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MODELING OF ENVIRONMENTAL EFFECTS ON THERMAL DETECTION OF SUBSURFACE DAMAGE IN CONCRETE Rilya Rumbayan and Glenn Alden Washer Civil and

Environmental Engineering, University of Missouri-Columbia, Columbia, Missouri, USA A significant form of deterioration in concrete is corrosion of embedded reinforcing steel that can cause subsurface delaminations and spalling. Infrared thermography can be used to detect delaminations based on variations in surface temperature that are caused by the disruption of the heat flow through the delaminated area.

The surrounding environmental conditions such as sunlight, ambient temperature variation, and wind speed are critical for heat transfer, and as such the technology depends on these environmental conditions. This paper describes a numerical model developed to predict thermal contrasts for subsurface delaminations based on a given set of environmental conditions surrounding the concrete. The finite element method (FEM) was used to perform 3-D nonlinear transient heat-transfer analysis of a large concrete block with embedded Styrofoam targets intended to provide an idealized model of subsurface delaminations.

The effectiveness of the modeling was evaluated by comparing the thermal contrasts predicted by the model and those obtained from experimental testing of an actual concrete block of the same dimensions. The correlation and error between the experimental testing and the model results indicated that the model could be an effective tool for the prediction of anticipated thermal contrasts based on given weather conditions. Keywords: delaminations/subsurface voids, environmental effects, numerical model, thermal contrasts, the shaded side, the sunny side 1. INTRODUCTION Reinforced concrete is commonly used as a construction material for highway bridge structures.

One of the most significant deterioration mechanisms in reinforced concrete is corrosion of the embedded reinforcement steel which results in subsurface damage to the concrete. As the steel corrodes, it expands, causing tension stresses in the surrounding concrete [1]. These tensile stresses result in cracks or subsurface fracture planes in the concrete at, or near, the level of the reinforcement. These subsurface fracture planes are commonly referred to as delaminations. As the deterioration process continues, a rupture between the delaminated region and the main structural component can occur, which results in spalling of the concrete [2].

Address correspondence to Glenn Alden Washer, Civil and Environmental Engineering, E209 Lafferre Hall, University of Missouri-Columbia, Columbia, MO 65211, USA. E-mail: wa <mailto:washer@missouri.edu> sherg@missouri.edu <mailto:sherg@missouri.edu>
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/urnd.235 This damage typically occurs at the level of the reinforcing steel mat in the concrete, normally at a depth of 25 to 75 mm in the concrete. This kind of damage affects concrete bridge safety and serviceability.

Spalling of the concrete deck surfaces can affect the ability of the deck to carry traffic at normal speeds, may accelerate the overall deterioration of the deck, and can require maintenance or renovation activities that disrupt traffic [3,4]. Concrete spalling on the underside of an overpass bridges can be a safety hazard to traffic passing below, if concrete falls from the bridge into moving traffic [5]. For these and other bridge components, delaminations and spalling are indicative of deterioration and active corrosion, such that locating and defining the extent of this damage provides important information regarding the current condition and future repair needs. The goal of this research is to improve the reliability of bridge condition assessments. The objective of this study is to develop a numerical model that could predict thermal contrast for subsurface voids (i.e.,

delaminations) in concrete under a given set of environmental conditions, for the purpose of providing a numerical tool to support the thermographic inspection of bridge components. The model developed in the research was analyzed using the finite element method (FEM) and verified using actual experimental test data from a concrete block containing simulated voids. Actual weather patterns, i.e., the actual weather conditions (solar loading, ambient temperature variations, and wind speeds) recorded during experimental testing were used as model inputs such that the resulting thermal contrasts from the model and actual experimental data could be compared. Analysis of the correlation and error was used to determine if the model was likely to be an effective tool for predicting thermal contrasts based on a given set of weather conditions.

Such a model could be an important tool for practical bridge inspections, allowing inspectors to determine the thermal contrasts expected for defects in bridge components based on the environmental conditions surrounding the inspection. 2. BACKGROUND Conventional methods of identifying subsurface delaminations include chain dragging and sounding with hammers or rods. These methods require hands-on access to the surfaces being inspected, are subjective, and can be inaccurate [6,7]. For highway bridges, achieving the access necessary to reach key bridge components for sounding can require special access equipment such as man lifts, and often requires lane closures that disrupt traffic.

