Detection of Hidden Disease of Concrete Bridge Based on Infrared Thermal Imaging

Jin Hui¹, Zou Lan-lin¹

¹School of Automobile and Transportation Engineering, Wuhan University of Science and Technology, Wuhan China

Abstract: Any object with temperature above absolute zero can radiate infrared energy outward [1]. According to this characteristic, the infrared thermal imaging method is applied to diseases of concrete bridges such as internal voids. The relationship between the hidden disease of concrete bridge and infrared thermal image is analyzed theoretically. The concrete model with internal cavity defects is established and the finite element simulation analysis is carried out to verify the feasibility of infrared thermal imaging method to detect the internal defects of bridge concrete. The final finite element simulation results are in agreement with the theoretical analysis, indicating that the method of detecting the internal defects of bridge concrete by infrared thermal imaging is feasible.

1. Foreword

void is one of the hidden disease forms of concrete bridge structure. The stress concentration will occur in the place where the voids appears, which will lead to the destruction of the bridge concrete. This kind of damage is often without warning. It is a kind of sudden damage, which has great impact on the safety of bridge structure negative impact[2]. The voids is located inside the concrete bridge structure, and it is highly concealed. It cannot be directly observed by the naked eye, and effective visual detection cannot be achieved. For the detection of concealed diseases of concrete bridge structures, there are currently the following methods: ultrasonic method, ground penetrating radar method, rebound method, pull-out method, etc[3]. These methods have some disadvantages in different degrees, such as large workload, many factors restricting accuracy, more influence by the media above the ground, and may affect the normal use of buildings. Finding a convenient and economical method to detect the inner cavity of bridge concrete structure is an urgent problem for civil engineering at home and abroad. Its potential social value and economic benefit are considerable. The infrared thermal imaging method is thus produced.

The use of infrared thermal imaging in the detection of internal defects in bridge concrete structures has a solid theoretical basis and practical feasibility. In the early 19th century, the scientist Herson discovered infrared radiation with a mercury thermometer. In the mid of the 19th century, the scientist Kirchhoff proposed the relationship between the absorption and emission of thermal radiation from an object[4]. Scientists Stephen and Boltzmann proposed the relationship between the absolute blackbody total radiant energy and its absolute temperature. In the early 20th century, the scientist Planck discovered the energy sub-model and the blackbody radiation law, and proposed the relationship between the blackbody spectrum radiant energy and the temperature and wavelength[5,6]. In 1983, infrared non-destructive testing technology was applied to a highway in Chicago, USA[7], which proved that infrared non-destructive testing technology can be applied to road surface detection, which is of great significance to infrared non-destructive testing technology. In 1987, infrared thermal imaging nondestructive testing technology was successfully applied to the inspection of concrete taxiways at...
Lambert-St. Louis International Airport [8]. Domestic research in related fields [9]: Suzhou Thermal Engineering Research Institute has developed the HSY01 infrared scanning thermometer, this instrument has reached the international advanced level in terms of various indicators and performance. The Xi'an Thermal Engineering Research Institute and the Kunming Institute of Physics and other units have jointly developed the HRD1 infrared thermal imager and applied it to practical testing, and achieved good testing results. Compared with the traditional concrete bridge disease detection method, infrared thermal imaging method has a long range, high spatial resolution, wide detection range, will not affect the normal use of buildings, and has a series of advantages such as complementary effects on other detection technologies.

This article first theoretically builds the correlation between the internal cavity of the concrete bridge structure and the infrared thermal image, and uses the ABAQUS comprehensive analysis software to perform finite element simulation analysis of the concrete model with voids defects under natural light to obtain the voids part and the adjacent normal part Temperature cloud image, verify the correctness of the theory, and then combine the working principle and functional characteristics of the infrared thermal imager to verify the feasibility of the infrared thermal imaging method to detect the internal defects of the bridge concrete.

2. Infrared thermal imaging method

Infrared thermal imaging method is a non-destructive testing method developed in recent years. This method uses Stephen Boltzmann's law to establish the relationship between the surface temperature of bridge concrete and its internal voids defects. The detection of the internal voids defects of bridge concrete is transformed into the test of the surface temperature of bridge concrete.

According to Stephen-Boltzmann's law, when the emissivity of an object's surface is constant, the radiant power of the object is proportional to the fourth power of its temperature. Stephen-Boltzmann's law is as follows:

$$\Phi = \varepsilon A \sigma T^4$$

- $\Phi$ - The total infrared energy radiated by the actual object, unit: w
- $\varepsilon$ - Object emissivity, always less than or equal to 1
- $A$ - Surface area of actual object, unit: m²
- $\sigma$ - Blackbody radiation constant, Stephen Boltzmann constant (blackbody radiation constant), value 5.4710⁻⁸ w/(m²k⁴)
- $T$ - The temperature of the actual object surface, unit: k

It can be seen from the above formula: the magnitude of the infrared energy radiated by the actual object is proportional to the fourth power of temperature. The higher the temperature, the greater the infrared energy radiated; otherwise, the smaller. All objects with a temperature above absolute zero can radiate infrared energy outwards, and objects detected with an infrared camera are no exception.

