Study of Pulsed Phase Thermography for the Detection of Honeycombing Defects in Concrete Structures

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Abstract:

In this research, infrared thermography is used to detect defects (honeycombing) in reinforced concrete structures and mainly in the walls of wastewater treatment plants and bridge decks. The problem we are facing when detecting defects by infrared thermography is the heterogeneity of the heating, which limits the detection. The objective of this work is to reduce this effect with the Pulsed Phase Thermography (PPT) and thus increase the detectability.

Keywords: Pulsed phase thermography (PPT), infrared pictures, civil engineering, concrete, rock pockets, wastewater treatment plants, bridges.

1. Introduction

1.1 Presentation of the research

This study is realized within a research project (FIRST / "DEFBETIR") led by the "Centre de Recherche de l'Institut Supérieur Industriel d'Arlon" (CRISIA). This project is followed by two Belgian colleges, a construction company, and two public services. Its objective is the development of new methods, based on thermography, to detect defects located near the surface in two types of civil engineering buildings: wastewater treatment plants, and pre-stressed concrete bridge decks. This work investigates the applicability and effectiveness of using Pulsed Phase Thermography (PPT) to improve defects detection in reinforced concrete structures.

With the results of this project, the construction sector will have new techniques to achieve efficient non-destructive analysis. This will provide full information on the internal condition of concrete structures.

Until now, Pulsed Phase Thermography was the subject of some studies led by people like Dr. Xavier Maldague [1] or Dr. Clémente Ibarra-Castanedo [2]. Their researches have developed the PPT for about fifteen years. However, these studies were confined at pointed industrial fields, like aeronautic or the aerospace. Moreover, these studies mainly concerned inspection of homogeneous material with a high thermal conductivity like aluminium or Plexiglas.

1.2 Targets of the study

The application of Pulsed Phase Thermography in the field of civil engineering for the study of concrete structures is relatively recent. Unlike previous studies performed on homogeneous materials with a high thermal conductivity, the application of this technique to a material like concrete is more delicate. Indeed, the thermal characteristics of concrete are radically different: the thermal conductivity of concrete is low and the studied thicknesses are much
larger. These specificities imply that the time scale of the analysis is strongly lengthened. The duration of the heating impulse of the former studies was a few milliseconds while, in the case of concrete, the scale of the minutes is necessary. This lengthening applies, of course, also to the cooling phase which goes up from a few minutes to several hours. Moreover, the structure of the concrete is made up of a mixture of gravel, sand and cement. It is not homogeneous.

In our case, the study focuses on the detection of an anomaly often encountered in reinforced concrete structures, the "rock pockets" which are also called honeycombing. Rock pockets are zones where some mortar is missing between the aggregates. A poor concrete making, a bad implementation or an insufficient vibration during concreting are generally at their origin. They constitute weak points in the water-tightness and in the stability of concrete walls. They present fuzzy contours and can take various forms. Rock pockets are particularly dangerous when they are near the steel reinforcements, i.e. when they range roughly between 4 and 5 centimeters under the surface. In the situation where water or other corrosive agents reach these defects, a phenomenon of corrosion of the steel bars may appear, with consequently a lack of resistance. The aim of the present research is to detect defects up to 6 cm under the surface.

Conventional active thermography is already used in concrete structures to detect voids or other defects, which have lower thermal conductivity than sound concrete. In this case, the surface of the wall is heated, and the heat flux penetrates deeply. The voids or defects make a thermal resistance to the progression of this flux. The consequence is a local temperature rise in front of the defect. This temperature elevation is then detected by the infrared camera.

The main difficulty involved in the detection of defects in concrete structures by conventional active thermography is the heating system. The one we use is a circular oil-fired infrared heater (thermal power: 15 kW) which creates a very non-uniform heating (central area is warmer). These heating inhomogeneities are extremely embarrassing because they reduce the detectability of the defects. The control of the heater is very difficult, so in these conditions the identification of defects is impossible with simple infrared pictures.

