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Study on Defect Detection Technology for Bridge Deck Pavements

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Abstract: The bridge deck is the most vulnerable part of a bridge over its life cycle. The deck pavement is often adversely affected by improper construction methods, the aging of concrete, and corrosion of steel bars, which adversely impact the structure and overall performance of the bridge. Therefore, it is necessary to determine the defects related to the bridge deck and to conduct relevant quality evaluations. This article describes the mechanism, application methods, and testing equipment of four mainstream nondestructive testing technologies used worldwide: ground penetrating radar, half-cell potential, impact echo, and infrared thermography. One or more of these methods can be used to accurately assess the deterioration of the bridge deck and make a rapid, nondestructive evaluation, which provides technical support for rapid detection and accurate evaluation of the deck situation. This leads to reduced structural defects and an extended bridge life cycle.

Keywords: bridge deck pavement; defect; nondestructive testing

1 Introduction

The United States is one of the most densely populated countries in the world in terms of basic transportation networks. There are millions of kilometers of roads throughout the United States. The interurban road is over 3×10^5 km, which includes tens of thousands of bridges [1]. In addition to the increasing demand for travel, the convenience of transportation has become a basic human right. A report issued by the American Society of Civil Engineers (ASCE) in 2013 stated that the assessment of the bridge is only C+ level (points A, B, C, D at four levels) [1]. Over 200 million people travel on defective bridges in 102 metropolitan areas in the United States. To address the structural deficiencies associated with bridges, the Federal Highway Administration (FHWA) estimates that 20.8 billion USD will be spent annually by 2028. In fact, the current annual investment is only 12.8 billion USD. To address the maintenance costs required for all bridges with structural defects across the country, states and local governments need to invest an additional 8 billion USD each year on bridges [2].

The bridge deck is the most vulnerable part of the bridge throughout its life cycle. This is mainly due to the use of salt to remove ice in winter, which leading to corrosion of the steel bars. Therefore, the bridge deck must be repaired and replaced frequently. Currently, the main methods used to judge the status of the bridge deck in the United States are the visual inspection and the chain drag method. In addition, considering the importance of bridges in the transportation system, it is important to detect and evaluate the deck condition quickly. This paper introduces some commonly used detection techniques, including destructive testing and non-destructive testing.

2 Destructive testing methods on bridge deck

In the testing of pavement and bridge decks, the drilling coring machine can core cement concrete with higher strength, as shown in Fig. 1. Then, the strength and thickness of the core sample are checked to observe its internal compactness. Asphalt concrete can also be cored and its thickness, density, compaction, porosity, oil-rock ratio, and Marshall stability can be checked. In

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(a) Petrol-driven drilling and coring machines (b) Site core samples

Fig. 1. Core drilling machine coring of cement concrete.

addition, the deck pavement drilling can determine the presence of the pavement and beam between the binding surfaces.

3 Non-destructive testing methods on bridge deck

The traditional non-destructive inspection of the bridge deck relies mainly on visual inspection and the chain drag method. Visual inspection is conducted on the basis of the annual inspection. The numbers provided by the inspectors are in the range of 0–9, where level 0 means complete damage, level 9 means undamaged [3]. Inspectors used visual inspection to locate the cracks, weathering, moisture deterioration, and other diseases on the surface of the bridge deck. However, an in-depth analysis of the reliability of this method showed that the evaluation of the bridge deck by this method is not reliable. In addition, there is a significant difference in the evaluation by different inspectors for the same deck.

The chain drag method is also a non-destructive test method. A vibration deck is dragged over the surface of the bridge, and the detector detects vibration in the chain to determine the source of the bridge deck problems. However, the analysis of this method shows that it can only be applied if the bridge deck has a large damaged area. In addition, similarly to the visual inspection, evaluations of the same bridge deck by different inspectors are also very different.

3.1 Half-cell potential method

The American Society for Testing and Materials (ASTM) standard C876 [3] provides guidelines for determining the corroded area of steel rebar inside the bridge deck. For example, when the voltmeter in the test equipment shows a voltage below −350 mV, the probability of internal steel corrosion is 90%. Similarly, when the voltmeter shows voltages above −200 mV, the probability of internal steel corrosion is 10%. The half-cell potential (HCP) method layout is shown in Fig. 2, where the reference electrode is a copper-copper sulfate electrode. The electrode is on the concrete surface with one end of the reference electrode connected to the voltmeter and the other to the exposed steel. The higher the corrosion on the reinforcement, the lower the voltmeter reading [4].

