EFFICIENT BRIDGE DECK INSPECTION AND ASSESSMENT FRAMEWORK UTILIZING IMAGE-BASED NON-DESTRUCTIVE EVALUATION METHODS

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ABSTRACT

Integrated implementation of infrared thermography (IRT) and high-definition (HD) image technologies has great potential to inspect bridge decks rapidly with reasonable accuracy, resulting in a drastic reduction of inspection time, labor, and budget. These advantages make IRT capable of bridge deck scanning at normal driving speeds without lane closures, which are usually required by traditional methods and other non-destructive evaluation (NDE) techniques. This paper presents several challenges and uncertainties such as data collection time, size of delamination, detectable depth of delamination, camera specifications, and data collection speed using IRT for bridge inspections. Furthermore, those solutions, proper methods and ideal conditions are discussed for applying IRT to enhance its usability, reliability and accuracy for concrete bridge inspections. Field laboratory experiments and a field test at a real bridge were conducted to evaluate the accuracy and reliability of high-speed scanning by IRT with three different types of IR cameras. These tests revealed that a cooled type IR camera used during nighttime hours offers competitive damage identification performance even when utilized at a normal driving speed. When used to compare sound and delaminated locations verified with 8 concrete cores, the accuracy of high-speed scanning with a cooled IR camera outperformed other NDE methods conducted by other researchers under stationary conditions in the past study. Therefore, the use of appropriate IR cameras makes it possible to collect reliable data at highway speeds without lane closures. Thus, IRT becomes a more practical and faster method of conducting bridge deck inspections than other NDE technologies, which mostly require lane closures. Furthermore, condition assessment, recommended bridge management practices according to image-based NDE methods, and a more effective, efficient, economical, and practical bridge inspection framework by means of several NDE technologies are also discussed.

Keywords: Infrared thermography, Non-Destructive Evaluation, Bridge inspection, Bridge management, high-speed scanning

1. INTRODUCTION

In the United States, every bridge as defined by the National Bridge Inspection Standards (23 CFR 650 Subpart C) is required to be inspected at regular intervals not to exceed 2 years (1). Among several components of bridges, degradation of concrete bridges, especially concrete bridge decks, is a widespread problem in the US since most bridge decks are made of concrete (e.g. highway bridges: 93 % - 346 km^2 out of 371 km^2 in bridge deck area as of 2016 (2)) and concrete bridge decks deteriorate faster than other bridge components due to direct exposure to traffic. Furthermore, most state Departments of Transportation (DOTs) spend 50 % to 80 % of their budgets for maintenance, rehabilitation, and replacement of bridges on concrete bridge decks (3). In order to prevent the impending degradation of these bridges, periodic inspection and assessment for proper maintenance are indispensable; thus, better methods are needed to detect defects and quantify the extent and severity of bridge deck conditions early, accurately, and rapidly with minimal traffic impact, ideally, without lane closures (3, 4). Under these circumstances, Non-Destructive Evaluation (NDE) techniques such as high-definition (HD) image-based crack detection, impact echo (IE), ultrasonic surface waves (USW), electrical resistivity (ER), ground-penetrating radar (GPR) and infrared thermography (IRT) have been developed to inspect and monitor aging and deteriorating structures rapidly and effectively in place of visual and sounding inspection methods.

IRT has been developed to detect existing subsurface deteriorations such as delamination and voids in concrete structures while HD techniques have been developed to detect surface defects such as cracks. Integrated implementation of IRT and HD image technologies has great potential to inspect bridge decks rapidly with reasonable accuracy. The great advantage of the combination is the capability for bridge deck scanning at normal driving speeds without lane closures, which are usually required by traditional methods and other NDE techniques. If these technologies are utilized with a vehicle driving at 50 mph (80 km/h), the data collection speed is 800 times faster than an integrated robotic system (e.g. the robotic system can scan 350 m^2 of bridge deck area in one hour (3) while the integrated systems proposed in this proposal scan the same area in 4.5 seconds). By decreasing the preparation and traffic control time, productivity increases substantially, also leading to significant cost reduction. Furthermore, as the number of bridges to be inspected increases, the productivity increases as well, at least 1,000 times more than the other NDE methods since this method can inspect bridge decks while driving the road network at normal driving speeds. In addition, this technology enables more frequent bridge deck inspections, e.g. annual basis, due to the efficiency and speed of the application with less or equivalent cost compared to current practice. This ensures more reliable and proper bridge management due to an increase of inspection record data and prevents serious deterioration of bridges by detecting defects quicker than current practices and enabling proper maintenance with minor repairs, furthering the life of the bridge. This novel technology and its proper implementation as a complimentary method to current practices will not only enhance the productivity of bridge deck inspections, but also avoid social impacts. Therefore, there are great benefits to implementing this innovative method of bridge deck inspection using the combination of IRT and HD systems effectively.