Pulsed Phase Thermography is a method that solves the problem of heating inhomogeneities because it is less sensitive to this non-uniformity of heating and to surface irregularities. However, Pulsed Phase Thermography requires a digital processing of thermographic images using a calculation software. It is important to conduct a study on PPT, as it is torn between efficiency and length of analysis. This study should show how this technique can be applied in an industrial process.
2. Theoretic study (finite elements pre-study) of Pulsed Phase Thermography (PPT)

We started the study of Pulsed Phase Thermography with a numerical model. In the first phase of the study, the creation of a model is necessary and will permit to simulate a lot of configurations and to analyze the thermal behavior of defects (mainly rock pockets) in concrete structures.

A tri-dimensional finite elements computer model has been developed in order to simulate the heat flow progression in a concrete material. It represents a cube of concrete of 10 centimeters of edge, which is part of a semi-infinite concrete wall. The cells of the model are cubes of 1 cm edge, so there are 1000 cells in total. The model takes into account physical principles of conduction, convection and radiation. The attributes of each cell can be modified, so it is possible to put virtual defects anywhere in the model. The aim of this program is to simulate various configurations, like different defect depths, heating powers or heating times, to check the value of the superficial thermal contrast. The program computes the surface temperature evolution in front of sound concrete and in front of an internal defect. It gives as well the thermal contrast, which is the difference of the latter two.

We used this model to create virtual infrared pictures and then to evaluate the efficiency of Pulsed Phase Thermography. We got a reliable idea on the possibilities of PPT for tests in laboratory or on site.

The PPT analysis, applied to the infrared images obtained by the model, improves the detection of defects even with a very non-uniform heating.
This phase was crucial and helped to make simulations in different configurations without leaving the office. In the laboratory, it was impossible to make the same number of tests, the model reduces the time needed and gives a good idea of the possibility of the technique.

The theoretical study has allowed to identify the sensitive parameters to obtain the best results (analysis time: 120 min and the time interval between each infrared picture: 60s).

The first results confirm:

- The maximum detection depth (6 cm under the surface)
- That the defect detection is better on phase images than on conventional infrared images
- The reduction of sensibility to the non-uniformity of heating
- The reduction of sensibility to color differences on the surface

3. Laboratory experiments

Various concrete slabs have been made in order to simulate the defects that need to be detected, the rock pockets. Those tests have also been useful in validating the results provided by the finite elements model. We conducted our tests on concrete slabs with rock pockets defects at 2, 4 and 6 cm depth.

3.1 Laboratory tests on PPT – artificial thermal stimulation

The study of Pulsed Phase Thermography in laboratory performs the transition between the theory and the application on real site. After the analysis of Pulsed Phase Thermography indoor with very controlled conditions, we tested the technique outdoors where weather conditions are unpredictable.

During testing in the laboratory inside and outside, the results have confirmed the trends predicted by the model:

- Reduction of sensibility to the non-uniformity of heating,
- Reduction of sensibility to color differences on the surface.

The slab is heated (artificial non-uniform heating) during twenty minutes, and then one infrared picture is taken per minute during a cooling time of 90 minutes. As with the numerical simulations, the best results are obtained with phase images.
Outdoor tests are performed on the same slab with artificial heating but under real climatic conditions disturbing the detection (Figure 7).

We discovered that PPT was sensitive to weather conditions (wind speed, solar radiation, ...) causing disturbance reducing the detectability of defects. To improve the detection of defects, we corrected digitally the cooling curves by smoothing before PPT analysis.

3.2 Laboratory tests on PPT – natural (solar) thermal stimulation

In opposition to earlier tests where the energy was produced artificially, this test uses only solar radiation. This new test examines the effectiveness of Pulsed Phase Thermography without artificial heating. The results obtained with thermal stimulation using only solar power are less good but still encouraging. The weaker performance of phase images is caused by low temperature drop during cooling. It is possible to solve the problem by placing a support with a Plexiglas window that allows increasing the solar energy absorbed by the concrete slab, by a limitation of convection on the surface of the concrete, and a limitation of
the emission of infrared radiation when the concrete runs hot. These tests also revealed that
the amplitude images allow better detection than phase images.