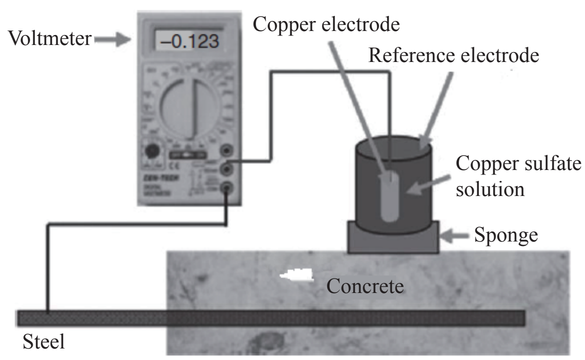

Fig. 2. HCP layout.

3.2 Ground penetrating radar method

During the inspection of bridge deck, ground penetrating radar (GPR) at high frequency (1–3 GHz) scans the bridge deck rapidly in running direction. The GPR signals differs between the corroded and non-corroded rebar. Therefore, the GPR method can be used to evaluate the deterioration status of the bridge deck.

The ground-coupled unipolar GPR data acquisition is shown in Fig. 3. To allow the testing equipment to move across the deck, the antenna is connected to a wheeled cart and a data acquisition unit that displays real-time data for real-time inspection as data is acquired. To obtain detailed information on each rebar on the bridge deck, the bridge deck width and length are inspected and data collected at 1- and 2-cm intervals, respectively. Data

Fig. 3. GPR data acquisition.

is usually processed after all the data has been collected, including the amplitude, time, and coordinates of each reinforcement inspection signal.

In China, with the continuous development of new and high-level technology and the continuous emergence of new materials, GPR technology has also gained rapid development. Thus far, GPR technology has been widely used in many fields such as road crack detection, underground hole detection, buried underground structure detection, and engineering geological exploration. In 2007, Luo [5] used GPR data acquisition for the detection, signal processing, and image recognition of bridge defects, by monitoring pavement structure layer thickness, damage conditions, and hidden dangers, and achieved the application of detecting hidden cracks in the road and the hollow roof of the bridge. In 2012, Guo et al. [6] adopted electromagnetic scattering superposition to analyze the electromagnetic wave response characteristics of vertical and oblique cracks, detecting the cracks and thickness of the hollow slab quickly and accurately, and provided a more comprehensive technical data. In 2012, Pan et al. [7] used GPR to detect whether the thickness of the protective layer of the steel bar of a bridge meets the design requirements using the principle of electromagnetism difference nondestructively and efficiently.

3.3 Impact echo method

The impact echo (IE) method is mainly used to determine the location, thickness, and degree of damage in the layered area of reinforced concrete. The IE inspection equipment is shown in Fig. 4. It works by propagating sound waves generated by mechanical excitation or shock waves in concrete, and reflecting them to the sources of impact when the sound waves encounter the interface between concrete and air—usually at the bottom of the delamination zone or bridge deck. After receiving the reflected wave, the receiver converts the time-domain data to frequency domain data using the fast Fourier transform formula, and then determines the frequency peak f of the echo to calculate the thickness or defect of the concrete:

$$d = V/2f \tag{1}$$

where d is the depth of stratification or concrete thickness, in (1 in≈2.54 cm); V is the specified speed of the stress wave, in/s; and f is the peak frequency of the recorded wave, Hz.

If the calculated thickness is equal to that of the deck, then that part is not delaminated. To determine the size of the stratified or defective areas more accurately, the bridge deck is meshed before testing and collecting the measurement information along the grid.

Zhang et al. [8] studied the feasibility of the IE method in the local accurate detection of reinforced concrete bridges. In single-sided testing, 2D or 3D images were formed and the reflected signals were analyzed directly to judge the defects, delamination, thickness of steel mesh protection layer, and the phenomenon of steel mesh sink accurately.