In the case of chain dragging, only bridge decks and other horizontal surface can be inspected. Due to the access requirements of these methods and their inherent subjectivity, nondestructive evaluation (NDE) techniques such as thermography, sonic testing, impact echo (IE), and ground penetrating radar (GPR) technology have been explored as a means of reducing the access requirements and improving the quality of inspections [2,4,8-11]. Sonic testing, usually implemented using an IE approach, requires impact at the surface of the material under test.

Consequently, hands-on access to the surface to be assessed is always required. In the case of GPR, air-coupled antennae can be used to reduce or even eliminate required traffic control for some bridge decks, but generally requires close access of about 1 m to the surface to be implemented. Of these technologies, infrared thermography is the only method that does not require direct access to the surface under inspection, because images can be captured from large distance using appropriate lenses.

Thermography employs infrared sensors to detect thermal radiation emitted from objects, and creates an image of surface temperatures based on the emitted radiation. The energy of emitted radiation is expressed by using the Stefan Boltzmann Law as $q_{rad} = \epsilon T^4$, (1) in which ϵ is infrared emissivity of the object, σ is the Stefan Boltzmann constant ($5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$), and T is the surface temperature. In concrete, subsurface anomalies such as delaminations interrupt heat flow producing localized differences in the surface temperature.

These localized variations in surface temperature effect the amount infrared radiation emitted from the surface, as shown schematically in Fig 1. As concrete warms (Fig. 1A), the surface temperature above a delamination is higher than the surface temperature of the sound concrete. Conversely, as concrete cools (Fig. 1B), the surface temperature of the concrete above a delamination may be lower than the temperature of the surrounding concrete [12]. The location of subsurface anomalies can be identified by

analyzing the surface temperature variations.

These surface temperature variations were examined in terms of thermal contrast to perform quantitative analysis of data in the study. Thermal contrast, ΔT , was defined as $\Delta T = T_{\text{void}} - T_{\text{sound concrete}}$, (2) where T_{void} is the surface temperature above a void area (i.e., embedded Styrofoam target) and $T_{\text{sound concrete}}$, the surface temperature in the intact area of the concrete. The effectiveness of thermographic imaging is highly dependent on environmental conditions at the time, and prior to, when a thermal image is captured.

The thermal gradient in the concrete that results from certain environmental conditions such as solar loading drives conductive heat transfer in the concrete. Disruptions in heat flow are caused by subsurface delamination, resulting in variations in surface temperature which can be used to identify the location of the subsurface damage in a thermal image. Suitable environmental conditions affecting the concrete at the time (and prior to) of imaging FIGURE 1. Thermal response of delaminations in concrete: (A) day time condition, and (B) night time condition.

is needed to make subsurface damage detection effective. Significant environmental parameters that affect the thermal gradient in the concrete are solar radiation, cloud cover, ambient temperature, wind speed, and surface moisture [13]. Previous research on the use of infrared thermography for bridge inspection has described the environmental conditions affecting thermographic detection of subsurface damage. Early studies by Manning found that delaminations in concrete decks could be detected using thermography in field tests [14].

His studies found that the delamination could be detected over a wide range of ambient temperatures, since the delaminated areas heat up faster due to solar loading, and could develop surface temperature from 1°C to 3°C higher than the surrounding areas. Manning found that in ideal summer conditions with no clouds or wind, surface temperature differences (i.e., thermal contrasts) as large as 4.5°C could be found between delaminated and solid sections of a concrete bridge deck. The temperature differential was reduced by wind, cloud cover, and high humidity [15]. Maser investigated the potential of NDE technologies to assess the level of deterioration of concrete bridge decks using radar and infrared thermography [2].

The study used theoretical models to evaluate the effects of variable depth of concrete cover, thickness, and materials for a subsurface void under a certain set of environmental variables. The response of IR cameras using a one-dimensional transient heat transfer model was developed. Analytic studies revealed that the ability of

infrared thermography to detect delaminations depended on the thickness of the void/delamination, the concrete cover above the void, and if there was an asphalt overlay applied.

The temperature difference produced by a delamination for bare concrete ranged from 3°C to 8°C, according to the model. The model was not compared to actual weather conditions or experimental results. The ASTM Standard Test Method for Detecting Delaminations in Bridge Decks Using Infrared Thermography describes environmental conditions for detecting delamination in bridge decks [16]. This standard indicates that thermographic imaging is dependent on the amount of direct sunlight, the ambient temperature change, and wind speed.

