NUMERICAL SIMULATION OF HEAT PROPAGATION IN CONCRETE WITH DEFECTS

Ersan GÜRAY*, Ph.D., Recep BİRGÜL*, Ph.D., P.E.
*Mugla Sitki Kocman University, Faculty of Engineering, Department of Civil Engineering, TURKEY  
rbirgul@gmail.com

Abstract
Nondestructive evaluation techniques have become an integral part of structural health monitoring inspections of existing bridges. Infrared thermography (IRT) is one of the nondestructive testing techniques. It is based on capturing the thermal gradient on a radiant surface. This study investigates the effects of a defect in a concrete bridge deck. To this end, a numerical model of a bridge deck with certain initial and boundary conditions was used to numerically obtain temperature differentials at any nodes across the model. The defect, a delamination with a constant thickness, was assumed to be filled with air in one case, and with water in the second case. The results were compared with the results obtained for the case of sound concrete. The transient solutions of the nonlinear partial differential equation were obtained by utilizing the finite element method. Output graphs showed that the temperature variation is about 4 °C on the surface of the deck whereas variations inside the deck present different temperature values; in turn, this creates a temperature gradient between the surface and the region around the defect. It is this temperature gradient that can easily be picked up by modern infrared equipment in order to locate the defect inside the concrete deck. Additionally, it was found that the type of material inside the defect, air or water, affects the heat conduction differently.

Keywords: Infrared thermography, bridge decks, delamination, heat propagation, numerical simulation

1. Introduction
In an industrialized country, infrastructure binds the country together making it possible to move the goods and services around the country. Without a doubt, bridges are important and essential constituents of infrastructure. However, travelers cross over bridges every day with no particular attention to their structural integrity. Yet, any conspicuous deterioration of a prime bridge in a transportation network would control the serviceability and efficiency of the network and adversely influence the economic growth of local and regional communities. Therefore, highway agencies have been expressing their concerns regarding maintenance, repair and replacement issues of bridges [1]. American Society of Civil Engineers (ASCE) also articulated worries and put forth close interest in the current conditions of infrastructures. As a specific example, 2013 Report Card for America’s Infrastructures: Bridges rates the bridges in the US as C+, meaning “mediocre” condition, since one out of every nine bridges is rated as structurally deficient [2].

Authorities are in a difficult situation when it comes to deal with the problem of structurally deficient bridges since available funds are nowhere near enough to replace the problematic bridges. Then the next best thing is to rehabilitate them because it is a cheaper alternative for the bridges suitable for remedial actions. However, it is obvious that choosing the right candidates for corrective actions must be substantiated by acceptable and scientific means. It appears that the use of nondestructive evaluation (NDE) methods may play an important role to inspect the current condition of existing bridges at a reasonable cost. Hence, NDE promises a way to improve the allocation of funding by improving the information these decisions are based on, by better assessing existing bridge conditions [3-4]. There are numerous NDE
2. Numerical model

The thermal model is a two dimensional cross-sectional area of a concrete bridge deck. It has a rectangular shape, the width (L) is set to be 400 mm, and the height (H) of the model is 200 mm as shown in Figure 1. The delamination has a thickness (t) of 2 mm; base depth is taken with the following configurations as d=187 mm, d=177 mm, d=167 mm and d=157 mm.

![Figure 1. The deck model geometry](image1)

The air temperature varies with respect to the time of the day; the ambient temperature (Ta) variation for the duration of a whole day is represented by a sine function as given in Figure 2. The top surface of the deck is assumed to be heated more than the bottom surface since the top surface is exposed to direct sun light during day time. The temperature values at different times of the day can be calculated by Equation 1 for the top surface and by Equation 2 for the bottom surface of the bridge deck as given below.

\[
T_a = 25 - 10 \cos \left(\frac{\pi (t - 240)}{720}\right) \quad \text{for} \quad 0 \leq t \leq 1440 \text{ minutes} \tag{1}
\]

\[
T_a = 20 - 5 \cos \left(\frac{\pi (t - 400)}{720}\right) \quad \text{for} \quad 0 \leq t \leq 1440 \text{ minutes} \tag{2}
\]

Heat energy is transferred in the form of convection between air and the surface of the deck. The convective heat transfer coefficient of air is taken as \(h_c = 20 \text{ W/m}^2\text{K}\) which refers to a mild wind with a constant velocity of approximately 1.1 m/s blowing close to the top and bottom surfaces of the deck.

![Figure 2. Ambient temperature variations at the top and bottom surfaces of the deck](image2)
3. Materials

Deck slab is made of concrete. The test cases considered are: a) concrete deck without any delamination (sound concrete), b) delamination filled with water, and c) delamination filled with air. Material properties of the concrete, water and the air is given in Table 1. Initial temperature distribution is set to 18 °C uniformly throughout the model.