When heat is conducted inside the material, the heat conduction equation followed is:

$$\frac{\partial t}{\partial \tau} = \alpha \left( \frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2} \right) \quad (\alpha = \frac{\lambda}{\rho c})$$

- $t$ - Temperature (℃ or K)
- $\lambda$ - Thermal conductivity [W/(m·K)]
- $\rho$ - Density (kg/m³)
- $c$ - Specific heat (J/kg·K)

Because of the difference of heat transfer performance and structure state between normal part and voids part material, that is $\lambda$, $\rho$ and $c$ are different, when heat flow passes through concrete with voids inside, the rate of heat flow passing through normal part and voids will accumulate too much in voids part. The difference in heat flow will be manifested by the difference in temperature. The difference in temperature between the normal part and the hollow part will cause the infrared energy of the normal part and the hollow part to radiate differently, and the infrared camera will detect the infrared energy
with different intensity of the object, and then obtaining the distribution map with temperature difference formed according to the distribution of the temperature field on the surface of the object is the basis of the infrared thermal imaging method to detect the internal defects of the bridge concrete structure. The difference in heat flow will be expressed as the difference in temperature. The difference in temperature between the normal part and the voids part will cause the infrared energy of the normal part and the voids part to radiate differently, and the infrared thermal imager will detect the infrared energy with different intensity of the object, and then obtain the formation according to the distribution of the surface temperature field of the object of the temperature distribution. This is the basis of infrared thermal imaging method to detect internal defects of bridge concrete structure. Using this relationship between the surface temperature of the concrete bridge and its internal voids defects, the internal voids detection, which is difficult to measure visually, is converted into a test of whether there is a temperature difference on the surface of the structure.

3. Concrete simulation model of bridge with voids inside

According to the relationship between the surface temperature of the experimental material and the internal voids defects, combined with the characteristic that any object with a temperature above absolute zero in heat transfer can radiate infrared energy outward, the interior of the test block is explored by testing the difference in surface temperature of the object empty existence. To verify the theory, taking a concrete test block model with internal voids (the voids is inside and not penetrating) as an example, the comprehensive analysis software ABAQUS was used to simulate the temperature load of the test block and analyze the temperature distribution on the surface of the test block.

3.1 Finite element simulation

The model used in this paper is a concrete solid model with internal voids (the voids are inside and do not penetrate). The concrete size is 0.12m×0.1m×0.05, the internal voids size is 0.04m×0.03m×0.02m, and the internal voids upper surface 0.01m from the upper surface of the concrete. The cross-sectional view of the model is shown in Figure 1.

![Figure 1](image)

**Figure 1** Section and dimensions of the model

The concrete solid model is defined as isotropic, has three directions of thermal conductivity, and has 8 nodes, each node has only one temperature degree of freedom, can carry out three-dimensional steady state or transient thermal load analysis, this model can achieve heat conduction with uniform heat flow.

Edit the material properties of each part of the model, enter the three thermal parameters of the $\lambda$, $\mathbf{C}$ and $\rho$ of the material [10-11], and find the specific values of the relevant thermal parameters according to the basic theory of heat transfer, as shown in Table 1.
Table 1 Thermal parameters

|          | \( \lambda (w/(m \cdot k)) \) | \( C(j/(kg \cdot ^\circ C)) \) | \( \rho (kg/m^3) \) |
|----------|---------------------------------|---------------------------------|-------------------|
| Concrete | 1.51                            | 920                             | 2400              |
| Air      | 0.03                            | 1009                            | 1.205             |

Create an analysis step, in order to be closer to the actual situation, use the software to simulate the temperature change of the concrete test block model under natural sunlight. That is, from 6 o'clock in the morning to 22 o'clock in the evening, adopting a 16-hour temperature change in the natural state, 8 analysis steps are set, and each analysis steps interval is 2 hours. In 1 to 5 analysis steps, the intensity of sunlight exposure is large, and the heat flux density is a positive value, which is the process of absorbing solar heat radiation, that is, the process of heating up the concrete test block model. In 6 to 8 analysis steps, the intensity of sunlight exposure is small, and the heat flux density is negative. It is a process without solar radiation, which gradually releases heat, which is the process of cooling the concrete test block model.

Edit the interaction to determine the interaction between the outside air and the concrete test block as convection heat transfer, and determine the interaction within the concrete test block as heat conduction. The concrete solid model is defined as isotropic, has three directions of thermal conductivity, and has 8 nodes, each node has only one temperature degree of freedom, can carry out three-dimensional steady state or transient thermal load analysis, this model can achieve Heat conduction with uniform heat flow.

Create a load. The first analysis step to the eighth analysis step correspond to 8 different heat flux densities. The load is applied from the upper surface to the lower surface in the form of step loading. Table 2 shows the heat flux density values at each time of each analysis step.