The Standard provides generalized guidance on appropriate conditions for detecting delaminations in bridge decks. Recent studies by Washer have investigated the application of thermography for subsurface defect detection in concrete. This research studied the effect of environmental conditions such as direct solar loading, ambient temperature variation, wind speed, and humidity on the surface temperature of a concrete block containing subsurface voids at different depths. The concrete block was constructed in a large field and aligned such that the South face of the block was exposed to direct solar loading, while the North side of the block was not exposed to direct solar loading.

Subsurface delaminations were simulated using Styrofoam targets at various depths. A FLIR S65 camera was used to capture thermal images of the surface of the block at 10 minute time intervals, 24 hours a day for three months on each side of the block. The thermal sensitivity of the camera is 0.08°C, coupled with a 320 x 240 pixel focal plane array to provide real-time imaging display and storage. It was found that direct, uninterrupted solar loading and low wind speeds provided optimum conditions for detection of targets for the South side of the block, while high rates of change in ambient temperatures were needed to create thermal contrast for the North side of the block, where no solar loading was present.

Quantitative values for the amount of solar loading, average wind speeds, and ambient temperature variations were determined statistically from the experimental results and used to develop guidelines for the use of thermography in the field [17]. The experimental results of this study provided the input and verification data for the present work described herein. These investigations indicate the importance of environmental conditions on the effectiveness of thermography for detecting delaminations in concrete bridge components.

For practical inspection scenarios, the environmental conditions obviously cannot be controlled and vary on a day to day basis. An accurate numerical model that could estimate the anticipated level of thermal contrast based on the anticipated depth of a delamination and for a given set of actual environmental conditions would provide an important tool for the inspection of concrete bridge components.

Such a model could be used to assess the combination of solar loading, ambient temperature change, and wind speed during, or leading up to, a field inspection, to predict the anticipated thermal contrast for a delamination at a given depth. These data could then be used to evaluate if sufficient conditions exist to make it likely that a delamination would be detected, to estimate the depth of a detected delamination based on the thermal contrast, and to determine if detected thermal differences correspond with actual subsurface defects. This article focuses on the environmental effects on thermal contrasts for a subsurface damage in concrete idealized using Styrofoam targets with a thickness of 13 mm.

Because the thickness of these targets is much larger than the anticipated thickness of delamination in the field, the magnitude of the thermal contrasts either modeled or measured in experiments are not representative of what would be detected under actual field conditions. The objective of the study is to develop a numerical model that could be used to support practical inspections, focusing on the effects of the environmental conditions surrounding the inspection. Once developed and verified, such a model could be utilized to assess subsurface damage with different thermal characteristics, such as different thickness of voids or different materials within the void.

The model could also be used to assess the result so thermal testing to determine, for example, the depth or thickness of subsurface delamination in concrete. For example, the model could be used to predict the thermal contrast if the void were filled with water or epoxy, such as is sometimes done as a repair strategy. This article reports on development of the model using actual, measured weather conditions surrounding an actual concrete block, and measured over long time period (six months total). 3.

HEAT TRANSFER MECHANISMS The numerical model developed using the FEM in COMSOL was based on a transient thermal energy balance between the concrete block and the surrounding environment. The heat transfer mechanisms occur at the concrete surface-atmospheric boundary including radiant heating from the sun, forced and natural convection, and emitted infrared radiation from the concrete surface. The heat transfer mechanism (i.e., conduction) occurs in the concrete itself [18].

The thermal energy due to the sun's rays received by the concrete surface can be

generalized as $q_s = \alpha_s I$, (3) in which α_s is the absorptivity of concrete, depending on the color and the texture of surface, and I is the total solar radiation on concrete surface in $W m^{-2}$. The solar radiation depends on geographical location and the position of the sun relative to the surface of the concrete, which varies over the course of a day and throughout the year. The thermal energy transfer by convection as a result of temperature differences between the concrete surface and the surrounding air is given generally by Newton's law of cooling as $q_{conv} = h$.

