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Reinforced Concrete Bridge Deck Condition Assessment Methods Using Ground Penetrating Radar and Infrared Thermography

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***Abstract*—**Reinforced concrete bridge deck condition assessments primarily use visual inspection methods, where an inspector looks for and records locations of cracks, potholes, efflorescence and other signs of probable deterioration. Sounding is another technique used to diagnose the condition of a bridge deck, however this method listens for damage within the subsurface as the surface is struck with a hammer or chain. Even though extensive procedures are in place for using these inspection techniques, neither one provides the inspector with a comprehensive understanding of the internal condition of a bridge deck – the location where damage originates from. In order to make accurate estimates of repair locations and quantities, in addition to allocating the necessary funding, a total understanding of the deck's deteriorated state is key. The research presented in this paper collected infrared thermography and ground penetrating radar data from reinforced concrete bridge decks without an asphalt overlay. These decks were of various ages and their condition varied from brand new, to in need of replacement. The goals of this work were to first verify that these nondestructive evaluation methods could identify similar areas of healthy and damaged concrete, and then to see if combining the results of both methods would provide a higher confidence than if the condition assessment was completed using only one method. The results from each method were presented as plan view color contour plots. The results from one of the decks assessed as a part of this research, including these plan view plots, are presented in this paper. Furthermore, in order to answer the interest of transportation agencies throughout the United States, this research developed a step-by-step guide which demonstrates how to collect and assess a bridge deck using these nondestructive evaluation methods. This guide addresses setup procedures on the deck during the day of data collection, system setups and settings for different bridge decks, data post-processing for each method, and data visualization and quantification.

***Keywords*—**Bridge deck deterioration, ground penetrating radar, infrared thermography, NDT of bridge decks.

I. Introduction

AMERICA'S infrastructure, including bridges, is in a state of disrepair. While vast improvements have been made to a significant number of bridges throughout the Nation, there isn't any evidence that one of the major causes of this condition, lack of proper inspection, has been fully addressed. Proper inspection of all bridge components, but specifically the deck which carries the traffic and therefore requires more frequent repairs/replacement than any other major component, is key to understanding if damage exists, how much damage is present, the intensity of the damage, when repair will be required, and how much it will cost to repair it. Without a completed and detailed condition assessment of reinforced concrete bridge decks, specifically beneath the surface, transportation agencies do not have enough information to efficiently and effectively manage their infrastructure.

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II. Current Inspection Techniques

The only required bridge deck inspection technique by the US Federal Highway Administration is visual inspection. However, often times transportation agencies will accompany the inspection with hammer tapping or chain drag in order to identify areas that are delaminated. A delamination is a thin air pocket that separates the top of the rebar from the concrete in an area where the rebar has significantly corroded.

Visual inspection requires a trained inspector to travel to the deck and observe (on all surfaces) if any cracks, potholes, efflorescence, rust, and other signs of deterioration exist. The length/sizes of the damage is recorded, and the inspector then rates the condition of the deck (until recently on a scale from 0-9, where 9 was the condition rating of a new deck) based on his/her observations. Pictures of any damage often accompany the inspection, which is then provided to the transportation agency. Regular inspections are required every two years.

A chain drag evaluation requires experienced individuals to drag chains across the top surface of the deck and observe any differences in the audible sounds produced by the vibration of the chains. A "pinging" sound is typically related to a deck free from delaminations. If a hollow sound is observed in an area, that location will typically contain a delamination.

A number of drawbacks are associated with each of these methods. Firstly, visual inspection cannot see below a surface and into the deck where deterioration has initiated long before it was visible on any surface. Having access to a subsurface evaluation will allow early repairs, service life extension, better infrastructure managing, and more accurate funding allocation. Chain drag is also associated with a number of drawbacks. For example, this method cannot be used on decks that are overlaid (have an asphalt covering). This is a significant drawback as most of the decks in the regions of the USA that require deicing salts during the winter months have asphalt overlays in order to protect the deck. Additionally, since the inspector must listen for audible sounds, if there is significant traffic noise, the inspections becomes quite challenging.

III. Nondestructive Evaluation Methods

In an effort to obtain more comprehensive evaluations of reinforced concrete bridge decks, the Rhode Island Department of Transportation in collaboration with Roger Williams University set out to develop a detailed step-by-step manual that provides inspectors with all of the information necessary to assess the internal composition of the deck using ground penetrating radar and infrared thermography. These methods were selected because they are able to "see" within the bridge deck, are nondestructive, have the ability to collect data at high speeds (without disrupting traffic) and have been proven as effective methods for evaluating the internal condition of bridge decks by a number of researchers.

