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A data processing methodology for infrared thermography images of concrete bridges

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ABSTRACT

This study presents a methodology to improve the usability and efficiency of infrared thermography (IRT) for subsurface damage detection in concrete structures. A practical and more objective approach to obtain a threshold for IRT data processing was developed by incorporating finite element (FE) model simulations. Regarding the temperature thresholds of sound and delaminated areas, the temperature of the sound part was obtained from the IR image, and the temperature of the delaminated area was defined by FE model simulation. With this methodology, delaminated areas of concrete slabs at 1.27 cm and 2.54 cm depths could be detected more objectively than by visually judging the color contrast of IR images. However, it was also found that the boundary condition affects the accuracy of the method, and the effect varies depending on the data collection time. On the other hand, it can be assumed that the influential area of the boundary condition is much smaller than the area of a bridge deck in real structures; thus, it might be ignorable on real concrete bridge decks. Even though there are some limitations, this methodology performed successfully paving the way towards automated IRT data analysis for concrete bridge deck inspections.

1. Introduction

Degradation of reinforced concrete bridge decks is a widespread problem in the United States. Concrete bridge decks deteriorate faster than other bridge components due to direct exposure to traffic. Moreover, the Federal Highway Administration's (FHWA's) Long Term Bridge Performance (LTBP) Program identified that the most important bridge performance issue was the performance of concrete bridge decks [1]. Cracking, spalling, and delaminations were common defects requiring maintenance and rehabilitation. Most State Departments of Transportation (DOTs) noted that repair, rehabilitation and replacement of concrete bridge decks account for 50–80% of their budgets for maintenance of bridges. These State DOTs are seeking methods to detect defects and quantify the extent and severity of bridge decks early, accurately, and rapidly with minimal traffic impact, ideally, without lane closure for inspections [1,2]. Furthermore, FHWA [3] requires biennial inspection of every highway bridge in the National Highway System (NHS). Therefore, Non-Destructive Evaluation (NDE) methods are desired to inspect bridge decks efficiently and effectively. Consequently, NDE techniques are being developed to examine and monitor deteriorating structures rapidly and effectively [4]. Most NDE methods aim to achieve the highest quality of visual imaging of the relevant internal features of structures [5,6]. However, there is still no international standard NDE methods for concrete bridges, although significant progress has been made towards an internationally common approach to NDE inspection [6]. As Gucunski et al. [1] reports, one of the limitations of NDE methods for bridge inspection is the speed of data collection.

Infrared thermography (IRT) is one of the NDE methods and has been developed to detect invisible deteriorations including delaminations and voids in concrete structures with reasonable accuracy; it also helps avoid the time and expense of gaining immediate access to the concrete surface to conduct traditional sounding tests. IRT is a suitable approach for inspection of civil infrastructures since it is a non-contact method and infrared (IR) images can instantly portray a wide range of concrete structures at one time [7–10]. Therefore, IRT can be the fastest and easiest NDE methodology regarding data collection among the other NDE methods, even though there are some limitations and

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uncertainties in using IRT for bridge inspections such as data collection time, size of delamination, camera specifications, data collection speed and data interpretation.

The objective of this study is to develop a methodology of how to objectively interpret and detect delaminations from IR images since it becomes very subjective judging whether or not the color contrast of the image is a damage indication. As Washer et al. [11] argued, if the temperature span for IR images is setup too high or too low, it appears in the IR image as if there is no anomaly even though there are some defects. Therefore, they recommended adjusting the temperature span of IR images continuously throughout inspections. However, it might require a lot of work during or after the bridge inspection. This study consequently explores a more objective method than just comparing IR images to assess IRT data. Kee et al. [12] and Oh et al. [13] processed IRT data mathematically by using MATLAB with certain thresholds defined by iterative trials until the operator obtained the clearest contrast between the sound and delaminated regions within each IR image. However, this procedure is very subjective since the operator has to determine whether the contrast depicts damaged or sound regions, even though these regions are usually unknown areas in terms of existing defects. Processing IRT data mathematically is more objective than judging the data from the color contrast since it does not require a temperature span setting as mentioned above. However, how to determine the thresholds, in other words, how to obtain the information of temperature difference between sound and delaminated areas becomes a challenge for their methodology to process mathematically without subjective trials.