$(T - T_a)$, (4) in which h is a convection coefficient, T is the surface temperature, and T_a is the ambient temperature. The convection coefficient is a function of several parameters such as wind velocity, surface roughness, thermal properties of the air, and surface area. The convective heat transfer is positive when the ambient temperature is less than the temperature of the concrete, such as may occur when radiant heating from the sun warms the concrete above the ambient temperature.

In this case, increased wind speed will result in increased energy transfer from the concrete to the surrounding environment, reducing the surface temperature of the concrete and thereby diminishing the thermal gradients in the concrete. If the ambient temperature is warmer than the concrete, such as would be typical when ambient temperatures are increasing, but there is no heating from the sun, i.e., shady conditions, then the convective heating transfer is negative. Under this scenario, increased wind speed will accelerate the heat transfer to the concrete and increase the thermal gradients in the concrete.

Within the concrete solid, heat transfer via conduction occurs and is affected by the thermal properties of material, including conductivity (k), specific heat (C_p), and thermal diffusivity (α). From a theoretical perspective, the transient 3D heat transfer for the concrete governed by the Fourier equation $\nabla^2 T = \frac{1}{\alpha} \frac{\partial T}{\partial t}$, (5) in which $\alpha = k/\rho C_p$, is the thermal diffusivity; ρ is the density; T is the temperature; t is time; and ∇^2 is the Laplacian operator. 4.

MODEL DEVELOPMENT The transient thermal behavior of the concrete block can be analyzed using numerical tools such as the FEM, the finite volume method (FVM), and the finite difference method (FDM). In this study, FEM was used for analyzing the effect of subsurface voids on heat transfer through a large concrete block under the actual weather conditions of solar radiation, ambient temperature variation, and wind speed. All the simulations were performed using COMSOL Multiphysics.

The mesh density for the COMSOL model was determined through a convergence study intended to provide a balance between mesh size and processing time, while still

achieving a sufficiently accurate model. Different types of standard element density options in COMSOL (course, normal, finer, extra fine, and extremely fine) were evaluated in the convergence study. The "finer" element size was selected as a balance between computational economy and accuracy in solution.

It was found that the average difference in maximum thermal contrast determined for 4 different days (different weather conditions) for the "extra fine" and "extremely fine" was only 3%, relative to the "finer" element size. The computational time increase was 2-fold for "extra fine" and 5-fold for "extremely fine," relative to the "finer" element size. Such a small difference in temperature contrast would generally not be observable under field conditions on a concrete structure, and as such the "finer" element size was used. This resulted in 62,734 total elements in the model of the 2.4 x 2.4 x 0.9

m block. Element types were primarily tetrahedral, with triangular, edge, and vertex elements also included. Second order Lagrange elements with full integration were used for the model. 4.1. Geometry and Material Properties Figure 2A shows the three dimensional geometry of the concrete block that was simulated using the FEM. The concrete block modeled had the same geometry as the block constructed for the experimental study, which is shown in Fig. 2B. The constructed block is a 2.4 m x 2.4 m by 0.9

m in thickness, and included Styrofoam targets (305 x 305 x 13 mm in dimension) at depths of 25, 51, 76, and 127 mm on each side. These Styrofoam targets have thermal conductivity close to that of air, such as would be present at a subsurface delamination in concrete. The thermal conductivity, the specific heat, the emissivity, and the density for the materials used in this model which were obtained from available published data and are summarized in Table 1.

In the model simulation, the material in the void was represented by the properties of air because preliminary simulation results showed that the thermal contrasts differences produced between air and Styrofoam in the void were not significant. FIGURE 2. Concrete block containing subsurface voids: (A) model, and (B) experimental test. TABLE 1 Material properties of the concrete block model

Material Properties	Concrete	Void (Air)
Thermal conductivity, k	1.8 W/m.K	0.024 W/m.K
Specific heat, Cp	1000 J/kg.K	0.95 700 J/kg.K
Density, ρ	2300 kg/m ³	1.2 kg/m ³

4.2. Boundary Conditions The boundary conditions in the model consisted of the weather parameters recorded in the experimental study [17].

A commercial weather station located adjacent the concrete block monitored the parameters of solar radiation, air temperature, and wind speed over a six-month

period. Details regarding the experimental measurement protocol, results, and analysis were given in previous works by Washer [17,19,20]. Figure 3 shows a single day of data as an example of the input data used to model the boundary conditions of the block. The data shown in the figure shows the solar radiation (Fig. 3A), variation of ambient temperature (Fig. 3B) and wind speed (Fig. 3C). The time period shown in the figures is midnight to midnight (0:00 hrs).