The combination of IRT and HD systems is a promising innovative approach of bridge inspections to reduce inspection time, labor and budget. The use of HD systems at highway speeds has been increasing since the accuracy of surface damage detection highly depends on the image quality, and line camera systems can take high quality visual images even at highway speeds. However, high-speed application of IRT is still mainly in the exploration phase. In fact, some DOTs have been conducting research on high-speed scanning using IRT in the Second Strategic Highway Research Program (SHRP2). In addition, the ASTM standard recommends speeds no greater than 10 mph (16 km/h) for data collection using IRT (5). Therefore, high-speed scanning using IRT is not a standardized method yet. Furthermore, there are several challenges and uncertainties such as data collection time, size of delamination, detectable depth of delamination, camera specifications, and data collection speed using IRT for bridge inspections (6). The authors have been working on IRT to reveal those challenges and uncertainties, and to explore solutions, proper methods, and ideal conditions for applying IRT in order to enhance the usability, reliability and accuracy of IRT for concrete bridge inspections. This paper presents the research progress of the authors for future effective and efficient infrastructure management.

2. EFFECT OF DATA COLLECTION TIME ON IRT RESULT

There are contradictory reports regarding appropriate time frames for IRT measurements. Some researchers recommend daytime data collection while others suggest early morning or nighttime (7). Moreover, Kee et al. (8) reported that no indication was found from the IR image taken 3 hours and 45 minutes after sunrise (even for the shallowest delamination located at 6.35 cm depth) while the IR image of the same test specimen taken 45 minutes after sunrise indicated even 15.24 cm deep delamination. Therefore, the effect of data collection time was investigated to clarify the controversy.

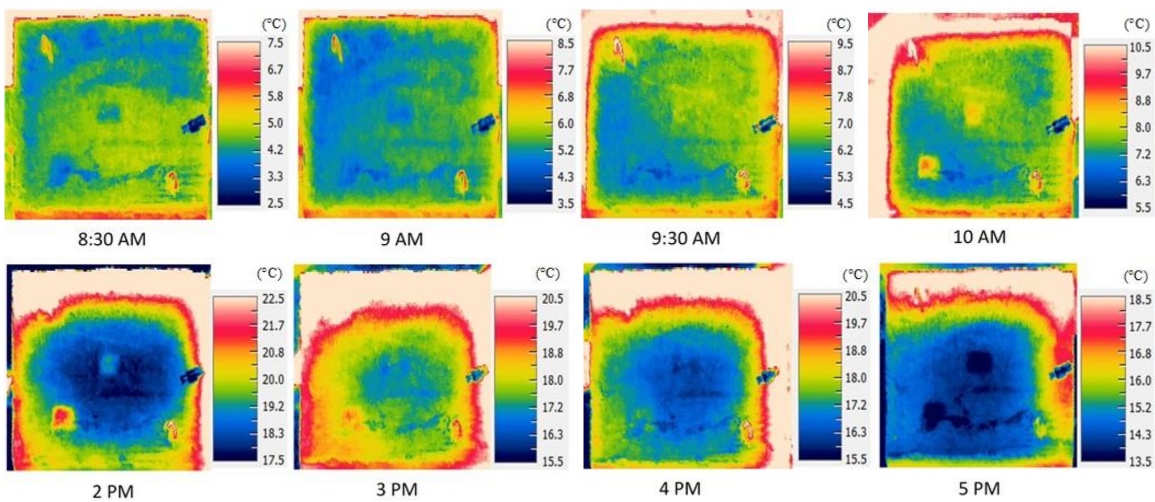


FIGURE 1 IR images for 1.27 cm depth of delamination taken in the morning and evening.

Through field experiments and finite element (FE) modeling, the authors concluded that nighttime application of IRT is the most suitable time window for concrete bridge deck inspections under the natural environment (passive condition) in order to reduce the possibility of misdetection (9). The study found that there are interchange periods between the nighttime cooling effect and the daytime heating effect, and IRT cannot detect delamination during these periods; 9:30 AM, 3 PM and 4 PM in the field tests under the given conditions, as displayed in Figure 1. In addition, through the FE model simulations and the results from IRT data, the period of these interchanges were assumed to be about 1 to 2 hours under the given conditions as shown in Figure 2. Moreover, surface temperature distribution during daytime varies depending on the location due to sunlight, even though the delaminated areas were also indicated clearly during the daytime. Furthermore, as can be seen in Figure 2, if IRT is used during the daytime, there is a possibility that the first or last few hours are an undetectable time zone. On the other hand, if IRT is implemented during nighttime, the maximum temperature difference occurs at night, around 7 PM in this case (one and a half hours after sunset), and then it decreases gradually from that time to the next morning; subsequently, reaching the interchange point a few hours after the sunrise. Hence, if IRT is applied after sunset, there is enough time until the interchange point of the next morning. It should be noted that if IRT inspection starts in the early morning, there is a high possibility to reach the interchange period during the bridge inspection.

