LONG-TERM NUMERICAL ANALYSIS OF SUBSURFACE DELAMINATION DETECTION IN CONCRETE SLABS VIA INFRARED THERMOGRAPHY

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ABSTRACT

One of the concerns about the use of passive Infrared Thermography (IRT) for structural health monitoring (SHM) is the determination of the favorable period to conduct the inspections. This paper investigates the use of numerical simulations to find appropriate periods for IRT-based detection of subsurface damages in concrete bridge slabs under passive heating along one year of time-span. A model was built using the Finite Element Method (FEM) and calibrated using the results of a set of thermographic field inspections on a concrete slab sample. The results showed that the numerical simulation properly reproduced the experimental thermographic measurements of the concrete structure under passive heating, allowing the results to be extended for a longer testing period. The long-term FEM results demonstrated that the months of spring and summer are the most suitable for passive IRT inspections in this study, with around 17% more detections compared to the autumn and winter periods in Brazil. The goal of this research was to enhance the possibility of using FEM beyond the design stage because this computation tool can provide support to SHM.

KEYWORDS: Infrared Thermography, Concrete Bridges, Non-Destructive Test, Delamination, Finite Element Method

1. INTRODUCTION

The aging of the transportation infrastructure raises questions about the safety and serviceability of the existing bridges worldwide, which requires pertinent planning for the maintenance of these infrastructure assets[1]–[4]. Inspections have a fundamental role in bridge management, allowing diagnoses and prognoses based on the existing state of the structural elements [5]. As the performance of a structure depends on the integrity of the elements that compose it, the number of interventions in an operating structure must be set to a minimum. Therefore, the use of non-destructive tests (NDT) has become attractive, representing a fast, harmless, and accurate approach to examine the structure without interrupting or impairing its operation [6].

Infrared vision (IR) has gained interest as NDT due to its capability of examination beyond the visible spectrum [7]. The inspection is based on the thermal contrast between different materials, given a heat flux variation [8]. Undamaged elements normally present uniform heat distribution on their surface, while internal or surface defects change the heat dissipation by providing resistance or increasing the heat dissipation through the element. As a result, the inspection reveals defected areas with high or low temperature patterns in the surface thermograms [9]. Moreover, the IRT approach is being constantly improved by the combination with other NDT methods and the use of computational techniques to advance the collection, storage, visualization, and analysis of the thermographic data [10]–[17].

Finite Element Method (FEM) constitutes one method of numerical simulation, where the domain of a complex problem is divided into sub-regions of simple geometry, i.e., finite elements [18]. This method could provide similar outputs to the realistic infrared thermography inspection, including the information about the temperature over time and the thermal map of the inspected surfaces [19]–[22]. Thus, this tool offers the possibility of reducing the time and cost required to make test samples and the need for numerous tests in the target structures.

Numerical analysis and IRT have been integrated to detect or examine damages in concrete structures [23]–[28]. However, only a few researchers have investigated the combination of IRT and FEM for the inspection of concrete bridges [22], [29]–[34]. Therefore, this study proposes the use of FEM to support long-term inspection plans in concrete bridges using the solar loading thermography. A thermal camera was used to inspect a sample of concrete bridge slab with artificial subsurface delamination during different seasons and weather conditions. A numerical model was developed to simulate the experimental concrete specimen, radiation source, and IRT inspection. To validate the model, a comparison between the experimental and numerical surface temperatures and thermal gradients was performed. Then, the calibrated model was used to predict the most favorable periods to detect the subsurface delamination during one year of inspection.
2. EXPERIMENT

2.1 CONCRETE SAMPLE

A set of IRT experiments were previously performed by Pozzer et al. [35] to collect thermographic data, which were used to develop the numerical model in this research. Three samples of bridge slabs were built with subsurface delamination simulated with Styrofoam, which has a thermal conductivity (0.027 W/m°C) close to the air (0.024 W/m°C) and can represent a real subsurface delamination [22]. These thermographic inspections were conducted once a month in November 2018, February, April, June, and July 2019, in an hourly interval from 7:00 am to 9:00 pm. One of these concrete samples was destructed after the end of the IRT experiments to obtain the exact position of the subsurface damages, which allowed to improve the numerical modelling of the present study. Each specimen had nine Styrofoam square defects of different lateral sizes (5.0, 10.0, and 15.0 cm) and located at different depths (2.0 ≤ z ≤ 5.0 cm). Fig. 1 shows the details of the inspected concrete sample with delamination.

