Non-Destructive Bridge Deck Assessment using Image Processing and Infrared Thermography

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Abstract

Traditionally, highway bridge conditions have been monitored by visual inspection with structural deficiencies being manually identified and classified by qualified inspectors. However, the quality of inspection results depends on the individual inspector's subjective judgment based on his/her knowledge and experience. Under these circumstances, innovative non-destructive bridge condition assessment technologies using infrared thermography and digital concrete surface imaging have been developed and applied to the highway bridge structures in Japan. This paper describes the results of integrated high-end infrared thermography and line sensors to obtain bridge deck defects and delamination with on-site applications for sample bridges in the state of Florida.

Introduction

Condition ratings of bridge components in the Federal Highway Administration (FHWA)'s Structure Inventory and Appraisal (SI&A) database are determined by bridge inspectors in the field for bridge deck, superstructure and substructure. This information has been used by bridge owners as a basis for decisions on bridge maintenance, rehabilitation, and replacement. The condition ratings also influence a bridge's Sufficiency Rating (SR), as well as whether the bridge may be classified as "structurally deficient".

However, the determination of bridge condition ratings is generally subjective depending on individual inspectors' knowledge and experience, as well as varying field conditions. For the evaluation and documentation of concrete deterioration (cracks, potholes, delamination, spalls, etc.) and changes over time, the current practice can be lacking in accuracy and completeness, as well as time consuming and costly if road closures are required for the inspection (Fig.1). Recent advancements in imaging technologies have made their applications practical and possible in more detailed bridge inspections. The technologies can overcome some shortcomings of human subjectivity and are intended to improve and complement, but not to replace, human inspections. The innovative technologies presented herein will be able to make bridge inspections more objective, more consistent, more scientific, and more efficient. The need for utilization of thermography has been advocated especially for detecting subsurface defects using low-cost hand-held infrared cameras by Washer et al. These thermal imaging cameras are intended to be used by the state DOT personnel using while they are conducting their conventional visual inspections and walk-throughs (Washer, et. al, 2009). Guideline requirements developed for the effective application

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of the technology in the field using the hand-held cameras are also described along with application of the technology for the detection of deterioration in a typical highway bridge (Washer, et. al, 2010). In this paper, the authors present the integrated use of high-end infrared thermography (IR) and line sensors to obtain bridge deck cracks, defects and delamination at a very rapid and high resolution for structural assessment and decision making. The authors present that the integrated system can scan a network of bridges with a special design truck running at 50 mph (without any lane closure) with excellent detail in a matter of couple days. In order to validate the effectiveness of the new inspection technologies, a pilot inspection project was conducted through a joint research effort with the University of Central Florida (UCF). The objective of the research project was to investigate the technologies on the selected bridges to objectively characterize these deteriorated bridges with a university-government-industry collaboration, by exploring the use of novel image based technologies in a way that the information generated through these technologies will provide useful data for the inspection and evaluation of civil infrastructure systems.

Fig.1: Current Bridge Inspection Practice

Innovative Imaging Technologies for Bridge Deck Inspection

The new imaging technologies for bridge inspection described in this paper include the following:

- Line Sensor Camera for deck top surface defects such as cracks and potholes
- IR (Infrared thermography) for subsurface defects such as delamination (detecting possible future potholes)

From November 12th to 14th, 2012, several reinforced concrete bridge decks carrying I-4 in Central Florida area were scanned while driving 50mph by line sensor cameras and an infrared camera mounted on the truck (Fig.2). No lane closures of any kind were needed during the field data collection. The system scanned approximately 13-ft of deck width from each run.

Before visiting the bridge site, detectable crack width was calibrated by scanning a large crack width ruler (Fig.3) at the campus of UCF (University of Central Florida). It was verified that cracks with 1/64” or greater can be successfully detected by the line sensor camera system.