Regarding the effect of seasonal environment, Hiasa (9) investigated the effect using FE modeling by simulating different seasons of temperatures in Orlando, FL from the weather record; 4/24/14 as spring, 9/2/14 as summer, 11/4/14 as fall, and 1/21/15 as winter. In each season, the days without any rain the whole day were selected for the FE modeling. Even though the surface temperatures of the concrete model differ at most 14.9 °C between summer and winter conditions, there were no significant differences regarding thermal contrast between sound and delaminated areas, at most 0.05 °C, depending on the season under the given condition.

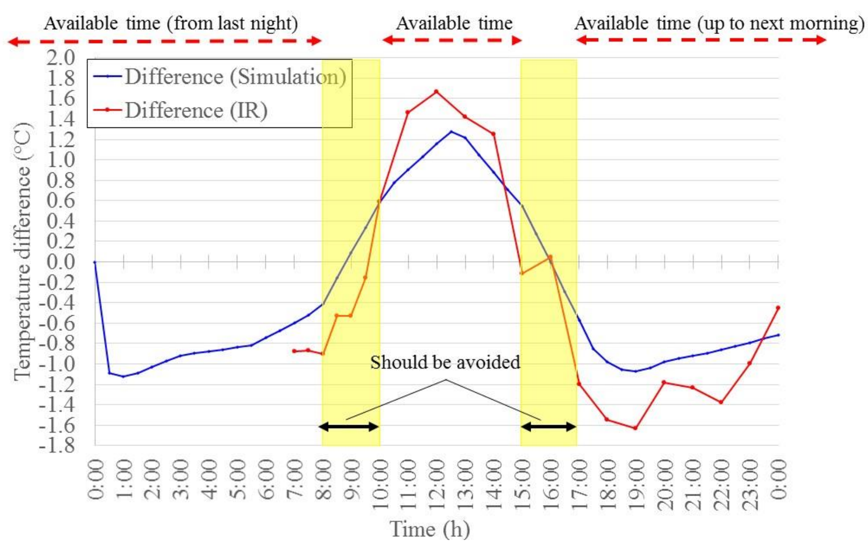
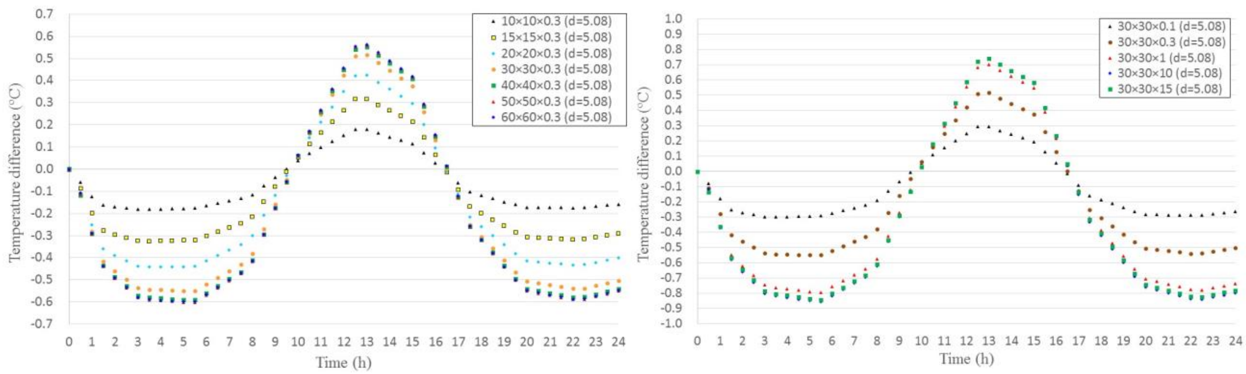


FIGURE 2 Available time window for IRT application.