Table 2 Heat flux value at each moment

| Analysis step | Time (s) | Heat flow \( \rho (w/m^2) \) |
|---------------|----------|-----------------------------|
| 1             | 7200     | 130                         |
| 2             | 14400    | 230                         |
| 3             | 21600    | 350                         |
| 4             | 28800    | 280                         |
| 5             | 36000    | 150                         |
| 6             | 43200    | -70                         |
| 7             | 50400    | -130                        |
| 8             | 57600    | -170                        |

Create a pre-defined temperature field. According to the characteristics of the concrete test block model and the convenience of the operation process, according to the adiabatic heat treatment around and at the bottom, set the initial temperature of the upper surface of the concrete test block model to 10\(^\circ\)C and the initial temperature of the bottom surface to 3\(^\circ\)C. Under the initial conditions, the steady-state heat conduction equation is solved.

After creating the job and solving the equation, the temperature field with temperature difference will appear in different parts of the concrete test block.
3.2 Result analysis

From the results of the finite element simulation, from the first analysis step to the eighth analysis step, the concrete test block model has obvious temperature differences between the voids parts and the normal parts. Choose the temperature diagrams of the first and second load steps arbitrarily, as shown in Figure 2. During the whole process, the temperature change curve of the central part of the voids and any point immediately adjacent to the normal part is shown in Figure 3.

It can be seen from Figure 3 that the temperature difference between the voids part and the normal part in the temperature cloud diagram of the first load step concrete test block model is 1.13. The temperature difference between the voids part and the normal part in the temperature cloud diagram of the second load step concrete test block model is 1.49, and there are obvious temperature differences between the voids part and the normal part of the remaining 6 analysis step concrete test block models, which are not detailed here. As can be seen from Figure 4, during the whole process, from 7200s, which is the first analysis step, there is a significant temperature difference between the voids and the normal part.
The simulation results show that the theory of determining the existence of voids defects in the concrete test block by temperature differences is correct.

The actual hidden structure of the concrete bridge has a temperature difference on the surface of the structure under the influence of the external natural environment or artificial environment. The infrared energy emitted from the structure is received by the infrared thermal imager after a series of processes such as atmospheric absorption and reflection. The processing is converted into image information, and finally the thermal image is used to determine the characteristics of the disease. At present, the temperature resolution of the high-precision infrared thermal imager is less than 0.001 °C \[12\], the amount of detected elements is 106, the upper limit of temperature measurement is 3600 °C, and the temperature difference less than 0.1 °C can be detected. It can fully meet the needs of the detection of concealed diseases of concrete bridges in practical engineering.

4. Conclusion

According to the above analysis, the following conclusions can be drawn:

1. The relationship between the internal voids of the concrete and the infrared thermal image is theoretically built, and the internal cavity detection that is difficult to visualize is converted into a test of whether there is a temperature difference on the surface of the structure. The finite element simulation results verify the internal voids of the test block and its surface temperature. The relationship between them has verified the correctness of the theory.

2. The combination of the working principle and functional characteristics of the infrared thermal imager with the actual situation shows that the method of detecting the voids in the concrete of the bridge by infrared thermal imaging is feasible.

References

[1] Shen Jie. "Basic Thermal Theory" and "Heat Transfer and Mass Transfer", Discussion on teaching methods and teaching and educating people[J]. Education Teaching Forum, 2013,000(014):122-123.
[2] Yao Shiwei, Zhan Jianying. Analysis and countermeasures of common diseases of highway bridges[J]. Heilongjiang Transportation Technology, 2014, 000(011):92-92,94.
[3] Wang Weiming. Development and application of non-destructive testing method for concrete[J]. Construction Technology Development, 2018, 45(17): 1-2.
[4] Li Xiufeng. Research on detection of hidden defects on road surface based on infrared imaging and finite element numerical simulation technology [D]. Harbin Institute of Technology, 2009.
[5] Chen Baoguo, Liu Ke. Research on the development of infrared detection technology [C]. Chinese Aerospace Society. Proceedings of the 10th National Optoelectronic Technology Academic Exchange Conference. Chinese Aerospace Society: Optoelectronic Technology Professional Committee of Chinese Aerospace Society, 2012: 127-135.
[6] Fan Jinxiang, Yang Jianyu. Infrared imaging detection technology development trend analysis[J]. Infrared and Laser Engineering, 2012, 41(12): 3145-3153.
[7] ASTM D 4788, Test Method for Detecting Delaminations in Bridge Decks Using Infrared Thermography, Annual Book of ASTM Standards, V01. 04. 03, West Conshohocken, PA, 2002.
[8] Niu Jinxing, Guo Pengyan. Infrared imaging technology and its application [J]. Journal of North China Institute of Water Conservancy and Hydroelectric Power, 2011,32(4).
[9] He Hu. Research on the application of infrared thermal imaging technology in non-destructive testing of retaining structures [D]. Chongqing University, 2012.
[10] Xiao Jianzhuang, Song Zhiwen, Zhang Feng. Concrete thermal conductivity test and analysis [J]. Journal of Building Materials, 2010, (2). 17-21.
[11] Zhang Feng. Research on concrete thermal parameters [J]. Shanxi Architecture, 2009, (3). 163-164.
[12] Yan Yuan, Zou Lanlin, Zhou Xinglin. Infrared thermal imaging nondestructive testing of steel bridge fatigue cracks[J]. Journal of Applied Sciences, 2016, 34(01): 106-114.