For example, [1] found significant correlations between GPR rebar level attenuation, where the data was collected from an overlaid deck, with visual and chloride analyses of cores taken throughout the deck. [2] used infrared thermography to assess an overlaid deck in Chicago, IL, where all delaminated regions detected with the infrared camera were confirmed with sounding and cores. [3] and [4] found a substantial relationship between the attenuation levels of rebar reflection amplitudes, and active corrosion of a decommissioned bridge deck and seventeen laboratory fabricated slabs with induced rebar corrosion. [5] assessed 87 bridge decks with and without asphalt overlays using high speed radar and infrared thermography, where the majority of defects determined by either method were confirmed with cores. Six laboratory slabs with artificially implanted defects were assessed with GPR, as reported in [6], in which the radar system detected almost all of the delaminations and voids that were larger than 7mm in diameter.

Even though research has been completed that shows the plausibility of these methods being implemented on bridge decks, this work has primarily been completed by researchers – and not bridge owners. Furthermore, very minimal literature exists that provides results of studies that couple the GPR and IR results. The manual discussed in this paper will provide the owners with the knowledge they need to assess bridge decks using these methods.

A. Ground Penetrating Radar

Ground penetrating radar works by sending electromagnetic pulses through the subsurface of the deck with a high frequency antenna that travels over the deck, and in the direction of vehicular traffic. When those pulses come into contact with a material of differing dielectric property, like the concrete rebar interface, some of the signal is scattered and captured by the antenna's receiver. Two examples of data collection using this method can be seen in Figs. 1 and 2.

Since corrosion of the reinforcing steel, is the primary cause for bridge deck deterioration, it is the signal information at this location that is used to evaluate if the deck is damaged or not.

Fig. 3 provides an illustrative example that shows the difference in return signals captured from an area of potential deterioration and an area free from deterioration. Fig. 3 is a gray scale B-Scan where the antenna's direction of travel is along the x-axis and the subsurface depth is along the y-axis. The gray scale represents the signal amplitude at any given location, and the hyperbolas in the image are the reflections from the reinforcing steel. The peak of each hyperbola is the location used for the evaluation since that is the actual location of the rebar. The left red circle in Fig. 3 is an area that contains potential damage, whereas the right red circle is an area free from deterioration. The difference between these two areas is the ability to clearly see the hyperbola's peak, in addition to its brightness. This is directly related to the amplitude of the signal at that location. Areas of potential damage have lower amplitudes than those free from damage.

Fig. 1 Picture one of GPR data collection

Fig. 2 Picture two of GPR data collection

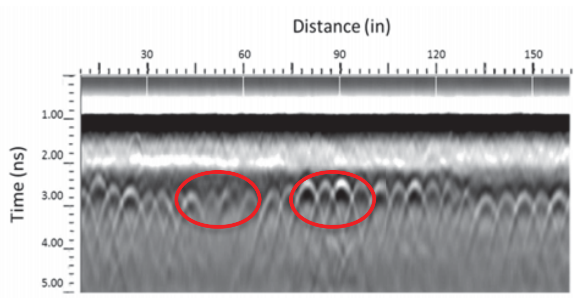

Fig. 3 GPR B-Scan

B. Infrared Thermography

Infrared thermography works by collecting emitted infrared energy, in the form of temperatures (degrees F), from the surface of the deck using an infrared camera mounted onto a vehicle, about 12-13ft above the surface (Fig. 4). The surface temperatures vary when a delamination is present within the subsurface. Since a delamination is an air pocket, it acts as an insulator for that location of the deck. So as the ambient air temperature rises early in the day, the delaminated area will heat up quicker than an area free from damage and appear as a hot spot.

Fig. 4 IR Setup

IV. Data Collection, Post Processing and Visualization

In order to develop the manual, GPR and IR data were collected, analyzed and visualized from five bridge decks. All of the steps completed during this process, and outlined and discussed below, are described in detail in the manual.

1. Place a 1ft by 1ft grid onto the testing area using transportation agency approved paint
2. Alter the settings of the GPR system so that the rebar is clearly visible in the B-Scans
3. Collect data along the entire length of the deck (joint to joint) at one-foot offsets from the curb
4. Setup the IR camera onto the mount and ensure the camera is in focus
5. Collect data along the direction of travel, an entire lane's width at a time, ensuring to get some artifact in the images (curb, white line, etc.)

Once all of the data were collected, the rebar reflection amplitudes were extracted from the GPR data and the surface temperatures were extracted from the IR data. The post-processed data were then plotted in a plan view manner, using color contour plots. An example of the contour plots of one the bridges data were collected from, is shown in Fig. 5.