3. EFFECT OF DELAMINATION SIZE ON DETECTABILITY OF IRT

Size of delamination is one of the most critical factors for detectability of IRT. Some researchers indicate that it affects the detectable depth of the delamination; as the size of the delamination increases, the temperature difference between sound and delaminated area also increases (10). However, the past studies on IRT have been conducted with limited experimental setups and limited conditions that would make a difference in delamination detection due to the difficulty of making and handling the large test specimens required to simulate bridge conditions. In order to overcome this limitation, FE model simulations were utilized to explore sensitive parameters for effective utilization of IRT. These simulations revealed that the most critical factor is the area of delamination; subsequently, the thickness affects the temperature difference of the surface. The volume of delamination is not a significant parameter for detection using IRT. In addition, the FE modeling also showed that as the area increases, the impact of the thickness also increases (9). Furthermore, the FE model simulation indicated that the effect of delamination size (temperature difference between sound and delaminated areas) converges to a certain value when the area is 40 × 40 cm and the thickness is 1 cm under the given conditions (11).

Figure 3.(a) depicts surface temperature differences (ΔT) between sound and delaminated areas; several models with square shaped delamination of 0.3 cm thickness located at 5.08 cm depth were simulated and compared. It is obvious that the area of the delamination strongly affects ΔT since ΔT increases as the area of delamination increases; however, ΔT converges to a certain value when the delamination area is approximately 40 × 40 cm. Furthermore, Figure 3.(b) illustrates the ΔT of each delamination with 900 cm^2 (30 × 30 cm) area at 5.08 cm depth. The result shows the thickness of delamination also affects ΔT, and as the thickness increases, the effect also increases. In addition, the effect of thickness also converges to a certain value of ΔT when the thickness of delamination is about 1 cm.



(a) Effect of area (L × L × 0.3 cm at 5.08 cm depth) (b) Effect of thickness (30 × 30 × L cm at 5.08 cm)

FIGURE 3 Effect of delamination size for damage detection by IRT.

In terms of delamination detectability by IRT, Clark et al. (12) found the effective delamination detection range of ΔT to be approximately 0.2 – 0.3 °C. Hiasa (9) found that within ± 0.3 to 0.4 °C of ΔT is the undetectable band of ΔT for IRT. Even though, more experimental data under different experimental and environmental conditions may be needed, it can be assumed that within approximately ± 0.2 °C of ΔT is a probable range for undetectability, between ± 0.2 to 0.4 °C is a range for probable detectability, and above ± 0.4 °C is an almost certain range for detectability using IRT as shown in Figure 4. IRT may be able to detect delamination that exist at 5.08 cm depth with dimensions of 15 × 15 × 0.3 cm or larger because such delaminations generate more than 0.3 °C of ΔT as shown in Figure 3.(a), which exceeds the probable range for undetectability of approximately ± 0.2 °C.

FE model simulation clarified that detectability is highly dependent on the size of delamination. However, it should also be considered that a defect is easier to be detected as its area is widened, increasing the severity of the delamination. Usually, bridge administrators make maintenance plans in order of severity of bridge conditions, and even if they find a minor defect, they might leave it as it is and keep monitoring it for several years until it becomes a severe defect. Therefore, even if IRT cannot detect small and/or deep defects which can be considered as minor damage at that time, the limitation is not a serious problem since those defects do not require immediate repair work. It should be noted that since a delamination at a maximum depth of 15.24 cm (6 in.) was detected in other research (8), the capability of damage detection regarding the detectable depth is highly competitive compared to other NDE methods. IRT has some challenges for subsurface damage detection of concrete structures due to its limitations under certain conditions and technology, such as data collection time and size of defect; however, the authors' work shows the potential for significant improvement of IRT to conduct efficient and effective bridge inspection.

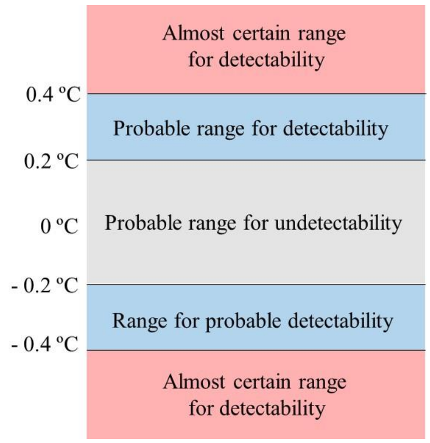
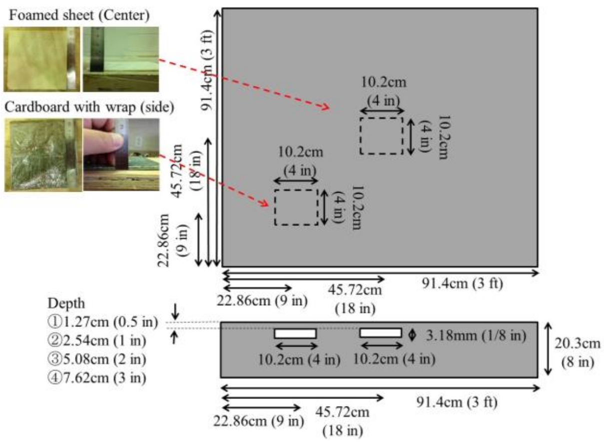


FIGURE 4 Assumed potential detectable and undetectable ∆T range.