![Concrete sample with artificial delamination](image)

**Fig. 1** Concrete sample with artificial delamination (a) 3D view (b) Coordinates of the fabricated damages

2.2 INFRARED THERMOGRAPHY MEASUREMENTS

The experiment was conducted outside of the Infrastructure Laboratory at the University of Passo Fundo, located in Passo Fundo, Rio Grande do Sul, Brazil (Lat. 28°13'36.28"S, Long. 52°23'10.92"W). Fig. 2 shows a concrete sample after construction and the location of inspections.

![Concrete sample after curing](image)

**Fig. 2** (a) A concrete sample after curing; (b) Location of the samples in the university site

Several studies demonstrated that the sensitivity of passive IRT inspections is associated with the variation of the environmental conditions [22], [30], [35]–[38]. This research study carried out the thermographic imagery in different times of the day and months to capture the effects of different seasons on the outcomes of inspections. All the experimental tests were performed under passive heating using a TESTO 881-1 (160x120 FPA, 50 mK, 8-14μm, 33Hz) infrared camera. The inspections were performed in the reflection mode, with the camera positioned in a vertical support at 2.5 meters from the inspected sample, considering a 90° angle from the concrete top surface. The variables of ambient temperature, wind speed, and solar radiation were monitored during the test periods. A digital J Prolab Thermometer was used to register the air temperature and a portable DAVIS Turbo Meter...
Anemometer was used to measure the wind speed. The solar radiation values were obtained from the meteorological station existing near the study site, which is linked with the Brazilian Meteorology Institute [39] database. The detection of the damage was measured by the thermal gradients, which represent the temperature difference between the concrete surface on top of the delaminated area and the concrete surface without delamination.

3. FINITE ELEMENT METHOD (FEM)

Heat transfer problems that include solar radiation are difficult to solve analytically, as they require transient solutions of complex nonlinear partial differential equations [18]. Thereby, FEM has become attractive for these iterative processes. This numerical modelling method includes reproducing the tested geometry, dividing it into finite elements (mesh), and exposing the sample to the heat source and boundary conditions through the time of interest. Then, the governing differential equation of the heat transfer problem is replaced by finite algebraic equations at the finite points created in the element at the given time. The COMSOL Multiphysics software, Version 5.2 from COMSOL Inc., was used for the finite element simulation. The Heat Transfer with the Surface-to-Surface Radiation module was used due to its ability to model solar radiation, which varies with the location and orientation of the samples.

3.1 MODEL GEOMETRY AND MESH

The thermal numerical simulation was modelled as a three-dimensional, non-linear, and transient analysis. The model represented the concrete sample and its damages at the identical position and dimensions as the experimental sample. The solar orientation was configured according to the experimental program as well, where the x-axis represents the North/South direction, and the y-axis represents the East/West direction. The slab sample was divided into a mesh of 22593 tetrahedral elements, in an adaptive refinement, i.e. changing according to the size and position of each solid. It used an element size named “Finer”, the third thinnest level among nine options available in COMSOL software. The dimensions of the mesh elements varied between 4.0 millimeters and 5.5 centimeters, with minimum element quality of 0.137. The quality of the elements can vary between 0 and 1, where 1 represents an optimal element and 0 indicates a degenerated component. There is no predetermined value for what the element’s quality should be since it depends on the analyst judgement and the required precision of the model. For the most applications, however, elements with a quality below 0.1 are considered limited [40]. In this case, the “Finer” option represented a balance between the element’s quality and the computational time. The model geometry and mesh definition are shown in Fig. 3.