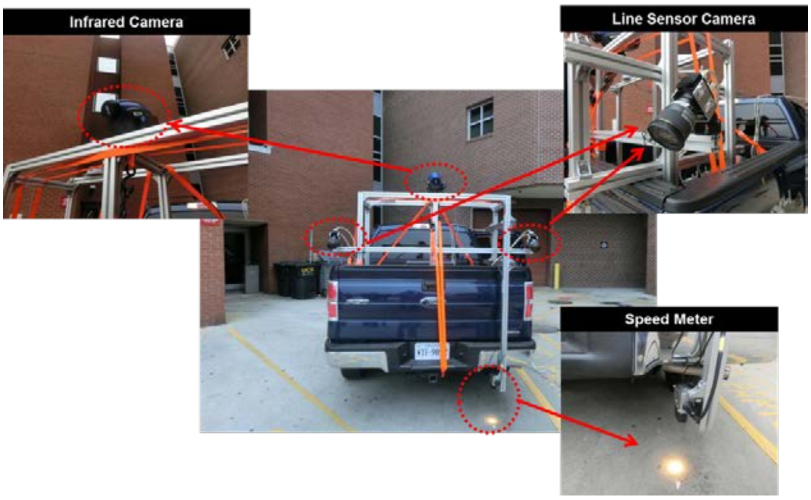
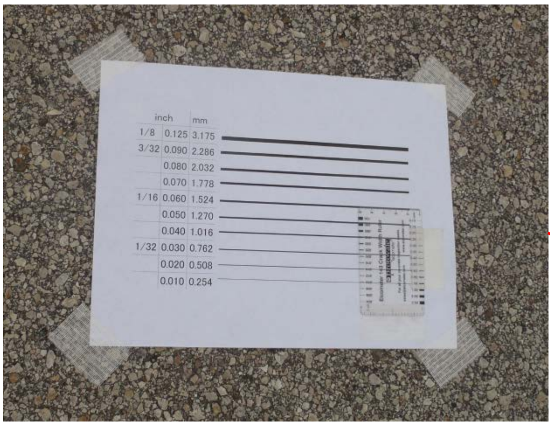


Fig.2: Truck-Mounted Line Sensor Cameras and Infrared Camera



(A Large Crack Width Ruler)

Fig. 3: Calibration of Detectable Crack Width by the System

<u>The pilot Project</u>

During the pilot application, 10 bridges carrying I-4 in Central Florida area were scanned by the system. Fig.4 is the photo of a scanned bridge located in downtown Orlando. The bridge includes 3 spans carrying 4 lanes of the traffic. The 4th (left) lane has been added to the existed three lanes during the recent bridge widening project. Fig.5 depicts the overall condition and defects on the deck surface. Small potholes with the size of 5”-10” and cracks with longitudinal and transversal direction were detected from the scanned visual images obtained by the line sensor camera system. Some of the cracks make hexagonal shape and causing delamination/potholes within the cracking areas. The detected cracks were typically 1/64” (0.3mm) in width. According to the Bridge Inspectors Field Guide (Florida Department of Transportation, 2008), cracks should be classified into three categories as shown in Table 1, and the NBI (National Bridge Inventory) specified “Distressed Area” is calculated for the rectangular area including “Moderate,” or “Severe” cracks. Most of the detected cracks on this bridge deck shall be categorized as ‘Insignificant’, and these cracks could not be detected by the traditional visual inspection that is typically performed by the bridge inspectors overviewing the deck surface defects from the shoulder. The infrared thermography camera successfully detected the possible delamination in deck concrete as shown in Fig.5 (hatched in pink colour). In order to find such deck subsurface defects traditional technique using chain dragging method (Fig.1- left) requires lane closure during the inspection period.