4. EFFECT OF DATA COLLECTION SPEED AND IR CAMERA SPECIFICATIONS

An advantage of digital image scanning is the high-speed of data collection as mentioned above; however, when IRT is utilized while driving at normal speeds, there is a possibility that data collection speed may affect the results (13). It should be mentioned that less than 16 km/h (10 mph) is recommended for data collection speed according to the ASTM standard (5). The IR camera specifications might also affect the result of IRT along with data collection speed. IR cameras can be classified into two types according to their detector type: thermal detectors and quantum detectors. These are often called uncooled and cooled detectors, or cameras, respectively. Typically, uncooled cameras have lower costs and a broader spectral response than cooled cameras, although their response is much slower and less sensitive than cooled cameras (14). Even though some literature points out the effect of IR camera specifications on detectability, most of the research on IRT has been conducted with one IR camera, and mostly uncooled cameras have been utilized due to their low costs. Therefore, the effect of camera specifications on IRT is not discussed sufficiently yet, and if IRT is utilized for high-speed application, there is a possibility of obtaining different results depending on IR camera specifications. Thus, comparative studies at normal driving speeds were conducted to investigate the effect of data collection speed along with camera specifications.

The field experiment utilized 4 test specimens with artificial delamination of the same size at different depths as shown in Figure 5.(a). In this test, three types of IR cameras with different specifications (T420, T650 (uncooled camera) and SC5600 (cooled camera) manufactured by FLIR Systems, Inc.) were used to evaluate the impact of camera specifications when IRT is utilized for defect detection of subsurface concrete structures. As shown in Figure 5.(b), 4 concrete test specimens were set up along the roadside. Concrete blocks were put on wooden stands and pallets to make space through which wind could blow under the concrete slabs as shown in the picture. IR images were taken from a vehicle equipped with the three IR cameras at the same time while driving down the road at varying speeds, from 0 to 48 km/h (30 mph). 0 km/h refers to an idling stop, so that the engine was working during the photography. Therefore, there was some vibration of the car due to idling even when the speed was 0 km/h. IR images were taken at multiple times, 9 AM, 3 PM, 8 PM and 12 AM (midnight). This field laboratory experiment proved that a cooled camera detected delamination very accurately even when it was utilized with a moving vehicle at normal driving speed as shown in Figure 6 (SC5600). On the other hand, uncooled cameras were strongly affected by data collection speed (some of them were affected by even the vibration caused by the idling of the car) as shown in the figures of T420 and T650 (15). When uncooled cameras were used from a moving vehicle, their area of damage detection became larger than those taken at 0 mph as shown in Figure 6.



(a) Dimensions of test specimens

(b) Test situation

FIGURE 5 Dimensions of test specimens and situation of the field laboratory experiment.

