black electrical tape as a function of temperature was derived from a quadratic approximation of the temperature calibration, and is shown in Figure 3. The temperature resolution is dependent upon both the temperature of the object and its emissivity. The difference in emissivity of copper and black electrical tape results in more than a factor of two difference in the temperature resolution. This means that if the maximum temperature resolution is desired, an object's surface should have an emissivity near one, and that the object's temperature should be as high as possible.

# **Control Rebar**

In order to determine the difference between rebars with and without defects, one rebar without any defects was embedded into a concrete test block. The control rebar was 1.9 cm in diameter and 93 cm in length and contained no apparent defects. An electrical current of 1500 A was applied to the rebar for 30 s. The power generated in the rebar was estimated to 1350 W. A series of infrared images acquired over a period of 3.5 minutes is



Figure 3: Plot of the estimated camera resolution for copper and black electrical tape.

shown in Figure 4. The thermal image times noted in the images are relative to the beginning of electrical heating. The observed temperature along the length of the control rebar is approximately constant, as expected. The slight variations seen in the pictures are probably due to the nonuniform nature of the concrete.

### Varying Cross-Sectional Area

Tests were next conducted to determine the ability of the thermal imaging system to resolve reductions in rebar cross-sectional area. Such reductions could result from corrosion or cracking. A drawing of the rebar specimen used in this experiment is shown in Figure 2. The temperature distribution of the heated rebar was first obtained by imaging the rebar outside of the concrete. This was done to find the bar's actual surface temperature image before the image propagated through the concrete it would be embedded in. The electrical current resulted in a total power of 1500 W and was applied



Figure 4: Resulting time varying thermal images from electrical heating of a rebar with no defects embedded 1.5 cm deep inside a test block of concrete.

for 30 s. At cross-section A, where the area is 60% of normal, the observed temperature increased from approximately 22° to 60°C, as shown in Figure 5. In Figure 6, temperature profiles along the exposed rebar are shown at four times during and after heating. At time t = 8 s, elevated temperatures are observed at cross-sections A and B. The maximum observed temperatures occur at time t = 32 s. The measured temperatures at cross-sections A, B, and C are approximately 15°, 7°, and 3°C greater, respectively, than neighboring undeformed portions of the rebar. The effects of thermal diffusion are apparent in the temperature profiles, as the temperature profile over the defects becomes less defined at later times. The increased "noise" in the temperature profiles at later times is attributed to variations in the surface finish of the rebar. An infrared image sequence of the unobscured rebar is shown in Figure 7.



Figure 5: Time history of the surface temperature at cross-section A of the test rebar. Heating is seen to occur during the approximate time period 5–35 s.

The rebar with the three defects was then embedded in concrete with the defect regions filled with iron oxide paste. Two sets of thermal images were taken: one with the defects oriented away from the camera, the other with the defects facing toward the camera. The electrical power in both cases was 1230 W applied for 30 s. The thermal images collected for the embedded rebar with defects facing away from the camera are displayed in Figure 8. These defects are 1.8 cm below the surface of the concrete. Shown in Figure 9, is a surface temperature profile of the concrete above the rebar, with simulated defects oriented away from the IR-FPA, measured approximately 90 s after the beginning of heating. Only slightly higher intensities can be seen in the infrared images for cross-sections A and C. No apparent intensity variation can be seen in the vicinity of cross-section B. This is supported by the surface temperature profile in Figure 9. One possible factor for the defects not being clearly visible is the presence of air bubbles in the concrete near the rebar. When pouring the concrete into the form, the wet cement may not have been sufficiently agitated below the rebar to remove air bubbles. As previously mentioned, the presence of air bubbles would reduce the thermal conductivity of the concrete and inhibit the flow of heat from the rebar to the surface of the concrete.

The thermal images collected for the embedded bar with defects facing toward the camera are displayed in Figure 10. These defects are 2.2 cm below the surface of the concrete. In this set of images, all three defects appear as dark (relatively cool) regions.



Figure 6: Surface temperature profiles observed by the IR-FPA during and after electrical heating of the exposed rebar. Heating occurred during the interval 0–30 s.

The defects are clearly evident in the image taken at time t = 37 s and remain visible for up to 3 minutes. Even cross-section C, 90% of normal cross-sectional area, is clearly visible during this time interval. Shown in Figure 11 is a surface temperature profile of the concrete above the rebar, with simulated defects oriented toward the IR-FPA, measured approximately 90 s after the beginning of heating. The three defects are clearly visible in the temperature profile. Temperature differentials between the concrete over the defects and adjacent concrete are in the range of 0.50–0.75°C. The reason all three defects show up as cooler areas is the iron oxide paste, with its relatively low thermal conductivity, impedes heat flow from the rebar to the concrete surface.

#### **Varying Defect Orientation**

A rebar with defects oriented in four different directions was prepared, as shown in Figure 2. The rebar was heated with 2460 W of electrical power applied for 30 s. The resulting thermal images are displayed in Figure 12. Defects B and C are visible in the infrared images as hot (light) and cool (dark) regions, respectively. However, defects A and D do not appear to be visible in these images. In these cases where the defect



Figure 7: The resulting infrared images from electrically heating a rebar, with defects oriented away from the IR-FPA. Defect A is on the left.

orientation is in the imaging plane, we believe thermal diffusion from the heated portion of the defect is being negated by the relative cool of the corrosion products in the defect. This results in what appears to be a "normal" image.

#### CONCLUSIONS

Infrared images of rebars, with simulated corrosion defects, embedded in concrete have been obtained using an electrical heating method and infrared focal plane array camera. Simulated areas of corrosion have been imaged through 2 cm of concrete. A defect with a 10% reduction in cross-sectional area has been detected by this method. Results suggest



Figure 8: Resulting thermal images from electrical heating of a rebar with three defect depths, defect A to the left. The defect notches are oriented away from the camera 1.8 cm deep inside the test block of concrete.



Figure 9: Surface temperature profile of the concrete above the rebar with simulated defects oriented away from the IR-FPA, approximately 90 s after the beginning of heating.



Figure 10: Resulting thermal images from electrical heating of a rebar with three defect depths with the defect notches oriented toward the camera buried 2.2 cm below the observed surface of the concrete. Defect A is on the left.



Figure 11: Surface temperature profile of the concrete above the rebar with simulated defects oriented toward the IR-FPA, approximately 90 s after the beginning of heating.



Figure 12: Resulting thermal images from electrical heating of a rebar with four defect orientations buried 1.1 cm below the surface of the concrete.

that orientation of the region of corrosion relative to the infrared imaging system is an important factor. Defects oriented toward or away from the imaging system were detectable. However, defects oriented in the imaging plane gave inconclusive results. Based on the current results, this method of sample heating and infrared imaging has the potential to be an effective tool in assessing critical reinforcing bars in concrete structures.

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