Fig.4: A Scanned Bridge in Downtown Orlando, FL

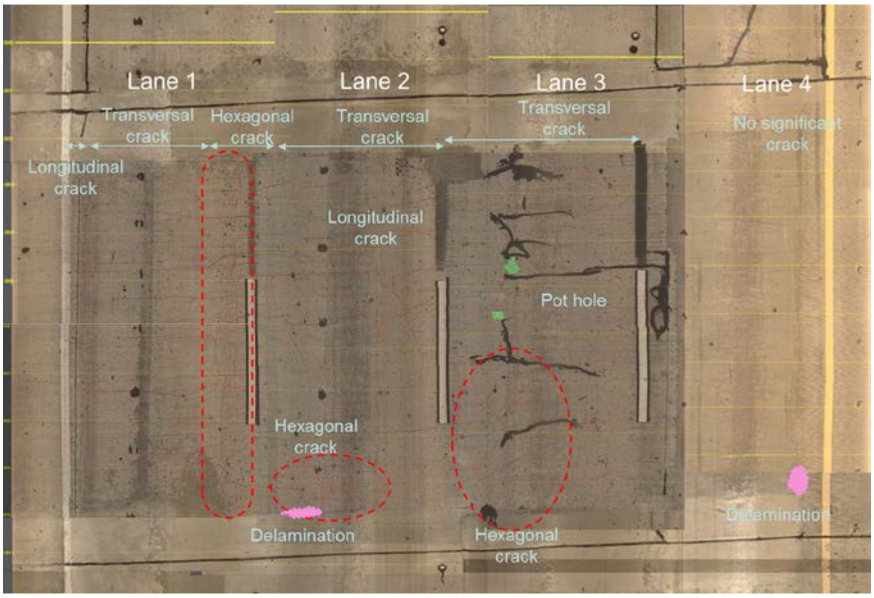


Fig.5: Overall Condition of the Deck at Downtown Orlando

In this study, a sophisticated IR camera was used, which is currently used in industry for delamination detection. The Infrared camera (FLIR 5600) has the shutter speed of 1/1400, enabling the bridge deck scanning team to drive 50mph while collecting the high quality IR images for analysis (where the conventional IR inspection uses lower standard IR camera with only 1/125 shutter speed). The uncooled detector which is used in the conventional IR inspection works by the change of resistance, voltage or current when heated by infrared radiation, thus requiring longer exposure time to take the IR image. In this study, raw infrared images were further analyzed based on algorithm developed and tested in Japan on many bridges. The proprietary IR software applied in this project can classify the damage rate into three categories; the classification categories being "Critical" (crack caused by delamination reaches on concrete surface and immediate attention is required), "Caution" (crack exists within 2cm from the concrete surface and close monitoring is recommended) and "Indication" (Currently satisfactory) (see Fig.6). Raw infrared (IR) image data is filtered and rated into three categories by the software to indicate and evaluate the severity of the subsurface defects in concrete structures. The real time monitor shows the raw thermal image and filtered/rated images at the field (Fig.7). Fig.8 is an example of the thermal image and software output for a scanned bridge in downtown Orlando.

Table 1: Categorization of Crack Size (FDOT, 2008)

	Insignificant	Moderate	Severe
Crack Size	<1/16"	1/16"-1/4"	>1/4"