The middle plot of Fig. 5 is of the GPR rebar reflection amplitudes. A red, yellow, green color scheme is used to indicate proposed healthy regions (green), proposed deteriorated regions (red) and those in between (yellow). This deck was a special case, as the concrete cover varied throughout the deck, causing the amplitudes to vary with respect to the cover as opposed to deterioration. So, while there are red areas, they are actually indicative of thick concrete cover, and not of deterioration. This was noted in the condition assessment report of this bridge deck which was provided to the department of transportation. In terms of deterioration, according to GPR, this bridge deck was almost entirely free from damage. The IR data also indicated that this deck was free from damage. There was minimal variation in the IR data throughout the entire deck which can be seen from the plot and from the scale. There were no hot spots caused by delaminations within this deck. Despite the GPR data having some (but minor variation) due to changes in the concrete cover depth, both methods point to the same result – a deck free from deterioration. These results were confirmed with concrete cores extracted from three different locations.

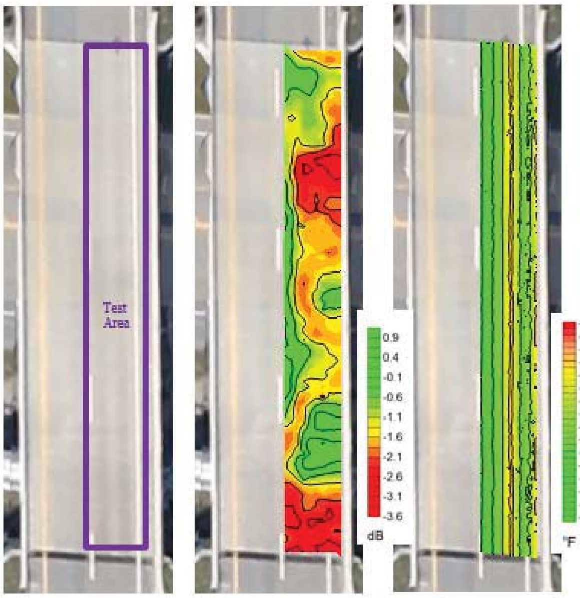

Fig. 5 Arial View of Bridge, GPR Amplitudes, IR Surface Temperatures

V. Damage Quantification

The plots shown in Fig. 5 provide evidence of any data variation, and spatially display locations of damage for if/when the transportation agency repairs those specific areas. (Depending upon the how much of the deck is damaged, it may be more economical to fully replace the deck.) In addition to qualitatively understanding the subsurface condition, the manual also provides a step-by-step quantitative procedure. This procedure shows an inspector how to spatially quantify the damage detected by each method, by calculating how many coordinates are considered to be damaged as a part of the whole.

TABLE I
Spatial Damage Quantification

% Deteriorated GPR	% Deteriorated IR	% Agreement
7	0	93

Table I provides the damage quantities for the bridge deck shown in Fig. 5. Again, even though there appears to be more red area in the GPR plot than 7% as noted in the table, this is mostly due to the variation in concrete cover and not subsurface damage. The IR surface temperatures did not indicate any sign of subsurface damage, and therefore the associated percent of spatial deterioration is 0.

Table I also provides a column for “% Agreement”. This compares the results of each coordinate in the GPR plot with those of the IR plot. Agreement is defined as both coordinates (GPR and IR) indicating damage, or both coordinates indicating healthy concrete. In this case, 93% of the coordinates, compared between the GPR and IR plots agreed. The “% Agreement” provides transportation agencies an additional level of confidence when diagnosing the condition of a bridge deck. If both methods have a high level of agreement, making the decision that the deck is safe for travel, needs immediate replacement, or requires minor repairs can be made with certainty. Using the chain drag method is typically the method used to outline areas that require repair, often times resulting in overestimating or underestimating the area – both of which come with significant consequences. Now, the areas determined for repair with chain dragging can be verified and modified if required using the spatial results of the GPR and IR data.

VI. Manual

The process briefly described above is a broad overview of what this manual provides. The manual itself is about 100 pages long, and provides a significantly larger amount of detail than what can be provided in a publication. For example, it provides photos that describe how to connect each component of the GPR system and IR camera. It also provides a list describing how each GPR system setting will alter the data collection, and suggested settings for bridge decks with an without an asphalt overlay. It also provides screen captures for each post-processing step. Whether that be extracting the GPR rebar amplitudes from the associated software, or assigning coordinates to each data set, every detail is provided so that someone who many not be familiar with these methods can complete a meaningful bridge deck assessment.

VII. Conclusions

Current bridge deck assessments do not provide subsurface information, which is the location that damage starts long before it is visible on a surface. Having this information will allow for a complete understanding of damage quantities within the entire deck. This information provides transportation agencies with the knowledge necessary to prioritize deck repairs or replacements, allocate the necessary funds to do so, and most importantly, keep the public safe. In addition, this paper discusses a manual that was developed which allows an inspector who may not be familiar with these nondestructive evaluation methods to collect, post-process, visualize and quantify damage within a bridge deck.

Acknowledgments

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