NDE of Concrete Structures Strengthened with FRP Using Infrared Thermography

Monica A. STARNES
Building and Fire Research Laboratory, NIST, 100 Bureau Drive - Stop 8611, Gaithersburg, MD 20899, Email: monica.starnes@nist.gov

Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, 77 Massachusetts Ave., MA 02139

Nicholas J. CARINO
Building and Fire Research Laboratory, NIST, 100 Bureau Drive - Stop 8611, Gaithersburg, MD 20899, Email: nicholas.carino@nist.gov

Eduardo A. KAUSEL
Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, 77 Massachusetts Ave., MA 02139

ABSTRACT
Numerical and experimental methods are used to investigate the effectiveness of infrared thermography to estimate the width of subsurface flaws in fiber-reinforced polymer (FRP) laminates bonded to concrete. The study focuses on establishing the potential for quantitative infrared thermography, i.e., not only detecting but also characterizing subsurface flaws.

Finite element analyses are used to examine surface temperature response due to simulated defects at the interfaces of FRP laminates applied to a concrete substrate. In particular, the effects of flaw width and flaw depth are studied. It is concluded that the minimum detectable flaw width depends on flaw depth and the thermal resolution of the infrared detection system. A procedure is proposed for estimating the flaw width based on the point of inflection in the surface temperature profile measured along a given line.

Controlled-flaw experiments are performed to verify the procedure for estimating the width of subsurface flaws. Good agreement is found between the estimated and actual flaw dimensions. Data smoothing is shown to be effective in removing “noise” from measured temperature profiles.

1. INTRODUCTION
Infrared thermography is being used successfully for defect detection in fiber-reinforced polymer (FRP) laminates bonded to concrete. Trial case studies performed by the FHWA and New York DOT (ALAMPALLI et al., 2001), among others, confirmed that infrared thermography is a promising nondestructive evaluation (NDE) method considering testing speed and ability to detect flaws. Infrared thermography is non-obtrusive and allows localized and global testing of structures. Technological advancements in uncooled infrared detectors are making infrared thermography a more accurate and economical testing technique than it was in the past. Inspections using infrared thermography are mostly focused on qualitative assessment of the presence of flaws. The qualitative nature of the results is due to the complex relationships among the variables affecting the thermal...
response of the bonded laminates. There is a need to develop the scientific bases for using infrared thermography for assessment of detected flaws, i.e., for estimating flaw size and depth.

To enable widespread use of infrared thermography for quantitative assessment of FRP materials applied to concrete and masonry structures, a standard test method is needed. To develop such a standard, however, it is necessary to have an understanding of the factors affecting the thermal response of flaws within FRP composites bonded to concrete. The National Institute of Standards and Technology (NIST), in cooperation with the Massachusetts Institute of Technology (MIT), is carrying out research to gain this understanding. The research involves numerical simulations using the finite-element method and experimental studies using controlled-flaw specimens (STARNES et al., 2002).

This paper presents the initial results dealing with estimation of the width of subsurface flaws from infrared thermography testing. First, the principles involved in infrared thermography are summarized. Then, the finite-element modeling is described along with results of the effect of the width of the flaw on the thermal response. A procedure for estimating flaw width is proposed, and the procedure is used to estimate the width of an air void in a controlled-flaw specimen.

2. THEORETICAL PRINCIPLES

Infrared thermography, as a nondestructive tool for flaw detection, is based on the principle that heat transfer in any material is affected by the presence of subsurface flaws or any other change in material thermal properties. The changes in heat flow cause localized energy differences on the surface of the test object, which can be measured using an infrared detector or radiometer. Through data processing, the measured infrared radiation levels are transformed into their corresponding temperature distributions and recorded in the form of thermograms (isotherm plots). Irregularities in the thermogram indicate the presence of subsurface anomalies in the test object.

Flaw detection and characterization in civil engineering structures require active thermography, which involves transient heat transfer phenomena. Moreover, defect characterization needs the use of time-resolved IR thermography. Using this technique, the surface temperature of the test object is monitored and analyzed as a function of time, instead of being monitored statically at only one particular point in time. To achieve the transient heat transfer behavior, an external thermal stimulus must be applied to the test object.