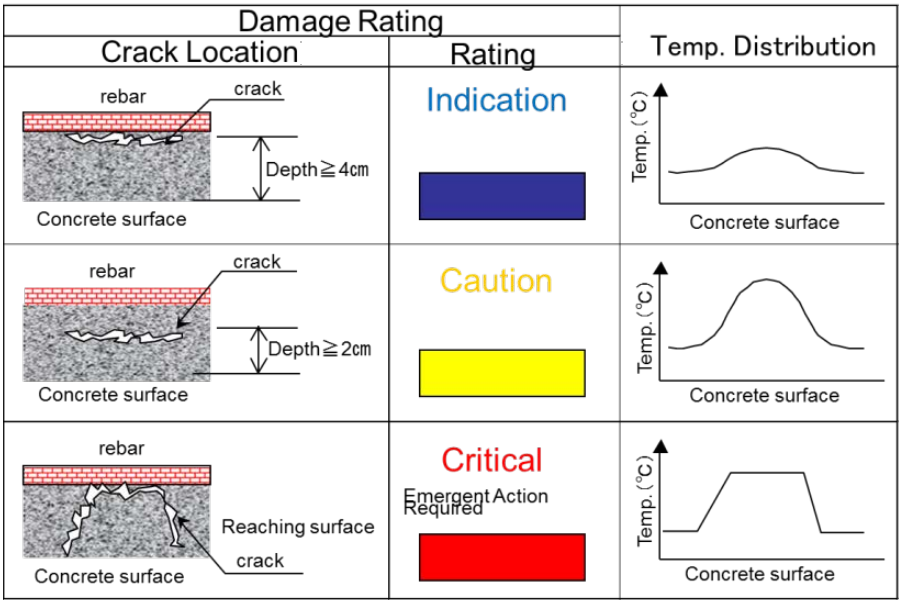


Fig.6: Damage Rating by Infrared Imagery Software

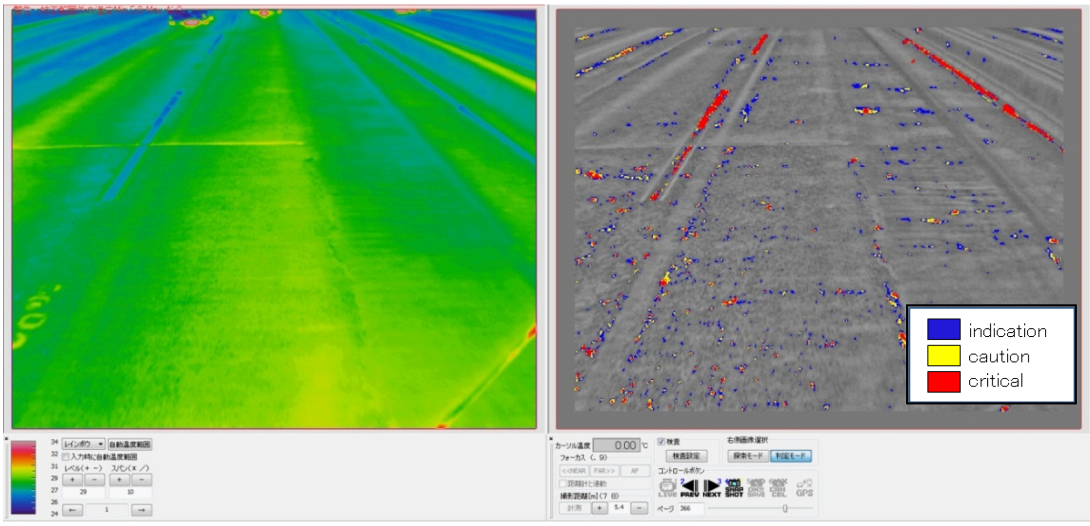


Fig.7: The Real Time IR Monitor (Thermal Image (left) and IR Software Output (right))

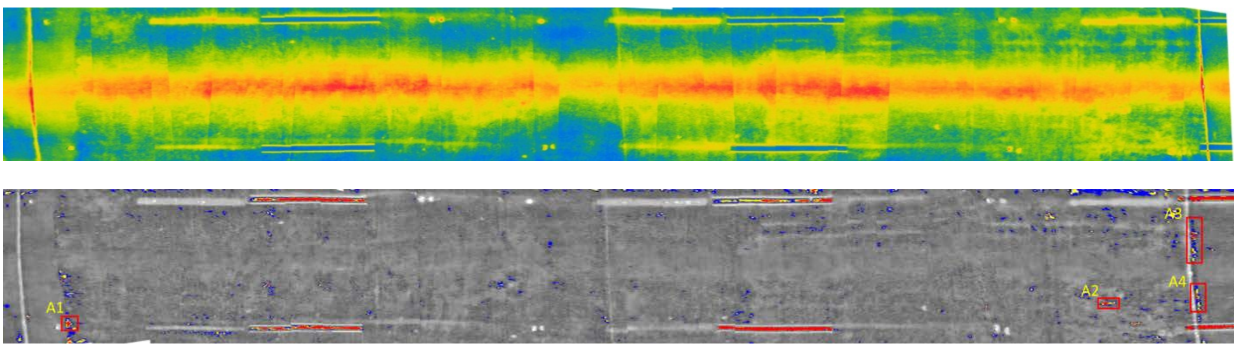


Fig.8: Thermal Image and IR Software Output for the Scanned Bridge

Fig.9 shows an example of detected pothole and possible delamination. Typically, perimeter of the pothole becomes vulnerable to further cracking and delamination due to the concentrated loading, causing the pothole area expanding to the surrounding area. Patching the potholes before it starts growing is a good maintenance strategy to increase the level of safety to the motorists and reduce the total maintenance cost for the bridge owner. Fig.10 shows the visual image and infrared software output at the third lane of the bridge deck. Some potholes and possible delaminated areas were found along the longitudinal construction joint between the widened and existed decks, especially at the shear key locations. Fig.11 shows an example of the visual image and infrared software output close to the expansion joint. Delaminated areas in concrete were found at the boundary of existing deck concrete and the concrete placed after the settlement of expansion joint. These ‘boundary’ areas between the concrete placed in different time period can be the possible weak spots to initiate potholes and delaminated areas.