In the experimental study, data on weather conditions and thermal images of the block were recorded at 10 minute time intervals, and this interval was used at the time-step in the FEM. Consequently, data from the FEM and the experimental data could be compared directly for each 10 minute time interval. The inclination of the concrete surface with respect to the direction of the sun's rays was considered in the model, to adjust field-measured isotropic solar radiation measurements.

The intensity and incident angle of solar radiation were applied as an inward heat flux onto the vertical plane boundary of the concrete block, adjusted appropriately to represent the actual field conditions. The ambient temperature variation and wind speed were simulated as convective heat transfer on the surface boundaries of the concrete block model. A three-month period (89 days) on the South side and a three-month period (92 days) on the North side of the concrete block were modeled. The model was simulated separately for each month, and for both the South face and the North face of the block.

As such, solar radiation incident on the south side of the block was not utilized as a boundary condition when simulating the north side of the block. Based on thermocouple observations during the experimental research, it was assumed that the thickness of the block was sufficient that these surfaces acted independently. The initial temperature for each monthly simulation was the surface temperature of concrete block at 12:00 a.m. (midnight) in the first day of each month, which was obtained from thermocouple measurement in the experimental test. 5.

SIMULATION RESULTS Simulation results of the numerical modeling, including thermal image, surface temperature, and thermal contrast, are presented below. 5.1. Thermal Images Figure 4 displays an example of typical thermal images obtained from the model for the South face of the block and the actual image data collected FIGURE 3. Environmental parameters as boundary condition in simulation on November 5, 2007: (A) solar radiation, (B) ambient temperature, and (C) wind speed. FIGURE 4.

Typical thermal images of the thermal behavior for the South side of the concrete block: (A) the model result at noon, (B) the experimental test result at noon, (C) the model

result at 8:00 PM, and (D) the experimental test result at 8:00 PM. in the experimental test. The data inputs for solar radiation, ambient temperature change, and wind speed are shown in Fig. 3 for this particular day. Figure 4A shows the surface temperature distribution obtained from the model at 12:00 p.m., and Fig. 4B shows the actual thermal image collected at that time during experimental testing. In Figure 4, variations in surface temperature are represented on a color scale applied over a temperature span of 7°C.

Figure 4C shows the surface temperature distribution obtained from the model at 8:00 p.m. (20:00 hours) of the same day, and Fig. 4D shows the actual thermal image at that time from the experimental test. As shown in the figures, the surface temperature distributions obtained from the model closely represent the data collected in the thermal image obtained in the experimental test. The variation of temperature contrast with the depth of the target can also be observed in Fig 4, as well as the transient changes in the thermal contrast at each target location.

A positive thermal contrast is obtained when solar loading from the sun is present (12:00 p.m.), and the negative thermal contrast is observed when solar loading is removed and ambient temperature is cooling (8:00 p.m., see Fig. 3). This figure illustrates the utility of the model for analytically predicting the thermal images that would be obtained in the field using an IR camera, using actual weather conditions (solar loading, ambient temperature variations, and wind speed) as inputs for the model. It should be noted that the images shown here are a subset of the data resulting from the simulation; in the modeling, the entire month was modeled for producing such images for each 10 minute time interval throughout the month.

5.2. Surface Temperatures and Thermal Contrasts In this section, an example of the modeled surface temperatures (Fig. 5) and resulting thermal contrasts (Fig. 6) are shown for the South and the North face of the block. For the South side, the data shown is for the same day as that shown in Fig. 3 and Fig. 4. It can be observed from Fig. 5A that between FIGURE 5. Surface temperatures: (A) the South face of the block, and (B) the North face of the block. FIGURE 6. The time varying thermal contrast: (A) the South face of the block, and (B) the North face of the block. Solid line is for the moving average an hour. Dashed line is for the raw data.

the hours of 0:00 and 8:00, the surface temperature of the deepest target (127 mm) is greatest and the most shallow target (25 mm) is lowest temperature. In the following time period, 8:00 to 16:00, the situation is reversed, with the 25 mm deep target having a greater surface temperature. Similar behavior is observed from the North side modeling results, shown in Fig. 5B. The significant difference between the observed

behaviors is the increased change in magnitude observed for the South side that results from the radiant heating of the sun; for the North side, only convective heat transfer from the environment is occurring, and as a result, the change in surface temperature over the course of the day is less pronounced. The surface temperatures shown in Fig.