3. ANALYTICAL MODELING

The differential equations that govern the temporal and spatial variations of temperature in an object under transient conditions are difficult to solve explicitly, except for simple boundary conditions. For realistic problems, however, it is possible to obtain approximate solutions using numerical tools such as the finite-difference or finite-element methods.

In this study, a commercially available multi-purpose finite element program is used to obtain the temperature histories at discrete points of models representing concrete substrates with bonded FRP layers. A series of parametric studies has been carried out to gain an understanding of the effects of various parameters on the thermal response of flawed test objects. This paper reviews the portion of the study dealing with the effects of flaw width, including estimation of flaw size and the minimum detectable flaw size.
3.1 Simulation Models

To reduce computation times, the numerical simulations were performed using two-dimensional finite-element models. The simulation object consisted of a 100 mm long by 20 mm thick concrete slab covered with several layers of carbon FRP (CFRP). Each laminate of CFRP was 0.5 mm thick. Subsurface flaws varying in depth and width were placed at the center of the model. Since the subsurface flaw was located at the centerline of the model, the simulation was simplified by using plane symmetry. Thus, only one half of the object was modeled.

Internal flaws were modeled as air gaps with a thickness of 0.1 mm. Flaw widths ranged from 3.0 mm to 25 mm wide. The models were arranged into three different groups depending on the depth of the flaw: delaminations 0.5 mm deep, debonds 1.5 mm deep, and concrete spalls 2.5 mm deep. Fig. 1 illustrates the geometries of the models.

The material properties of the model were those of concrete for the substrate, air for the defect, and CFRP for the bonded composite. The CFRP layer in direct contact with the concrete had the fibers running in the longitudinal direction (x-direction), while each of the adjacent laminates had its fiber direction rotated by 90 degrees.

The model was meshed using 2-D solid elements. Four-noded quadrilateral elements were used. Each node had one degree of freedom, temperature. The simulation object was meshed using mapped meshing, since it allows the user to directly control the element size and type. The global element size was set to 0.5 mm. Mesh refinement was applied to the thin composite layers and at the FRP/concrete interface.

The analysis was defined as a transient heat transfer problem. A square pulse of intensity 20 000 W/m² and duration 2 s was applied uniformly to the top surface of the test object. Adiabatic conditions (dT/dx = 0 and dT/dy = 0) were assumed for the additional surfaces. The assumption that there is no temperature gradient at the bottom of the concrete is reasonable because during the short time interval for thermography testing the heat pulse does not reach this surface. The assumption that there is no temperature gradient on the vertical surface implies that the specimen is sufficiently large relative to the flaw width so that heat flow is unaffected at the boundary. The latter assumption was verified from calculated temperature contours. The initial temperature for all the simulations was 23 °C, which represented ambient temperature. For simplification, uniform heating, no convective losses, and perfect contact between layers were assumed for the analyses.

3.2 Thermal Response Parameters

In these analyses, surface temperatures above the flaw and in the background where no internal flaw was present were recorded (Fig.2), from which the following quantities were determined: maximum surface temperature, thermal signal, and time to maximum signal. The maximum surface temperature occurs above the flaw and at the end of the thermal pulse. The thermal signal is defined as

\[ \Delta T = T_{\text{defect}} - T_{\text{background}} \] (1)

where \( \Delta T \) is the thermal signal, \( T_{\text{defect}} \) is the temperature above the flaw, and \( T_{\text{background}} \) is the temperature above sound material. The time to reach maximum signal \( t_s \) is the time from the start of the heating until \( \Delta T_{\text{max}} \) is reached.
3.3 Effect of the Width of the Flaw

The size of subsurface flaws could affect the performance of the FRP composite bonded to concrete. With this concern, requirements on allowable flaw size have been introduced by the International Conference of Building Officials Evaluation Services (ICBO ES). Among the conditions of acceptance, the ICBO ES states that flaws larger than 13 cm² should be repaired.