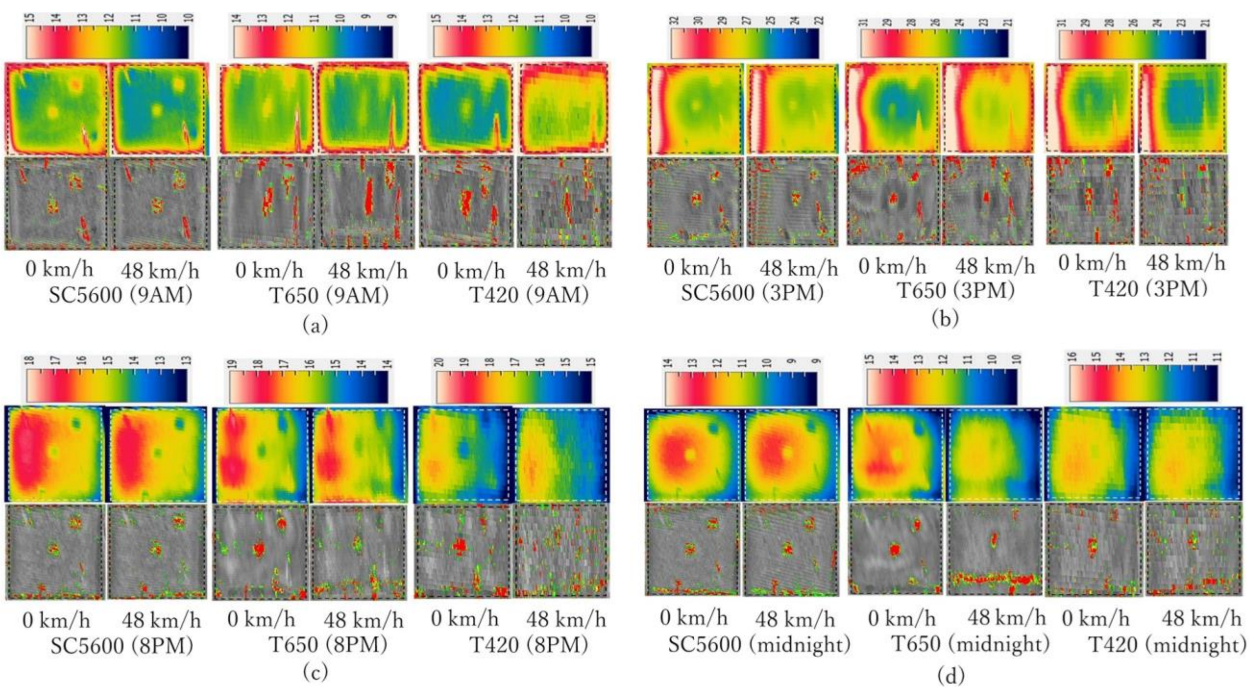
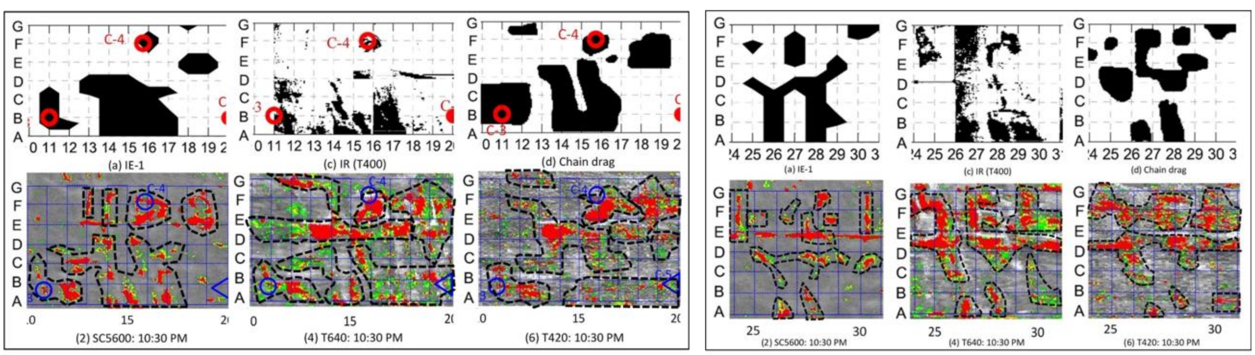


FIGURE 6 Effect of data collection speed (up: raw IR images, down: processed IR images).

Furthermore, another comparative study was conducted on a bridge where other researchers implemented bridge inspection with several NDE methods (16, 17). When the results from sound and delaminated locations verified with 8 concrete cores in past research (5 sound and 3 delaminated cores) were compared, it was found that a cooled camera (SC5600) distinguished all sound and delaminated areas accurately, while uncooled cameras (T640 and T420) showed several False Positive (FP) misdetections, which indicated sound areas as delaminated areas. Moreover, the location and shape of delamination obtained by three IR cameras were compared to other NDE methods from past research, and the result revealed that the cooled camera showed almost identical shapes to other NDE methods such as impact echo (IE) and chain drag, which provided accurate results in the past research, as shown in Figure 7. It should be noted that the data were collected at a normal driving speed without any lane closures, thereby making it a more practical and faster method than other NDE technologies. On the other hand, both uncooled cameras showed a relatively larger delamination area than other methods, which would lead to excessively detailed inspections. This result indicates that these two cameras were affected by high-speed applications. Although these two cameras can detect delaminations, there is a high probability that the identified areas are larger than the actual size (FP misdetection).

Through a field laboratory experiment and field test on a bridge, it was found that the factor most likely to be affected by data collection speed is the integration time (shutter speed) of an IR camera, and short integration time cameras are not affected by data collection speed (15, 18). Therefore, cooled cameras are the ideal devices for high-speed bridge deck scanning since cooled detectors have much shorter integration time than uncooled detectors. However, this is not widely known in the field of NDE and usually uncooled IR cameras have been used for past studies due to economic reason. Thus, when high-speed bridge deck scanning is conducted by IRT, IR camera specifications must be considered carefully. These studies proved that a cooled type camera detected delaminations very accurately even when it was utilized from a moving vehicle at a normal driving speed. On the other hand, uncooled cameras were strongly affected by data collection speed, and when they were used from a moving vehicle their damage indication area became larger than those taken under stationary condition.