3.2 MATERIAL PROPERTIES

The thermal properties of the materials were determined according to the concrete and Styrofoam used in the experimental program, complemented by technical references presented in previous studies [17], [22]. The values are presented in Table 1.

| Material properties | Unit of measure | Concrete | Styrofoam |
|---------------------|----------------|----------|-----------|
| Density             | kg/m³          | 2400     | 25        |
| Specific Heat       | J/(kg. K)      | 1008     | 1130      |
| Thermal conductivity| W (m.K)        | Temperature dependent | 0.027 |
| Emissivity          | -              | 0.9      | -         |

Table 1 Materials properties for the numerical simulation
3.3 BOUNDARY CONDITIONS

Solar radiation, convection, and ambient temperature were set as boundary conditions for the simulated model. The main heat source was the incident solar radiation over time, which varies according to the geographic location of the sample and the Sun orientation (zenith angle and solar elevation). This parameter was included using the External Radiation Source feature in the software, which was configured based on the latitude (28°13'36.28"S), longitude (52°23'10.92"W), and time zone (-3) of the test location.

The second boundary condition was the heat transfer by convection. Since Sharples and Charlesworth [41] established an approximate correlation between the wind speed \( V \) and convective heat transfer coefficient \( h_w \), their study was used to determine a daily wind-induced convective heat transfer in the present study, using the following equation:

\[
h_w = 6.5 + 3.3V \text{ (W/m}^2\text{.K)} \quad V \leq 6 \text{ m/s}
\]  

(1)

Hiasa et al. [22], [32], [33] used a similar approach to calculate the convection coefficient for their numerical thermographic simulation. However, they performed a one-day test and stipulate a constant heat transfer coefficient based on the maximum wind speed data. In this study, the daily average of wind speed was used to find the daily convective heat transfer coefficients.

The third boundary condition was the ambient temperature. The diurnal variation of the ambient temperature \( T_{\text{amb}} \) follows a simple sinusoidal periodic distribution of 24 hours, depending on the average daily temperature \( T_{\text{avg}} \) [42]:

\[
T_{\text{amb}}(t) = T_{\text{avg}} + \Delta T \cos \left( \frac{2\pi (t-1/4)}{24} \right)
\]

(2)

Where \( T_{\text{avg}} \) and \( \Delta T \) are parameters corresponding to the average daily temperature and half of the daytime temperature variation, respectively. The variable \( t \) represents the time and is expressed in hours. Table 2 shows the information about the environmental conditions measured during the field test days. The solar radiation value in each day was set according to the average of the positive irradiation values registered by the database. The FEM analysis was carried out in an hourly basis.

| Month    | Day of inspection | Solar Radiation (W/m². s) | Wind speed (m/s) | Average Temperature (°C) | Half diurnal Temperature Variation(°C) |
|----------|-------------------|---------------------------|-----------------|--------------------------|----------------------------------------|
| November | 22/11/2018        | 574.02                    | 3.21            | 23.95                    | 6.90                                   |
| February | 23/02/2019        | 524.14                    | 1.30            | 27.00                    | 8.85                                   |
| April    | 18/04/2019        | 464.19                    | 1.71            | 17.55                    | 5.80                                   |
| June     | 14/06/2019        | 276.48                    | 2.85            | 20.28                    | 5.60                                   |
| July     | 06/07/2019        | 408.58                    | 1.38            | 3.81                     | 6.35                                   |

Table 2 Meteorological data used in the numerical simulation

4. RESULTS AND DISCUSSION

The results of one of the inserted delamination are presented to perform the comparison between the experimental and numerical surface temperatures and thermal gradients. Other studies showed that different internal defect characteristics (size, thickness, and depth) have distinct thermal responses through the day [32], [33], [35], [38] affecting the favorable period to detect the damages using IRT. In the present study, both experimental and simulated results for the upper-right (2 centimeters deep) delamination will be shown next, followed by the yearly analysis performed using the finite element method.