The objectives of this parametric study were to understand the effect of flaw width on the thermal response, establish a procedure to estimate flaw width and determine the minimum width of detectable flaw. With these objectives, the variation surface temperature with distance from the center of the flaw must be considered. Figure 3 illustrates a typical temperature-distance plot. It is seen that the temperature is fairly constant over the central part of the flaw and drops rapidly at the edge of the flaw. It was decided to investigate whether the location of the inflection point could be used to estimate the flaw width. A similar idea was proposed independently by Vavilov (2000). The location of the inflection point may be computed by setting the second derivative of the distance vs. temperature curve equal to zero

\[
\frac{\partial^2 T_s}{\partial x^2} = 0 \quad \text{at } w_{\text{estimate}}
\]

where \( T_s \) is the surface temperature, \( x \) is the distance from the centerline along the x-axis, and \( w_{\text{estimate}} \) is the estimation of the distance of the edge of the flaw from the centerline.

For each simulation, the surface temperature at the time of maximum signal was recorded as a function of the distance. The second derivative was approximated by numerical differentiation using a spreadsheet, and the point where the second derivative equaled zero was taken as the estimated flaw width. The results of the estimation using the location of the inflection point are presented in Table 1. The estimation error, that is, the difference between the estimated and the actual width of the flaw, is also presented in Table 1. The results indicate that flaw width may be underestimated while the width of smaller flaws tends to be overestimated.

The results given in Table 1 are presented in Fig. 4 and reveal that the estimation error increases with the depth of the flaw, that is, the estimation of the width of delaminations (flaws between layers of FRP) is more accurate than the estimation of the width of debonds (flaws at FRP/concrete interface) or concrete spalls. Most estimation errors, however, are only on the order of a few millimeters, which is very encouraging.

An important issue that needs to be addressed is the minimum width of detectable flaws. The minimum width of detectable flaws is influenced highly by the thermal sensitivity of the infrared detector or camera and environmental “noise”. Thus, the minimum detectable flaw depends on the required maximum thermal signal. The minimum detectable flaw was estimated for three different cases: \( \Delta T_{\text{max}} \) equal to 0.1 °C, 1.0 °C, and 2.0 °C. Analysis of the FEM output revealed that, for the 0.1 mm thick air void, the maximum signal \( \Delta T_{\text{max}} \) could be expressed as the following hyperbolic functions of the width of the flaw; for delaminations (depth = 0.5 mm):

\[
\Delta T_{\text{max}} = 20.95 \frac{0.40 \,(w-1.86)}{1+0.40 \,(w-1.86)}
\]
for debonds (depth = 1.5 mm):

\[ \Delta T_{\text{max}} = 5.95 - \frac{0.14(w-1.9)}{1 + 0.14(w-1.9)} \]  

(4)

and for concrete spalls (depth = 2.5 mm):

\[ \Delta T_{\text{max}} = 3.12 - \frac{0.10(w-1.87)}{1 + 0.10(w-1.87)} \]  

(5)

In these equations, the constants in front of the quotients represent maximum values of thermal signal for large 0.1 mm thick flaws. Using Eqs. 5, 6, and 7, the minimum width of detectable flaws can be estimated for different values of maximum signal. These estimated values are shown in Fig. 5 for three values of \( \Delta T_{\text{max}} \). Thus, the minimum width of detectable flaws could be computed using Eqs. 5, 6, and 7. The results from the calculations are presented in Fig. 5.

Observation of the results presented in Fig. 5 indicates that as the magnitude of the signal that can be detected decreases, the minimum width of detectable flaws also decreases. For a given magnitude of maximum signal, the relationships between minimum width of detectable flaw and depth could be approximated by the following power functions:

\[ w_{\text{min}} = 1.61 + 0.36d^{0.53} \quad \text{for} \quad \Delta T_{\text{max}} = 0.1 \text{°C} \]  

(6)

\[ w_{\text{min}} = 1.86 + 0.61d^{2.27} \quad \text{for} \quad \Delta T_{\text{max}} = 1.0 \text{°C} \]  

(7)

\[ w_{\text{min}} = 1.68 + 1.33d^{2.87} \quad \text{for} \quad \Delta T_{\text{max}} = 2.0 \text{°C} \]  

(8)

where \( w_{\text{min}} \) is the minimum width of detectable flaws in millimeters and \( d \) is the depth of the flaw in millimeters. The results indicate that near-surface delaminations should be detectable down to widths of 2 mm.