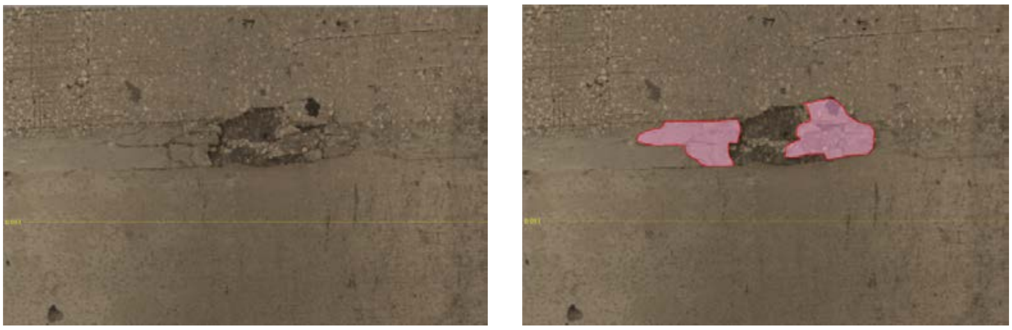


Fig.9: Detected Pothole and Possible Delamination

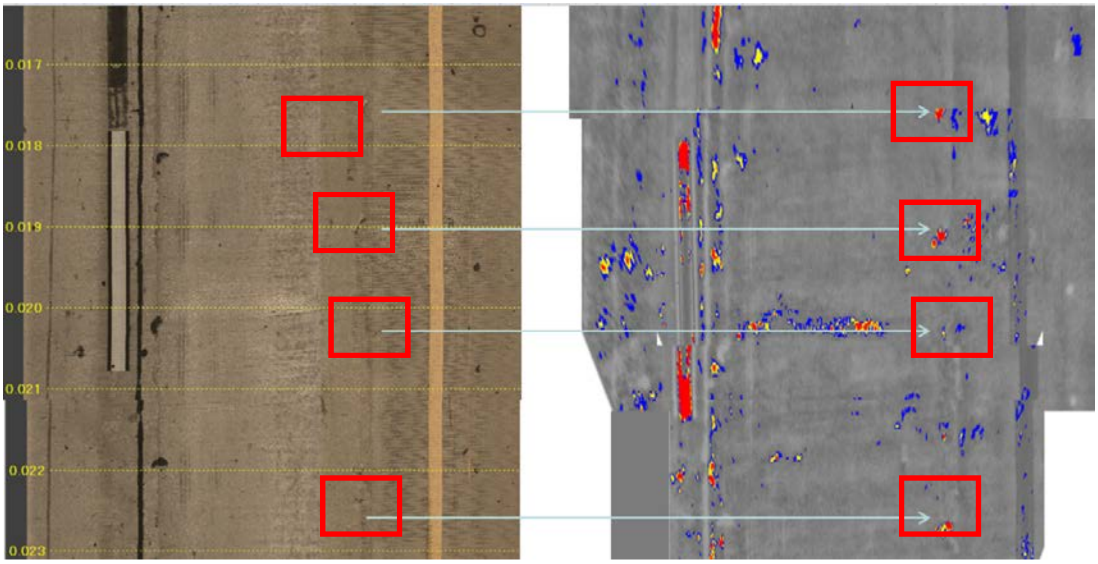


Fig.10: Visual Image (left) and IR Software Output (right) at Longitudinal Construction Joint