3.4 Infrared (IR) thermal imaging method

Infrared equipment that has been used to measure the radiation temperature of materials has been used in bridge concrete defect detection. IR detection can detect concrete delamination and voids quickly. The concentration of stress due to reinforcement corrosion can lead to deterioration of the concrete above and below the rebar, resulting in small voids in the vicinity of the rebar where the delaminates and the delamination of the concrete initiate. Delamination blocks the propagation of heat along the slab so as to change thermal distribution; sensitive infrared cameras capture the layered area, and the gap area represents a “hot spot” [9].

The infrared data acquisition area includes the full position of the bridge deck. Vehicles equipped with infrared devices collect data at approximately 30-cm intervals during operation. The original image is shown in Fig. 5. After the data is collected, the data analyst uses dedicated software to process the image into a single strip of images for each lane. During the analysis, each image is integrated with the reference temperature to adjust for

Fig. 4. Impact echo (IE) testing equipment.

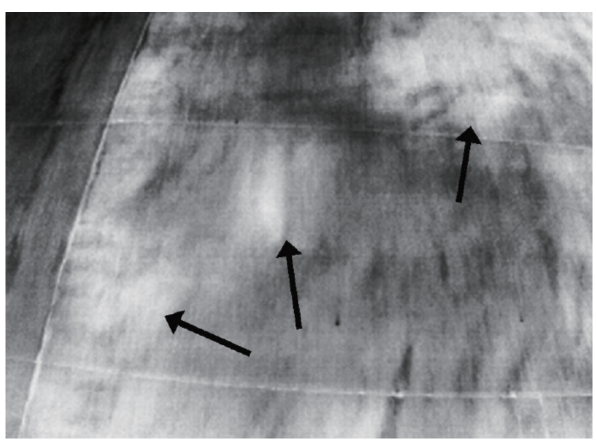

Fig. 5. Typical raw image with arrows showing layered areas.

temperature fluctuations caused by wind, passing vehicles, or other factors, and the striped image of each channel is placed next to the adjacent channels to generate a thermal image of the entire surface.

When the concrete is damaged and loose, the strength is reduced. The temperature distribution of these loose parts is significantly different from that at intact sites; this difference in the infrared thermal imager shows the "hot" and "cold" spots clearly in areas of damage. As shown in Fig. 5, the white spots indicate the stratified or void zone. The abnormal area in each image is indicated with arrows, and then mapped and quantified. Figs. 6 and 7 show the composite infrared thermal image and the resulting mapping, respectively.

To evaluate the delamination of bridge deck concrete and the corrosion of steel bars quickly and accurately, various sensing technologies have been developed in recent years. Table 1 lists the current commercial sensing technologies used to evaluate bridge decks.

In recent years, infrared detection technology has developed rapidly; in particular, there has been a breakthrough in uncooled infrared focal plane array technology, and infrared thermal imaging technology has become a popular international concern. In China, infrared thermography has been widely used in the temperature detection of asphalt pavement construction. In terms of material defect detection and evaluation, the non-destructive testing method of infrared thermal imaging based on the electrothermal effect of carbon fiber concrete was proposed by Huang et al. from Wuhan University of Technology; the transient thermal conductivity temperature analysis model and the defect body of the carbon fiber concrete infrared thermal imaging method were established in an electrothermal coupled finite element analysis model. In addition, researchers at Harbin Institute of Technology, Northern Jiaotong University, Southeast University, South China University of Technology, Xi'an Jiaotong University, Tianjin University, and other universities conducted systematic and in-depth studies, and generated some valuable research results for the testing and evaluation of materials and components of state, which laid the theoretical and experimental foundation.

4 Conclusions and prospects

Based on the domestic and international bridge deck non-destructive testing technology literature, the author introduces four main kinds of non-destructive testing technology. After decades of development, the existing testing technology and equipment and functions are very mature and accurate.