To summarize, the results of these numerical simulations indicate that the minimum width required for detection depends on the depth of the flaw and the detection limit of the infrared system. As the maximum signal required for detection decreases, the detectable flaw width also decreases. As the depth of the flaw increases, so does the detectable flaw size. While these relationships are not unexpected, the simulations revealed the quantitative aspects of the relationships.

4. EXPERIMENTAL STUDY

4.1 Test Configuration

The second phase of the research program involves laboratory studies. The results presented in this paper focus on measurement of emissivity, detection of debonds, and on the estimation of the width of a debond in a controlled-flaw specimen.

A controlled flaw specimen was constructed by using a 610 mm x 250 mm x 45 mm precast concrete slab as the substrate. Two pultruded carbon FRP (CFRP) laminates were bonded to the substrate parallel to each other and running lengthwise as shown in Fig. 6. The laminates contained unidirectional carbon fibers. Each laminate had the following dimensions: 609 mm x 102 mm x 1.3 mm. The composite laminates were bonded to the concrete substrate using bonding epoxy supplied by the composite manufacturer. Eight
“flaws” were created by placing different low thermal-conductivity materials at the interface between the concrete substrate and the FRP. Each flaw was approximately 25 mm x 25 mm in plan. The materials used to simulate flaws included air, a low-conductivity fabric, a ceramic insulating sheet, and several types of plastic (STARNES et al., 2002).

The components of the test system are shown in Fig. 7. The infrared camera was connected to a computer with software for data capture and analysis.

Two 250 W infrared heating lamps mounted at 200 mm on center were used for the thermal input. An aluminum frame was made to hold the heating lamps and an aluminum shutter. The shutter was necessary to block radiation from the lamps after they were turned off. At the end of the heating pulse, an electrical trigger turned off the lamps and the electromagnet, and the shutter fell in front of the lamps. The shutter system was needed to create a sharp pulse as used in the numerical modeling.

An infrared camera in combination with data acquisition and real-time software was used to record the surface temperature. The infrared camera operated in the long wavelength infrared spectral band, thus minimizing the atmospheric attenuation of the received radiation. Data acquisition was triggered at the time the heating lamps were turned on.

4.2 Determination of Material Emissivity

The infrared detector measures the radiation emitted by the test object. This radiation is a function of the surface temperature and the emissivity of the specimen, \( f(T, \varepsilon) \). The value of the emissivity is needed if knowledge of the surface temperature of the test object is of interest. In this investigation, the emissivity of pultruded CFRP was determined for two reasons: determination of actual surface temperatures and comparison with FEM simulations. Estimation of the width of the flaw, however, does not require knowledge of the actual surface temperatures since the locations of the roots of the second derivative of the surface temperature profile are invariant of the absolute value of the surface temperature.

The emissivity measures the capability of a material to emit radiation. In particular, emissivity is the ratio of the radiance of a body at a given temperature to the radiance of a black body at the same temperature (ASTM E 1316, 2001). Accurate determination of surface emissivity is key for the correct measurement of surface temperatures by using an infrared camera. Standard methodology for determining emissivity is described in ASTM E 1933 (2000). The contact thermometer method described in the standard was used in this experimental study.

First, surface temperatures of the FRP laminate were measured using a copper/constantan thermocouple (ANSI type T, special limits, 0.010 mm in diameter). The thermocouple was embedded in the FRP so that half of the perimeter of the wire was in contact with the composite and the other half was in contact with air. A small notch was cut into the laminate and epoxy adhesive was used to hold the thermocouple in place.

The test specimen was located at a distance of 0.55 m from the infrared camera. Since emissivity varies with the angle of view, the specimen was placed perpendicular to the line of view of the IR camera. Surface temperatures were measured with the infrared camera at 3 locations next to the thermocouple using the real-time analysis software. The emissivity value was varied until there was agreement between the temperature recorded with the thermocouple and the temperature recorded with the camera. One hundred and sixty-five measurements were obtained, and the average was 0.80, with a standard deviation of 0.016.
Thus the expanded uncertainty interval for the emissivity of the pultruded laminate is $0.80 \pm 0.03$.