![Image](image-url)

Figure 9. Solar heating. (a) infrared picture; (b) phase image at $1.85 \times 10^{-4}$ Hz; (c) amplitude image at $1.85 \times 10^{-4}$ Hz; (d) amplitude image at $3.70 \times 10^{-4}$ Hz. Defect depth: 2cm, 4cm, 6cm; solar heating: 120min; cooling: 90min; parameters PPT: $\Delta t [s]=60$, N=90.

4. On-site auscultations

The use of Pulsed Phase Thermography on real site is a very delicate phase. The transition
between numerical simulations and real laboratory tests went off without too much trouble,
but the transition between laboratory and real site is accompanied by much more difficulties
such as:

- The weather conditions (wind speed, solar rays intensity, rain, …)
- The difference of structure and thermal behavior between real defects and artificial ones
  created in laboratory
- The larger size and thickness of concrete walls, which strongly modify the heat flux
  behavior
- The accessibility of the zone which has to be auscultated: the distance between the
  infrared camera and the wall must be sufficient to observe the entirety of the zone

4.1 Application of Pulsed Phase Thermography with artificial static heating and moving
heating, on the wastewater treatment plant of Hamme-Mille (Belgium)

We carried out a lot of trials on the walls of the wastewater treatment plant of Hamme-Mille
and we discovered many defects (which present a diameter of 3 to 4 cm). These defects would
probably be rock-pocket defects or air bubbles. It is however very difficult to evaluate their
depth in an accurate way. These results must be verified by other detection techniques (radar,
ultrasonic, ...).

![Image](image-url)

Figure 10. The wastewater treatment plant - The heating system - Thermal imaging camera
4.2 Application of Pulsed Phase Thermography with solar heating only, on the bridge of Moyen (Belgium)

We tried to apply on a real site the technique combining Pulsed Phase Thermography with passive thermography. The lie of the site, and the localization of the zone to study on the bridge strongly restricted the possibilities of using an artificial heater, either electrical or by combustion. It was thus more interesting to take advantage of natural solar energy by using only solar heating.

The studied bridge was particularly interesting because concreting phases were not done very carefully during the construction. Indeed, a lot of honeycombing defects were discovered twenty years ago by the Ministry of Equipment and Transport, after a non-destructive auscultation of the bridge by ultrasonic method.

Our experiment, which consisted of trying solar heating in a Pulsed Phase Thermography analysis, revealed to be very satisfactory. Such quality of results was possible thanks to very good weather conditions (little wind, very sunny day) and to the presence of large and important defects.

Except when there were surface color differences, amplitude images didn't improve the ability to detect the defects already present on the infrared picture. Besides, the defects were less visible on the phase images than on the amplitude images, like we have already verified in passive thermography tests done in laboratory. However, phase images gave an additional information allowing evaluation of the defects’ depths.
5. Conclusion

The application of Pulsed Phase Thermography to the field of civil engineering, in order to detect and localize rock pocket defects in reinforced concrete structures, proved to be very successful. Indeed, defects detection has been strongly improved with this technique. Pulsed Phase Thermography does not only allow to considerably amplify thermal contrasts due to the presence of subsurface defects by the use of phase images, but it also allows reducing the influence of heating inhomogeneities (in active thermography analysis) or surface color variations (in passive thermography analysis).

After the whole analysis of the obtained results, it can be said that the aim of using PPT to improve the detection of defects up to 6 cm under the surface was achieved. This technique is worth taking a special interest. Of course, one must keep in mind that its application in the scope of civil engineering non-destructive testing is not easy and that many difficulties remain and have to be solved to improve its efficiency.

References

2. Ibarra-Castanedo C., Quantitative subsurface defect evaluation by Pulsed Phase Thermography: Depth retrieval with the phase, Université Laval, Québec, 2005.