(a) 10 to 20 of Horizontal Test Coordinate (b) 24 to 31 of Horizontal Test Coordinate

FIGURE 7 Comparison of indicated shapes of delamination (Source (upper three): *(17)***).**

5. BRIDGE MANAGEMENT USING IMAGE-BASED NDE METHODS

The accuracy and reliability of IRT, especially in high-speed applications, were evaluated in consideration of data collection time, size of delamination, data collection speed, and IR camera specifications by field laboratory experiments using test specimens with known defects and a field test at a real bridge in a comparison to other NDE techniques used by other researchers. Through these studies, it was found that high-speed scanning by IRT with a cooled type IR camera during nighttime offers competitive damage identification performance compared to other NDE methods such as IE, GPR and chain drag. Therefore, the use of appropriate IR cameras makes it possible to collect reliable data at highway speeds without lane closures. Thus, IRT becomes a more practical and faster method of conducting bridge deck inspections than other NDE technologies, which mostly require lane closures.

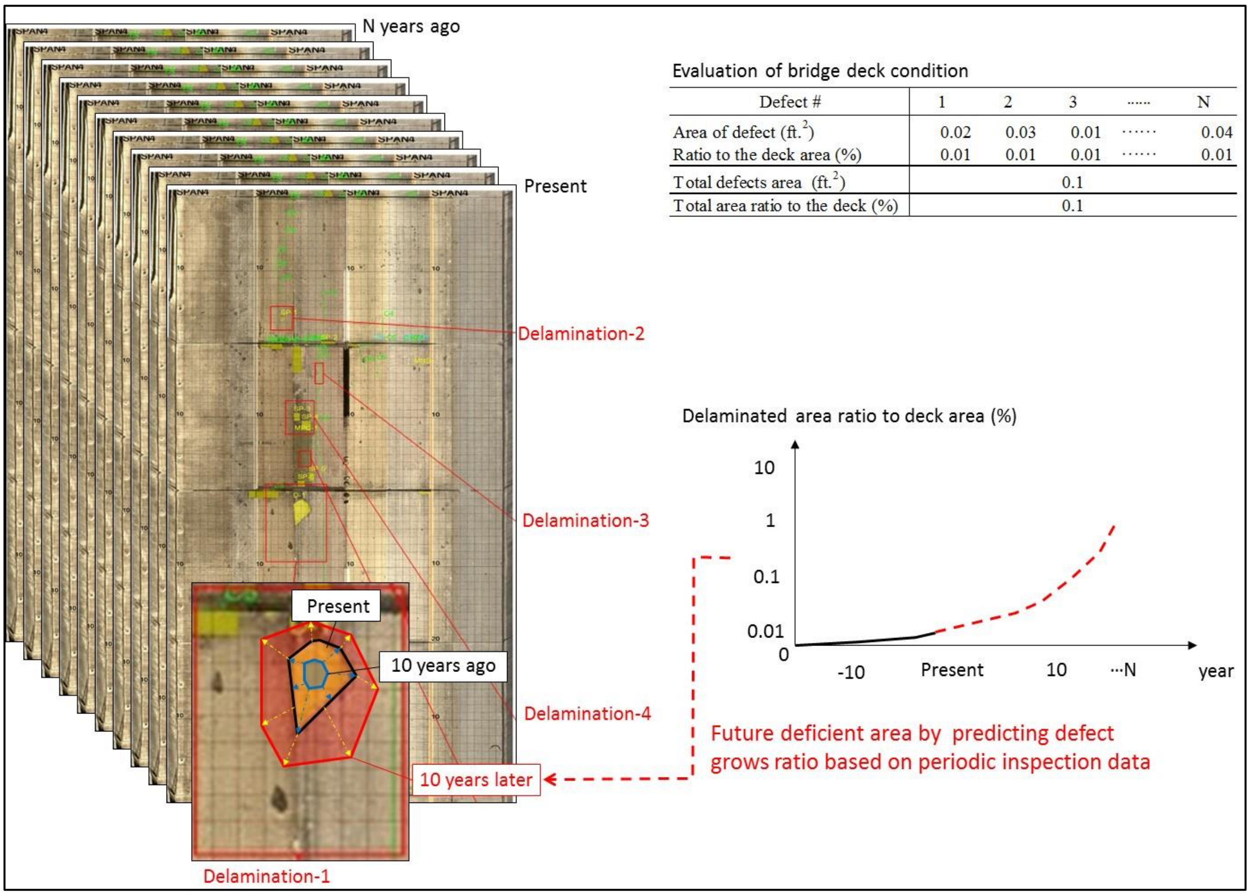


FIGURE 8 Example of utilization of IRT for bridge management.