### 4.3 Infrared Thermography Test Procedure

The first series of measurements were qualitative in nature, and were intended to evaluate the potential detection of each simulated flaw embedded in the test object. The entire surface of the specimen was heated by sweeping an infrared heat lamp along the length of the FRP at a distance of 50 mm from the surface and at a speed of approximately 0.15 m/s. This technique is similar to the method used in practice (HAWKINS et al., 1999). A visual image and a thermogram (infrared image) of the test object are presented in Fig. 8. Observation of the thermogram revealed that all eight flaws were detectable. The most visible flaws were numbers 5, 6 and 8, which corresponded to low-conductivity fabric, air, and ceramic sheet, respectively.

During the qualitative test, it was observed that the air-filled flaw #6 was not square as intended. The bonding epoxy apparently flooded over the “wire dam” that was used to exclude epoxy and create the intended flaw. Thus flaw #6 was chosen for verification of the procedure for width determination.

The specimen was tested using the experimental configuration described in Fig. 7. The specimen was placed at 0.33 m from the camera lens. Moreover, the test object was placed so that the air-filled flaw was positioned at the centerline between the two heating lamps. The duration of the thermal pulse was set to 10 s, and the thermogram data were recorded at 15 Hz for a period of 60 s.

The surface temperatures above the flaw ($T_{\text{defect}}$) and above the bonded laminate near the flaw ($T_{\text{background}}$) were obtained as a function of time. The maximum thermal signal ($T_{\text{defect}} - T_{\text{background}}$) was 2.7 °C, which occurred at 12 s after the beginning of the test. The maximum surface temperature registered was 28.4 °C.

### 4.4 Estimation of Flaw Width

To estimate the width of the air-filled flaw, the thermogram corresponding to the time of maximum signal was analyzed. The surface temperatures of the region surrounding the flaw were retrieved using an area-measuring tool. The retrieved area had dimensions of 35 pixels x 28 pixels. Since the analysis software provides surface temperatures at each pixel, a conversion between pixel size and actual physical size was required. The conversion was done using the known dimension of a heat flux sensor and a piece of tape located on the surface of the specimen as references. The heat flux sensor and the tape had actual widths of 25.4 mm and 18.7 mm, respectively, and in thermogram image the corresponding dimensions were 23 pixels and 17 pixels. Thus each pixel corresponded to a 1.1 mm square, and the analyzed region surrounding the flaw was 38.5 mm x 30.8 mm. This area box is shown in Fig. 9.

The plan dimensions of the flaw were estimated by analyzing the surface temperatures along three lines, as shown in Fig. 9. Unlike the FEM output, the surface temperature data along each line did not vary smoothly, and a 5-point moving average was computed to smooth the data. This smoothing was also applied to the second derivative of the temperature profile.

The smoothed surface temperature and the smoothed second derivative along the horizontal line (LI01) are presented in Fig. 10. The roots of the second derivative ($\frac{d^2T}{dx^2} = 0$) were located at 8.8 mm and 25.6 mm from the origin. Thus, the estimated width of the flaw along the horizontal line is 16.8 mm.
A similar procedure was used for the vertical line (LI02). In this case, the surface
temperature profile and the second derivative curve were smoothed using the moving
average of 5 points and 3 points, respectively. The resulting smoothed plots are shown in
Fig. 11. The roots of the second derivative were located at 4.7 mm and 21.0 mm from the
origin of the line. Thus the estimated width of the flaw along the vertical line is 16.3 mm.

Finally, the diagonal dimension was estimated. For this case, temperatures along the
diagonal of the surface temperature matrix were used. The surface temperature were
extracted every 3.97 mm along the diagonal. No smoothing of the temperature profiles and
second derivative was required in this case. The temperature profile and its second
derivative are presented in Fig. 12. The second derivative provided four roots. Based on
observation of the surface temperature profile, the outer roots were used for estimation of
the width. The outer roots of the second derivative were 1.4 mm and 29 mm, and the
estimated diagonal width of the air void is 27.6 mm.