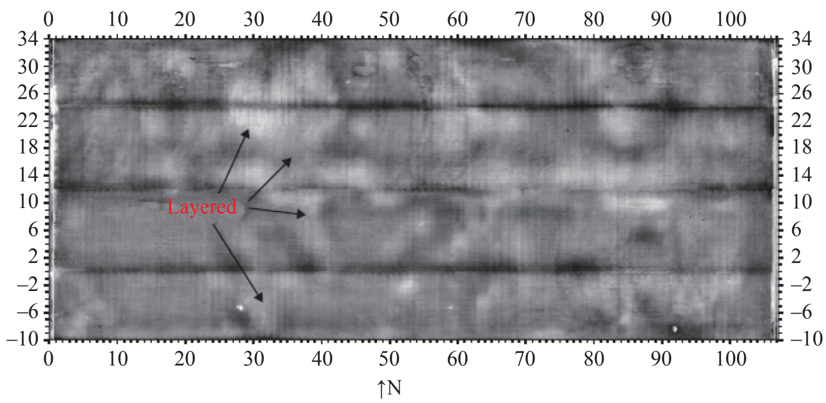

Fig. 6. Full bridge composite infrared image (unit: cm).

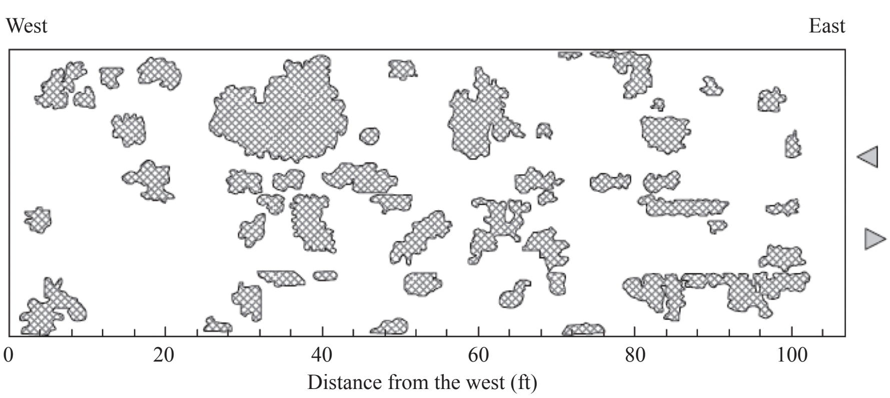

Fig. 7. Mapping results of infrared thermal imaging (1 ft = 30.48 cm).

Table 1. Commercial sensor technology for bridge deck evaluation.

Position	Business sensing technology	Measurement standard
Surface	3D photogrammetry	Loss of sealant, cracking, peeling within two feet, surface indentation, surface voids, bridge sinking
	Street style camera	Loss of sealant, cracking, peeling within two feet, surface indentation, surface voids
	Optical interferometry measurement	Loss of sealant, cracking, peeling within two feet, surface indentation, surface voids, vibration
	Digital-image correlation method	Horizontal and vertical bridge displacement, vibration
	Spectral analysis	Loss of sealant, cracking, peeling within two feet, chemical etching, surface indentation
	Photoelectric aircraft and satellite image	Loss of sealant, cracking, peeling within two feet, surface indentation, surface voids
	Lidar	Loss of sealant, cracking, peeling within two feet, surface indentation, surface voids, horizontal and vertical bridge displacement
	Thermal infrared imaging	Loss of sealant, cracking, peeling within two feet, surface indentation
	Radar	Loss of sealant, cracking, peeling within two feet, surface indentation, surface voids, vibration
	Acoustics (such as IE)	Surface cracking
Under the panel	Thermal infrared imaging	Crack moisture content, horizontal cracks, surface indentation, parallel cracks, voids
	Radar	Fracture surface, corrosion changes, chloride ion content with depth change
	Ground penetrating radar	Fracture moisture content, fracture surface, surface indentation, horizontal fracture sag, corrosion changes, change in chloride with depth
	Acoustics (such as IE)	Internal horizontal cracks, hollow echo, fracture surface, corrosion changes
	Half-cell potential	Highly corrosive area for steel

After investigating and summarizing the research status both locally and globally, it is considered that there are currently four main problems associated with non-destructive testing (NDT) of bridge decks in China: ① Detection is highly subjective, time-consuming, and causes traffic congestion; ② detected information is limited, and regular and real-time inspections are not possible; ③ many decisions are based on limited, subjective, speculative, outdated information; the accuracy of the test should be improved; ④ There are some defects in the post-processing of data, especially in the automatic identification of images and audio.

Therefore, the future focus of NDT of bridge deck pavement should be the realization of complete, rapid, and automatic identification of inspection images along with methods for ensuring a fairly high accuracy, which is also a technical issue that scholars in the relevant fields need to solve urgently.

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