5 were used to calculate the time-varying thermal contrast for each of the subsurface voids, and these data are shown in Fig. 6. The thermal contrast data were processed using a 1-hour moving average to filter short-term transient spikes in the thermal contrast data. The moving average of thermal contrast data (solid lines) and the raw data (dash lines) are shown in the figure. As can be seen in the figure, these transient spikes are primarily in the South side data, and result from short-term effects such as a cloud moving in front of the sun, or a short period of sunshine on an otherwise cloudy day. For the South face (Fig.

6A), the thermal contrast for each of the targets starts increasing at different times of the day, with deeper targets developing thermal contrast later in the day. Also, the maximum thermal contrast is decreased as the target depth increases, as would be expected. The maximum thermal contrast for 25, 51, 76, and 127 mm deep targets at the day was approximately 7°C, 4°C, 2°C, and 1°C, respectively. The North face (Fig. 6B) has a lower thermal contrast value for each target, and these contrasts are more consistent over the course of the day, as shown in the figure.

The maximum thermal contrast for target depth of 25, 51, and 76 mm was approximately 3°C, 2°C, and 1°C, respectively. For the 127 mm deep target, the maximum thermal contrast was minimal due to the depth of the target. 6. EVALUATION OF MODEL PERFORMANCE The objective of the model evaluation in this section is to quantify level of agreement between thermal contrast results from the model and actual field test. Analysis was performed by comparing trend characteristics and correlations of thermal contrast data between the model and the experimental test results over the entire month.

Analysis of the error and bias was also conducted to assess the agreement of the model with the actual field test results. The evaluation reported herein is focused on 51 mm and 76 mm deep target, which most closely represent typical depths where delaminations may take place in a concrete structure. Figure 7 shows two weeks of the thermal contrast data for 51 mm deep target as an example of the comparison between model-predicted and FIGURE 7.

Comparison of model predicted and field-measured of thermal contrast for 51 mm deep target of the South (sunny) side. field-measured results for the South side of the block. It

can be observed that the curve patterns of the thermal contrast results from the model are in reasonably good agreement with field experiment, that is, the overall trend of the model-predicted data is consistent with the field-measured data, generally, over the course of 14 days. Figure 8 shows an example of the comparison between model-predicted and field-measured thermal contrast for 51 mm deep target for the North side of the block.

In this case, there appears to be less agreement between the model and experimental test results. The Pearson correlations (r), which is a measurement of covariability between estimated values and observed values of thermal contrast, were assessed for the 6 month time interval modeled. In these analyses, days in which rain occurred were excluded because water on the surface of the concrete would affect the emissivity of the concrete and evaporation could affect the thermal behavior of the block.

Consequently, practical thermal inspections of bridges are not conducted on rainy days. Examining all the datasets of the South (sunny) side together, the thermal contrast correlations between model results and field observed for 51 mm and 76 mm targets are 0.92 and 0.89, respectively, as shown in Table 2. Those values indicate high correlations between model and experimental results. When the North (shaded) side is examined, the correlation coefficients are 0.70 for both 51 mm and 76 mm targets. It can be noted that the model

FIGURE 8. Comparison of model predicted and field-measured of thermal contrast for 51 mm deep target of the North (shaded) side. TABLE 2 Thermal contrast correlation (r) between the model and the experimental results; and errors time series analysis of thermal contrast differences between the model and the experimental results. MBE is mean bias error in $^{\circ}\text{C}$, and MAE is mean absolute error in $^{\circ}\text{C}$

Side	Depth (mm)	r	MBE ($^{\circ}\text{C}$)	MAE ($^{\circ}\text{C}$)
The South (Sunny)	51 mm	0.92	0.70	0.78
	76 mm	0.89	0.67	0.70
The North (Shaded)	51 mm	0.70	0.22	0.70
	76 mm	0.70	0.22	0.56

correlates better in the sunny side compared in the shaded side.

The absence of solar radiation in the shaded side is likely responsible for the lower correlation, since this provides a strong driving force for thermal contrast on the South side of the block. On the North (shaded) side, convective heat transfer results in much lower magnitude contrasts, and the correlation between the model and the experimental results is decreased. However, the model results give a good correlation with the field-observed behavior.