Regarding the bridge management based on high-speed scanning using IRT with HD systems, by superimposing detected delaminations from IRT on visual images of bridge decks as shown in Figure 8, the deficiency map can be made to show locations of each defect of the bridge deck. Since HD systems detect defects visible from the surface, such as cracking, by combining scanned data from these two technologies, engineers can easily see both visible and invisible defects and understand the severity of the deck condition visually. Since sounding inspections require measurements and recording of each size of defect after the defect is found by on-site inspection, it requires extra inspection time and labor work at the site. On the other hand, once an IR image is taken and a defect is found from the data, it is possible to measure the quantity from the image easily after the inspection; i.e. IRT can reduce not only inspection time, but also measuring and recording time of the result and condition assessment time significantly.

Furthermore, IRT enables bridge administrators to conduct frequent inspections, making it possible to predict more reliable future condition of the bridge based on the periodic inspection data. Figure 8 depicts the example of how to utilize periodic IRT data. In each inspection time, delaminated areas are depicted on the visual image and those areas are calculated and listed by each defect, as can be seen in the table. Then, each defect's growth can be predicted statistically based on the inspection data; consequently, total deficient area is also predictable. Thus, the combination of IRT and HD systems has great potential for not only increased data collection speed, but also improved condition assessment and bridge management.

6. CONCLUSION FOR EFFICIENT AND EFFECTIVE BRIDGE INSPECTION

As presented in this paper, IRT sometimes fails to detect some defects (e.g. small delamination at deep locations) depending on several conditions which might affect the detectability of IRT, such as data collection time, data collection speed, and IR camera specifications. However, the data collection speed is a great advantage for periodic bridge inspections compared to other NDE methods, and engineers can maximize the advantages for bridge inspections, especially for network level inspections, by understanding the limitations and capability of IRT as discussed in this paper. There is great potential to significantly reduce inspection time, labor, and budget if high-speed bridge deck scanning by IRT and HD systems becomes a standard bridge deck inspection method. Even though IRT presented a high level of performance throughout the study, it can be construed that IRT is not a perfect method for damage detection of concrete bridge decks. Therefore, to complement the imperfections of IRT, conventional methods or other NDE techniques, such as sounding tests and robotics-assisted systems, should also be utilized at intervals greater than the minimum requirement, currently 2 years, for a more comprehensive and detailed diagnosis of concrete bridge decks. As shown in Figure 9, bridge inspections at the local level have potential to be more effective, efficient, economical, and practical than current practices by performing frequent inspections at 1 to 3 year intervals on most bridge components using IRT and HD systems, and at 6 year intervals, or greater, using other time-consuming methodologies.

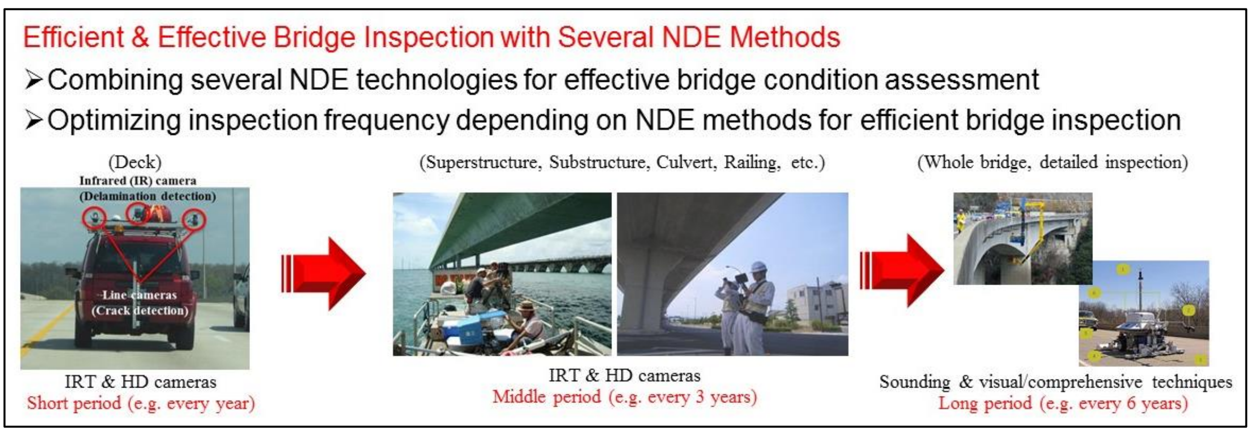


FIGURE 9 Example of utilization of IRT for bridge management.

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