4.1 COMPARISON OF EXPERIMENTAL AND SIMULATED RESULTS

Fig. 4 shows four pairs of thermograms obtained from the experiment and FEM simulation. The temperature range of the thermograms was unified to facilitate the surface temperature comparison and the color pallet was adjusted to improve the visualization of the damages in each experiment. The chosen palette has one scale where the red color represents the highest surface temperatures, and the blue color is associated with the lowest surface temperatures. The presented thermograms are from 12:00 (noon) and 9:00 pm, representing heating up and cooling down phases registered in the passive IRT inspection, respectively.
In Fig. 4 it is possible to observe a non-uniform heating in the experiment, where the heating and cooling processes follow the solar movement, which varies through the day and the months. Fig. 4(b) confirms the work of Hiasa et al. [22] by showing that the numerical model can reproduce the heating of the sample edge according to the solar orientation. In general, the surface temperatures are convergent. However, the experimental thermograms present a high level of non-uniform heating when compared to the FEM simulations, which were caused by the environmental conditions on the field. Relative humidity, presence of clouds, and surroundings elements were not considered in the numerical simulation which could have led to the inconsistencies observed between the actual temperature measurements and simulation [22]. A higher discrepancy exists between Fig. 4(g) and Fig. 4(h), where the difference in the surface temperature reached 7°C. One possible explanation for this difference could be the presence of humidity and fog in the experiment environment, which is a common situation during the winter mornings and nights, causing a lower temperature in the concrete surface in the experimental sample. A complete quantitative temperature comparison for the delamination is provided in Fig. 5.
The differences between simulated and experimental surface temperatures were observed mainly during the morning and evening. As reported in the thermograms analysis, these differences are probably due to the boundary conditions assumed in the model, which only considered the sample orientation related to the Sun, solar radiation, coefficient of convection based on the wind speed, and ambient temperature at the study site. Also, several susceptible errors in the technique could have contributed to the observed difference, including errors in the accuracy of the thermal camera, in the instrumentation used to measure the environmental conditions or by the local weather station. Also, the modelling errors relating to the temperature differences between the equation used for calculating the ambient temperature in the software, and the estimated material properties. However, the purpose of this study was to verify the competence of the computer-based technique to detect subsurface damages and identify a convergence with the thermal gradients' detections in the IRT practical application, under different boundary conditions. Further works will address the FEM updating to optimize the parameters used in the proposed model.

The thermal gradient between the healthy and damaged surface temperatures is the main parameter for detecting damages in infrared thermographic inspections. In this context, Fig. 6 shows the difference between the measured and simulated contrast values during the days of experimentation.

Fig. 6 shows that the contrast values obtained by the numerical simulation are aligned to those calculated from the measurements performed by the IRT thermal camera, even with the temperature differences reported in the previous figures. The amplitude of the simulated contrast followed the periodic variation of the gradients through the days that the experiments were carried out, where gradients were small for the autumn and winter months (April, June, and July) compared to spring and summer months (November and February). The Pearson Correlation (R), the Mean Bias Error (MBE), and the Mean Absolute Error (MAE) were calculated to assess the covariability and the deviation among the simulated results from the FEM model and the observed results from the IRT experiments (Table 3).

| Experiment   | Healthy Area | Damaged Area | Thermal Gradient |
|--------------|--------------|--------------|------------------|
|              | R       | MBE(°C) | MAE(°C) | R       | MBE(°C) | MAE(°C) | R       | MBE(°C) | MAE(°C) |
| 22 Nov. 2018 | 0.98    | 0.02    | 3.07    | 0.98    | 0.31    | 3.37    | 0.97    | 0.29    | 0.51    |
| 23 Feb. 2019 | 0.97    | 0.20    | 2.17    | 0.97    | 0.63    | 2.46    | 0.97    | 0.48    | 0.51    |
| 18 Apr. 2019 | 0.99    | -0.93   | 4.21    | 0.99    | -0.55   | 4.36    | 0.98    | 0.38    | 0.47    |
| 14 Jun. 2019 | 0.96    | 2.51    | 2.78    | 0.97    | 2.73    | 2.96    | 0.97    | 0.22    | 0.29    |
| 06 Jul. 2019 | 0.98    | 3.24    | 3.95    | 0.98    | 3.82    | 4.38    | 0.97    | 0.58    | 0.58    |