To verify the estimated dimensions, the portion of FRP laminate above the air flaw was
removed carefully by using a miniature high-speed cut-off wheel. This procedure revealed
the shape of the air void. A visual image of the exposed air void is presented in Fig. 13 and
compared with its image during thermographic testing.

The measured horizontal, vertical, and diagonal dimensions of the actual air void were a
horizontal width of 17 mm, a vertical width of 17 mm, and a diagonal width of 31 mm.
Table 2 summarizes the estimated and the actual widths of the air void.

The maximum estimation error was in the diagonal dimension, where the width was
underestimated by 3 mm. Observation of the flawed region revealed that in the lower left
corner of the flaw there was an unbonded area with a thin layer of epoxy on the concrete
(see Fig. 13). Thus the thickness of the air void was reduced in this region. The estimated
diagonal width matched the distance between the upper right corner of the flaw and the
edge of the thin layer of epoxy. The thinner air gap at the lower-left corner produced a
lower signal than the rest of the flaw where there was no epoxy between the FRP and the
concrete. It is possible that the error in width estimation could have been reduced by
analyzing surface temperature measurements over a larger area.

These results show that curve smoothing using a moving average algorithm is an effective
means for dealing with noisy signals. The number of points used in the smoothing may
depend on the surface temperature profile. The goal is to easily identify the roots of the
second derivative curve while minimizing the distortion of the original data. Thus, the
number of points used to smooth the curves should be kept as small as possible.
Additional studies on estimating flaw size should lead to guidelines for proper smoothing
of temperature profile data.

5. CONCLUSIONS

The finite element method was used to gain quantitative understanding of the effect of flaw
width on the surface temperature response due to pulsed heating. The objective was to
determine whether characteristics of the temperature distribution could be used to measure
flaw widths and to establish the key factors affecting the smallest detectable flaw width.
The results indicated that the smallest detectable flaw width increases nonlinearly with
increasing depth. In addition, the smallest detectable flaw width is a function of the
required thermal signal for detection by the test system.

The experimental portion of the study involved thermographic testing of a controlled-flaw
specimen. The experiments included measurement of the emissivity of the FRP surface,
evaluation of different materials for simulating flaws, and estimation of the width of an irregular shaped air void. The estimation of the width was done by determining the location of the roots of the second derivative of the surface temperature profile above the flaw. Smoothing of the temperature profiles and second derivatives using a moving average filter was effective in reducing “noise” in the data. With this procedure, the size of the flaw could be estimated within a few millimeters of the actual size. Additional studies are underway to verify the accuracy of this procedure in multi-layer FRP systems bonded to concrete.

6. REFERENCES


Table 1: Estimated flaw width based on point of inflection in temperature profiles from numerical simulations

<table>
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<tr>
<th>Flaw depth (mm)</th>
<th>Actual width (mm)</th>
<th>Estimated width (mm)</th>
<th>Estimation error (mm)</th>
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Table 2: Estimated and actual widths of air void

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Fig. 1: Summary of geometry of models used in simulations to investigate the effects of flaw width
Fig. 2 Schematic of the infrared thermography method to detect presence of flaw based on surface temperature differences.

Fig. 3 Estimation of width of flaw from temperature profile.
Fig. 4 Estimation error as a function of flaw width and flaw depth

Fig. 5 Minimum width of detectable flaw as a function of flaw depth and instrument sensitivity

Fig. 6 Controlled-flaw test specimen
Fig. 8 Visual image and thermogram of test object during qualitative detection of internal flaws created artificially with different materials

Fig. 9 Thermogram of air flaw at time of maximum signal
Fig. 10 Smoothed surface temperature profile and second derivative with respect to distance along horizontal line (LI01)

Fig. 11 Smoothed surface temperature profile and second derivative with respect to distance along vertical line (LI02)

Fig. 12 Surface temperature profile and second derivative with respect to distance along diagonal line (LI03)
IR thermogram at time of maximum signal

Visual image of air void after removing FRP

Close-up

Fig. 13 Thermogram and visual images of air flaw