The residual (or error) analysis was also completed to evaluate the magnitude of variations between the model and experimental test results and evaluate the accuracy of the model predictions. The results of mean bias error (MBE) and mean absolute error

(MAE) are given in Table 2. On average, the mean bias of the sunny side dataset is 0.7 °C for both 51 mm and 76 mm deep target, and the mean bias of the shaded side dataset is 0.2 °C for both 51mm and 76 mm deep target. It can be seen that all of the MBE results produce positive values, indicating that the model tends to overestimate the thermal contrast.

The unaltered magnitudes (absolute values) of each thermal contrast difference between the model and the test results of the sunny side dataset was about 0.9°C for both 51 mm and 76 mm deep target and the absolute values of thermal contrast difference of the shaded side dataset were 0.7°C and 0.6°C for 51 mm and 76 mm deep target, respectively. Figure 9 and 10 show the results of percentage distribution for the bias of thermal contrast between model and experimental for all datasets of the sunny side and the shaded side, respectively. They are grouped into ranges from lower than -1.5°C to higher than 1.5°C with increment 0.5°C. For all FIGURE 9. Percentage distribution for thermal contrast differences between modelpredicted and field- observed of the South (sunny) side: (A) 51 mm deep target, and (B) 76 mm deep target. FIGURE 10.

Percentage distribution for thermal contrast differences between modelpredicted and field- observed of the North (shaded) side: (A) 51 mm deep target, and (B) 76 mm deep target. datasets of the South (sunny) side with 51 mm deep target (Fig. 10A), 72% are within 1°C difference, and 38% are within 0.5°C difference. For that side with 76 mm deep target (Fig 10B), 77% are within 1°C difference, and 38% are within 0.5°C difference. For all datasets of the North (shaded) side with 51 mm deep target (Fig. 11A), 76% are within 1°C difference, and 42% are within 0.5°C difference. For the side with 76 mm deep target (Fig 11B.), 86% are within 1°C difference, and 50% are within 0.5°C difference. The distribution of thermal contrast differences is more concentrated in the range 0.5°C to 1°C for the sunny side, and in the range 0°C to 0.5°C for the shaded side.

It can be deduced that the model predicts the thermal contrast with reasonable accuracy. CONCLUSION This paper has presented results from modeling of environmental effects on thermal detection of subsurface damage in concrete. A 3D numerical model of transient heat transfer was developed using finite element analysis to study the environmental effects on thermal response of simulated subsurface voids in a large concrete block. The effects of solar radiation, ambient temperature variation, and wind speed on the thermal images that appear on the South and North side of the concrete block model with subsurface voids were presented.

The model performance was evaluated by comparing the thermal contrast of the model results with those reported from a previous experiment. It was found that the model provided an overall pattern of temperature contrasts that were similar to the pattern of

experimental results, showing the model was successful in capturing the basic physical behavior of concrete block. Thermal contrast correlations between model and experimental results in the South (sunny) side were 0.92 and 0.89 for 51 mm and 76 mm deep target, respectively. These results were better than the correlation in the shaded side (0.70).

An evaluation of the model performance was also made from the quantitative difference measured with the experimental results. For the South (sunny) side, the distribution of thermal contrast differences is concentrated in the range 0.5°C to 1°C for both 51 mm and 76 mm deep target. For the North (shaded) side, the distribution of thermal contrast differences is within 0.5°C for both the 51 mm and 76 mm deep targets. With respect to MBE and MAE, overall the model seemed to perform the good results with errors below 1°C. These results indicate that the model predicted the thermal contrasts with reasonable accuracy when compared with experimental data.

Based on these data, it was concluded that the modeled developed was sufficiently accurate to provide a useful tool for estimating the thermal contrasts resulting from subsurface voids in the concrete, and provide a tool to support practical thermal inspections. For example, the model could be used to predict if a particular day's weather would produce the thermal contrasts required to be imaged using a common thermal camera given the anticipated depth of a delamination and predicted weather conditions. Alternatively, such a model could be used in post-test analysis of data to estimate the depth of a delamination, given the known weather patterns surrounding the test and the measured thermal contrast detected during the test. REFERENCES 1. L.

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