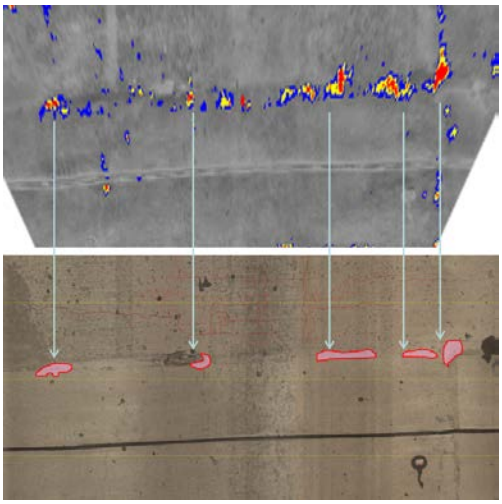


Fig.11: Visual Image (bottom) and IR Software Output (top) at Expansion Joint

Table 2 describes the four condition states defined in the AASHTO Guide Manual for Bridge Element Inspection (AASHTO, 2011). Based on the AASHTO Manual, the condition states for each span/lane of the bridge deck were determined and summarized in Fig.12. Cracking significance and patterns varies for each span/lane of the bridge deck. If we could apply this deck scanning system to the corridor level inspection and determine the condition state for each span/lane of each bridge in the network, the bridge owner can use this information to prioritize the bridge deck repair/rehabilitation program and efficiently allocate the limited budget to obtain the maximum return on investment for the network level bridge management.

Table 2: Standard Condition States for Defects in Bridge Elements (after AASHTO, 2011)

Condition State #	Condition State
1	Good
2	Fair
3	Poor
4	Severe

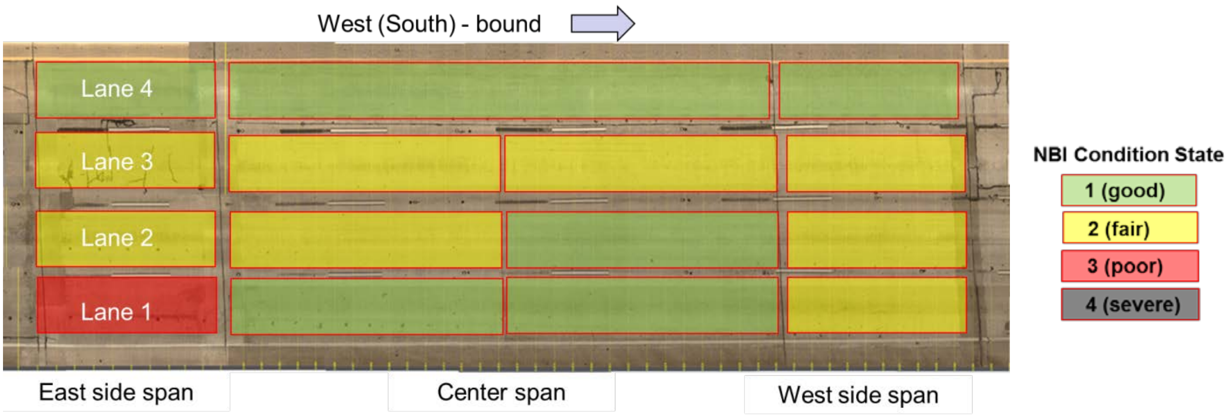


Fig.12: Determining the Condition States for Each Span/Lane of the Bridge Deck

Fig.13 shows an example of potholes with corroded rebar exposed on the deck top for another bridge on I-4. The cause of the spall in deck top concrete could be lack of cover thickness and/or corrosion of rebar. The infrared software shows some potential delamination around the spalled concrete and other potential deck subsurface delamination as shown in Fig.14, indicating the possible rebar corrosion and occurrence of future pothole. The red line in Fig.14 is estimated re-bar location on the deck top side (interval of rebar estimated to be approximately 8” from the two exposed rebar shown in Fig.13).