Table 3 R, MBE, and MAE for the surface temperatures and thermal gradients measured and simulated in the daily experiments
The MBE measures the overall bias of the model and MAE measures the absolute extent of the errors without considering their directions [43]. Table 3 shows that in most cases the MBE produced positive values for the surface temperatures and thermal gradient, indicating that the model has a trend to overestimate the experimental results. An exception is seen in April, where MBE showed that the model underestimates the surface temperatures. However, thermal gradients were constantly overestimated. These trends can be confirmed by looking at the curves in Fig. 5 and Fig. 6. The MAE is greater for the surface temperatures simulations, with averages differences ranging from 2.17 °C to 4.38 °C. However, the absolute error is under 0.6°C in all thermal gradient tests, which indicates that the contrast between healthy and damaged area is convergent, despite the surface temperature differences. Therefore, these results are aligned with previous studies findings[22], [29]–[34], where the numerical simulation presented the capability of reproducing the thermal gradients measured in the thermographic inspections using passive heating. Rumbayan and Washer [29] reported the deviation measurements for the thermal contrast between their model and the experimental results. The correlation indices (R) were between 0.70 and 0.92 and the contrast differences (MBE) and absolute error (MAE) were below 1 °C. In this sense, we confirm the authors' conclusion that the FEM can represent a tool to support practical IRT inspections.

The computational modelling showed the possibility of identifying subsurface damage in reinforced concrete bridge slabs at different times of the year, under different environmental conditions of temperature, wind speed and solar radiation. Although the simulated thermal gradient results present an average difference of 0.39°C compared to the experimental inspection, the correlation between the model results and the experimental study was equal or above 0.97 in all the thermographic tests. Consequently, the reasonable accuracy of the simulation supports the extrapolation of the model analyses to a large period.

4.2 DISCUSSION ON APPROPRIATE PERIODS FOR IRT INSPECTION OF CONCRETE BRIDGE SLABS BASED ON LONG-TERM FEM ANALYSIS

Numerical simulation of one year of the inspection was performed using the FEM model and the weather conditions data available in the meteorological database [39] near the study site. The period of simulations started on November 1st, 2018, the same month that the experimental program started, and ended on 31 October 2019, with hourly time steps. Each daily simulation took an average time of 152 seconds, which reduced an entire year analysis to approximately 16 hours. The simulations were performed using a desktop computer with 16 GB RAM, 2.3 GHz Intel Core i7 CPU, and an NVIDIA GeForce MX250 GPU. The varying input parameters of the model are presented in Table 2. Conventionally, the year was divided into the local seasons: autumn (March, April, and May), winter (June, July, and August), spring (September, October, and November) and summer (December, January, and February). The results are separated by the seasons and are presented in Fig. 7.

![Fig. 7 Thermal gradient results from the FEM simulation of one year of IRT inspection](image-url)
The incidence of the rain was plotted in Fig. 7 and the numerical model correctly simulated the low thermal gradients values in these events, mainly between the ±0.5°C thresholds. The solar radiation parameter allows this prediction, as rainy days usually have low solar radiation levels, generating a model outcome that correctly shows these days as not favorable for inspections. ASTM D 4788-03 [44] recommends that the bridge deck remain dry for at least 24h hours before an IRT inspection. Also, the regulation prescribes a minimum thermal gradient of 0.5°C between healthy areas and areas with suspected delamination. A dashed line was inserted in Fig. 7 to highlight the detection threshold stipulated by the ASTM D 4788-03 [44]. The direct observation from Fig. 7 allows us the perception of difference in the thermal gradient behavior along the seasons, where months with warmer weather have greater thermal gradient values and a larger number of simulations with reliable thermal gradients (out of the ASTM D4788-03 boundaries). The greater thermal gradient between damaged and undamaged areas facilitates subsurface damage identification [8], [9], [32], [36], because the contrast in the thermograms colors becomes more noticeable with the increase of the temperature difference. Table 4 presents the number and percentage of IRT simulations that exceed the ASTM D4788-03 recommendation of a minimum thermal gradient, according to the different seasons considered in the simulation.