Hiasa et al. [14] proposed a data processing method; however, it was also discussed how obtaining the information of temperature difference between sound and delaminated areas becomes a challenge. In this study, an easier and more objective method to obtain the threshold for IRT data processing is explored by incorporating finite element (FE) model simulations. The use of FE model simulation has been increasing recently to simulate the temperature distribution of the object's surface [7,15–19]. In the past study, Hiasa et al. [20] employed the FE model simulation to explore sensitive parameters for effective utilization of IRT without a large number of experiments, which require extremely time-consuming work. This study uses the FE model developed in the past study. The aim of this study is twofold: to obtain information regarding the temperature difference between sound and delaminated areas from FE modeling, and to process IRT data in order to objectively detect invisible subsurface delaminations. In this study, the IRT data obtained from a field laboratory experiment under passive IRT conditions [21] are used to develop a more objective data processing method with the combination of FE model simulation.

2. Current practice and future potential of infrared thermography for bridge inspection

Through literature reviews, several factors that might affect the performance of IRT can be excerpted such as data collection time, size of delamination, data collection speed and IR camera specifications. In terms of data collection time, Washer et al. [22,23] recommended daytime measurements of 5–9 h after sunrise to detect subsurface delaminations for the solar loading part. On the other hand, Gucunski et al. [24] mentioned that a thermal image recorded 40 min after sunrise yielded a much clearer image than another one recorded around noon. Additionally, Yehia et al. [25] found that the response of delaminations were described as weaker in IR images as the time approached 3 PM. Moreover, Kee et al. [12] also concluded that no indication was found from the IR images taken 3 h and 45 min after sunrise (with the shallowest delamination located at 6.35 cm depth) while the best results were achieved using the cooling cycle in which even 15.24 cm deep delaminations could be detected. Furthermore, Watase et al. [26] proposed a favorable time for inspection depending on the parts of the bridge; noon time for the deck top, and midnight for the deck soffit. Through a field laboratory experiment and FE modeling, Hiasa [27] concluded in his Ph.D. dissertation that the preferable time period to apply IRT for concrete bridge deck inspection is during the nighttime cooling effect in order to reduce the possibility of misdetection due to sunlight, even though the delaminated areas were also observed clearly during the daytime heating period in the study. Hiasa [27] also found that there are interchange periods between the nighttime cooling effect and the daytime heating effect about 1–2 h in the morning and evening under the given conditions, and IRT cannot detect delaminations during these periods. This can be considered as the cause that several researchers concluded different results; the reason why Kee et al. [12] could not detect delaminations from the IR images taken 3 h and 45 min after sunrise can be due to that time was the interchange period from cooling to heating cycles. Regarding Yehia et al. [25], 3 PM might be close to the interchange period from heating to cooling cycles under the experimental condition. It can also be considered that Gucunski et al. [24] captured clear IR images during the cooling cycle effect in the early morning while Washer et al. [22,23] took IR images during the heating cycle effect.

Regarding the effect of delamination size, some researchers indicate that the size of delamination affects the detectable depth of the delamination [25,28–30]; however, different size of artificial defects have been utilized in their studies and they reported different detectable depths using IRT for inspections. While Cheng et al. [29] could not detect even 3 cm depth of delamination ($5 \times 5 \times 7$ cm in size) in their experiment, Kee et al. [12] detected 15.24 cm depth of delamination ($61 \times 61 \times 0.1$ cm in size) in their studies. The past studies on IRT were conducted with limited experimental setups and limited conditions which make a difference in delamination detection due to the difficulty of making a large number of test specimens since those specimens become relatively huge to simulate concrete bridges. In order to overcome the limitation, Hiasa et al. [20] utilized FE model simulation to explore sensitive parameters for effective utilization of IRT. Through the FE model simulations, it was found that the most critical factor is the area of delamination; subsequently, the thickness affects the temperature differences of the surface between sound and delaminated areas. The volume of delamination is not a significant parameter for interior damage detection using IRT. In addition, the FEM analysis also shows that as the area is getting larger, the impact of the thickness is also increasing. Therefore, differences in delamination size can be considered as the cause that past research concluded different detectable depths by IRT; smaller delaminations were detected at only shallower depths while larger delaminations were detected at deeper locations. As it was clarified by FE model simulation, the detectability is highly dependent on the size of delamination. However, this can also be considered that as a defect increases the severity by widening the area, the easier it is to be detected by IRT. Usually, bridge administrators make maintenance plans in order of severity of bridge conditions, and even if they find a tiny/light 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 taken into account as minor damage at that time, the limitation is not a serious problem since those defects do not require immediate repair work [27].

In regards to the effect of data collection speed and camera specifications, Hiasa et al. [21,31] conducted comparative studies with three different types of IR cameras at a normal driving speed, from 48 to 64 km/h (30–40 mph). It was found that if shorter integration time devices, which cooled type cameras are typically