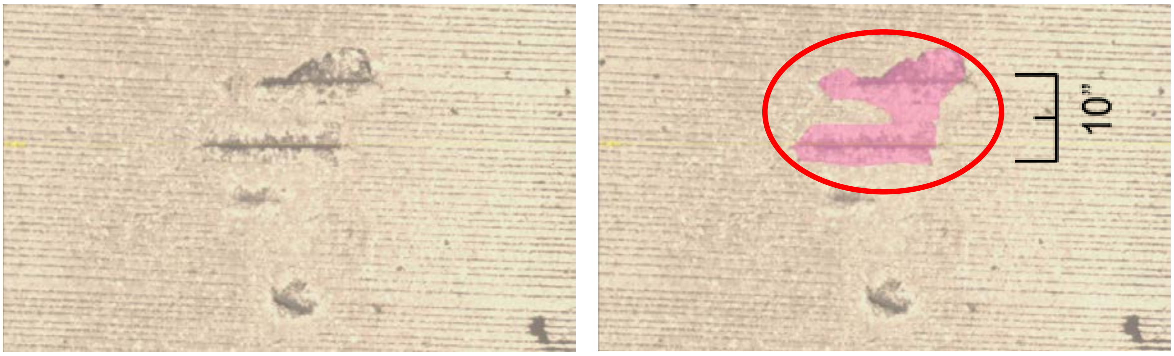


Fig.13: An Example of a Pothole with Corroded Rebar Exposed

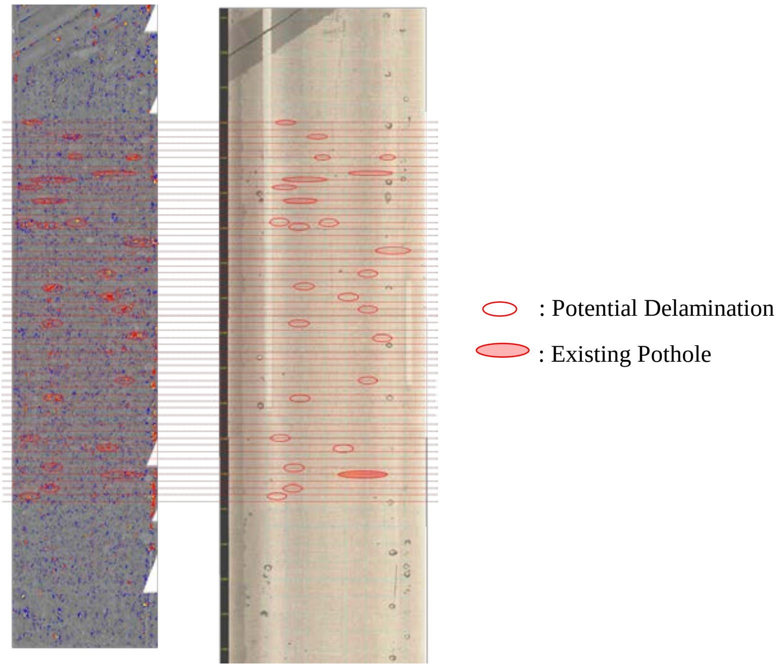


Fig.14: Visual Image (right) and Infrared Software Output (left)

<u>Application to the Corridor Level Inspection</u>

Bridge decks with some possible symptom of deterioration detected by overviewing the scanned images require further intensive analysis using the combination of high resolution digital image and the results of infrared thermography. The deck scanning system can calculate the distressed deck surface area in terms of cracking and delamination. The percentage of distressed area for the total deck surface can be used as a quantitative index to determine the degree of deterioration for each span/lane of the bridge. If we could apply this deck scanning system to the corridor level inspection and determine the condition state for each span/lane of each bridge in the network, the bridge owner can use this information to prioritize the bridge deck repair/rehabilitation program and efficiently allocate the limited budget to obtain the

maximum return on investment for the network level bridge management.
Fig.15 depicts the recommended flowchart for phase-by-phase corridor level bridge deck inspection. The purpose of the first phase of corridor level inspection is to collect the high resolution digital image and infrared inspection results in the field without any lane closure. The Phase 1 inspection generates the edited video image for deck top scanning results with potholes and major crack location identification. The scanned image of the structural members can be used to locate the areas of cracking and delamination and quantitatively summarize the distressed deck areas and determine the condition state for each span/lane of the bridge (Phase 2). Based on the quantitative summary of percentage of distressed deck surface area, the span/lane of the bridge with distressed areas over pre-determined threshold value can be 'flagged' and lined up in the list of 'candidates' for bridge repair/rehabilitation program. Threshold values for percentage of distressed area in determining the AASHTO element level inspection is proposed in Table 3 (edited from the reference, Minnesota Department of Transportation, 2011). The threshold values and decision making indices can be tailored based on the need and requirements of different bridge owners. The outcome of the Phase 2 inspection can be used to pre-screen the bridges possibly being deteriorated or showing symptom of future deterioration, and support the bridge inspection engineers to determine the priority for repair/rehabilitation program in a quantitative matter. Moreover, the new inspection technology provides additional benefits by increasing the level of safety for both inspectors and motorists and storing historical inspection data for the monitoring of crack/delaminated area propagation. In addition, deck underside scanning (Matsumoto, et. al, 2013) may be recommended for selected spans of the bridge deck requiring additional information to further investigate the cause and/or degree of deterioration (Phase 3). The digital record taken by the deck top scanning system can contribute to monitor the progress of damage over time, allowing the bridge owner to monitor the long-term bridge performance and predict the future condition of the bridge deck that would support the better decision on bridge maintenance and management.