| Season  | Month  | Nº of detections | Nº of simulations | Monthly Detection Percentage (%) | Season Detection Percentage (%) | 6-Months Detection Percentage (%) |
|---------|--------|------------------|-------------------|-------------------------------|-------------------------------|----------------------------------|
| Autumn  | March  | 367              | 744               | 49.33                         | 35.46                         | 35.87                            |
|         | April  | 275              | 720               | 38.19                         |                               |                                  |
|         | May    | 141              | 744               | 18.95                         |                               |                                  |
| Winter  | June   | 227              | 720               | 31.53                         | 36.28                         |                                  |
|         | July   | 216              | 744               | 29.03                         |                               |                                  |
|         | August | 358              | 744               | 48.18                         |                               |                                  |
| Spring  | September | 326          | 720               | 45.28                         | 48.08                         | 53.29                            |
|         | October | 325             | 744               | 43.68                         |                               |                                  |
|         | November| 399             | 720               | 55.42                         |                               |                                  |
| Summer  | December| 456             | 744               | 61.29                         |                               |                                  |
|         | January | 428             | 744               | 57.53                         |                               |                                  |
|         | February| 381             | 672               | 56.70                         |                               |                                  |

Table 4 Quantitative results of thermal gradient observations above the threshold recommended by ASTM D4788-03 [44]

In a monthly analysis, December presented a larger percentage of contrast results exceeding the 0.5°C threshold. This month represents the beginning of the summer in Brazil and together with January and February, compose the summer season in the southern hemisphere. This season had a higher quantity of simulations of thermal gradient values exceeding the ASTM D 4788-03 recommendation. The warmer weather in the summer facilitates the heating propagation by solar radiation, the main heating source for passive IRT inspection, which increases the heating of the concrete sample and therefore, the identification of the damages [32], [35]–[38]. Winter and autumn months also present a high incidence of solar radiation; however, the air temperatures usually are lower than summer and spring, and the presence of humidity and fog are more frequent, which make the heat propagation difficult. In general, it can be observed that the summer and spring represent favorable periods to perform infrared thermographic inspections under passive heating in the location of study, with 17.42% more reliable detections than the autumn and winter period. These findings challenge the observation of Hiasa et al. [32], which reported no significant effect of seasonal environment on the simulated thermal gradient in Orlando, Florida. One explanation could be the extent of the simulation, where they simulated one sunny day in each season, while this study performed an extended simulation of the entire seasons. Moreover, the study location probably has a different weather condition, which naturally produces different results. On the other hand, our data support the Al Gharawi et al. [45] work by showing that the thermograms captured in warmer months tend to have higher contrast results compared to colder months.

The results of this research imply that having the geographic information of the location (coordinates and global zone), a reliable meteorological database and the characteristics of the damaged structure, the inspector may simulate the daily thermal oscillation at the inspected structure. Thus, by evaluating the results of the finite element simulation, the inspector would be able to assess the most favorable time window to carry out the thermographic inspection of subsurface defects in reinforced concrete bridge slabs, avoiding excessive visits to the bridge field and/or experimental tests, as was previously stated by previous studies [22], [30], [32]. The use of numerical simulation to support the IRT-based bridge inspections highlights an application for the finite element method in infrastructure health monitoring. The proposed simulation approach also meets the premises of sustainability since it intends to help the maintenance of the structures to allow their use by the next generations.

To the best knowledge of the authors, the studies present in the literature did not simulate a passive IRT numerical analysis for an entire year. The complete simulation of a long period allows us to assess the effects of the seasonal variations in the IRT inspections.
without excessive tests, showing that spring and summer seasons are favorable periods to use the IRT technique. Although the presented results depend on the characteristics of the sample and the study location, the general concept of the model can be considered for further analysis of other concrete structures, and in other locations, and environmental conditions. Moreover, the model can be improved by adding a greater number of experimental tests and more precise physical parameters. In addition, an agenda of the practical tests must be maintained since the thermal proprieties of the structural materials may change along the lifetime of structures and the FEM model requires calibration [46].

5. CONCLUSION

We proposed a numerical simulation for supporting long-term inspection plans using a passive IRT method for the detection of subsurface damages in concrete bridge decks. The model was developed using FEM which showed promising agreement with surface temperatures and thermal gradients measured in the experimental tests, supporting the extrapolation to long-term analysis to find favorable windows for inspections. A major advantage of numerical models to simulate IRT inspections is the thrift of time, effort, and resources spent in the construction of the samples or in the visits to the structure to find the best times to perform the measurements. The number of factors that influence passive IRT inspections is a limitation of this approach and can lead to discrepancies in the surface temperatures simulations. Further research efforts could use the finite element model updating technique to improve the accuracy of the results and also to provide a table with validity periods for inspection related to latitude of interest.

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