Table 1. Respective properties of the materials in deck mod

<table>
<thead>
<tr>
<th>Materials</th>
<th>Heat Conductivity($k$) [kcal/hr.m°C]</th>
<th>Specific Heat($c_p$) [J/kg°C]</th>
<th>Density($\rho$) [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>2</td>
<td>880</td>
<td>2500</td>
</tr>
<tr>
<td>Water</td>
<td>0.58</td>
<td>4200</td>
<td>1000</td>
</tr>
<tr>
<td>Air</td>
<td>0.024</td>
<td>1000</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Heat is transmitted by conduction through the concrete deck and the delamination. In the cases of water and air filled delamination, the heat flows only by conduction since the delamination thickness ($t$) is sufficiently small and the temperature difference is small enough between the top and bottom surfaces of delamination such that convection does not start on. The governing equation of the problem, to solve the transient temperature variation inside the deck with the delamination, is defined with the well-known heat equation but ignoring the radiation and convection terms such that: where $\Delta$ is the Laplacian operator and $\alpha$ is the thermal diffusivity.

4. Results and Discussion

The transient solution of the problem is performed on ANSYS Mechanical Workbench. After geometry of the model is defined in an APDL (ANSYS Parametric Design Language) input file, a finite element mesh is generated with rectangular elements subjected to a mesh size from 0.5 mm to 20 mm (Figure 3). The model contains approximately 7500 quadrilateral elements. The mesh becomes much denser in the delamination region. Convection boundary condition is imposed to the top and bottom surfaces of the deck whereas the side boundaries are assumed to be heat insulated. Temperature data is collected from nodes approximately at $x=0$, $y=200$ mm(at the top surface), $x=0$, $y=190$ mm and $x=0$, $y=100$ mm, for all cases.

![Figure 3. Finite element mesh of the case when d=157 mm.](image)

![Figure 4. Temperature variation at y=200 mm when d=187 mm.](image)
Figure 5. Temperature variation at \( y=200 \) mm when \( d=157 \) mm.

Figure 6. Temperature variation at \( y=100 \) mm when \( d=187 \) mm.

Figure 7. Temperature (T) at 4 pm. at \( y=190 \) mm vs. depth of the delamination (d).
Existence of a delamination inside the slab causes an extensive change of the temperature variation on the surface especially in the case of the air-filled delamination (Figure 4). When the cavity is filled with water, since its conductivity is higher than that of air, heat energy is transferred easier, in other words, as a material; the water cannot prevent the heat transition from passing through the delamination. However, air filled delamination provides some insulation which results in higher temperature values on the surface. The extreme variations of temperature disappear with deeper delamination locations. They vary almost in the same manner when d=157 mm as shown in Figure 5.

At 8 pm., the temperature becomes slightly higher than 18 °C which was the initial temperature at mid-depth when the delamination was at the depth of 187 mm for sound concrete and water filled cases as shown in Figure 6. In the case of air filled delamination, on the other hand, the middle of the region does not present sufficient heat variation so that the variation throughout the day becomes negligibly small. This can be interpreted as the insulation property of the air filled delamination. But in the case of sound concrete the temperature increases slightly more.

Temperature variation on the surface is also affected considerably by the delamination depth. But at y=190 mm, which is slightly below top surface, especially in the case of air filled delamination, the temperature changes substantially, there is almost 4 °C temperature difference between the cases d=187 mm. and d=157 mm, respectively as shown in Figure 7. It can be concluded that the air filled delamination makes noticeable temperature differences close to the surface as well as on the surface.

Heat transfer through a media can be well observed by means of the heat flux, it depends on the gradient of the temperature
such that:

\[ \varphi = -k \nabla T \]  

(4)

where \( \varphi = \left( \frac{\partial \theta}{\partial x}, \frac{\partial \theta}{\partial y} \right) \) is the heat flux and the \( \nabla \) is the gradient operator.

It is shown from the beginning of the analysis that the heat flux is essentially prevented in the case of air filled delamination. This can be well observed in Figure 8 such that the magnitude of the heat flux values become quite different at the top and bottom surfaces of the delamination throughout the day.

5. Conclusions

The detection of delamination is very simple and practical by Infrared Thermography (IRT) measurements as a nondestructive evaluation method. Even a small temperature difference can be well captured by the modern equipment. The following conclusions can be drawn from the results of the present work:

- The delamination always causes a drawback for the heat transfer since it creates a discontinuity for the conduction process and it will always be a reason of higher temperature close to the top surface.
- The temperature becomes much higher especially in the case of air filled delamination, it is almost 4 °C at most, for the case \( d=187 \) mm.
- The temperature variation is very limited even in the case of sound concrete. But, even the small differences can be measured by modern and highly accurate equipment.
- The depth of the delamination is also an important parameter such that it can cause remarkable temperature differences over the deck when it is closer to the top surface.

In the present work, the heat transfer through the deck is investigated when a delamination with a constant thickness is located at various depths inside the deck; the delamination is assumed to be filled with water or air. The results were compared with sound concrete case. This study attempts to provide a preliminary numerical analysis on heat propagation in concrete with defects; the effects of delamination thickness are not studied. However, the thickness of the cavity is presumed to be an influential parameter that needs to be studied. One another point, to be included in a future work, is the inclusion of the radiation effects on the variation of temperature in the deck. But, at the end, the numerical model at its present form worked well and some useful observations have been made out of this study.

6. References