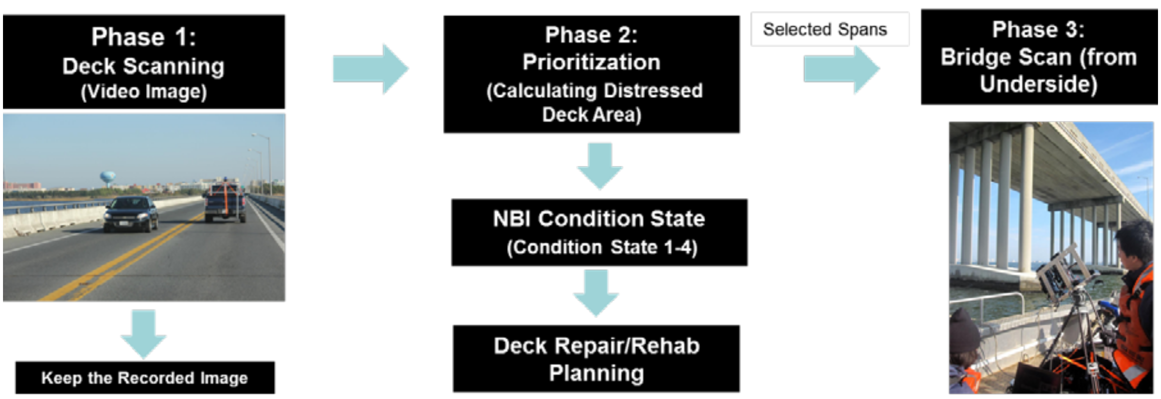


Fig.15: Recommended Flowchart for Phase-by-Phase Corridor Level Inspection

Table 3: Proposed Threshold Values in Determining the Condition States
(edited from MnDOT, 2011)

Condition State	Description
Condition State 1	The combined area of unsound wearing surface (spalls, delaminations, delaminated temporary patches) is 2% or less of the total deck area
Condition State 2	The combined area of unsound wearing surface (spalls, delaminations, delaminated temporary patches) is more than 2% but not more than 10% of the total deck area
Condition State 3	The combined area of unsound wearing surface (spalls, delaminations, delaminated temporary patches) is more than 10% but not more than 25% of the total deck area
Condition State 4	The combined area of unsound wearing surface (spalls, delaminations, delaminated temporary patches) is more than 25% of the total deck area

Summary and Conclusions

(1) The field data collection by deck top scanning system using line sensor cameras and infrared camera was successfully finished without any kinds of lane closure. Cracks with 1/64” (0.3mm) or greater in width and possible delaminated areas were successfully detected by the system.

(2) Combination of line sensor cameras and IR camera system (Deck Top Scanning System) will provide complete information on surface and subsurface conditions of concrete bridge decks and contribute to find a symptom of possible future deterioration in its early stage, allowing the bridge owner to proactively take an action to make a batter decision on repair/rehabilitation planning.

(3) The phase-by-phase corridor/network level bridge inspection described in this paper can efficiently pre-screen the bridges with potential problems and need more detailed analysis to determine the NBI condition states for each span/lane of the bridge deck.

(4) Periodic collection of the data will allow consistent and accurate documentation of structural condition changes over time. For example, temporal subtraction of crack map will present changes of crack widths and lengths, as well as other surface features, between specific times in a concise and scientific manner. This function of the scanning system can replace the ‘in-situ monitoring’ of crack length/width and deformation of the structure.

(5) Selected imaging data and results of periodic temporal subtractions can be prepared in any file format and integrated into the Bridge Management System (BMS), such as Pontis® or bridge inventory database system to provide complete and objective information for better bridge management decisions.

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