The Role of Infrared Thermography in Nondestructive testing of Civil Engineering Structures

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ABSTRACT *- In Civil Engineering, the application of infrared thermography is not limited to passive investigations of the quality of thermal insulation of building envelopes. Basic principles of the two main techniques of active infrared thermography, which are pulse thermography (PT) and Lock-in thermography (LT), are briefly recalled. In this paper, the use of passive infrared thermography technique for detecting defects in reinforced concrete structures and possible use of active thermography with post processing techniques that can be applied for defect characterization is presented.*

1. INTRODUCTION

Infrared thermography is one of the non-destructive thermal methods which is becoming ever more popular in nondestructive testing of materials and structures since it is completely noncontact and may be faster than many other techniques that are being used.

Thermal methods generally consist of the thermal stimulation of the object (under examination) and monitoring of its surface temperature variation during the transient heating or cooling phase. The analysis of heating and cooling processes during and after warming up with an internal or external heat source is well established technique for the characterization of composites and metallic materials [1, 2].

In Civil Engineering, the application of infrared thermography is not limited to passive investigations of the quality of thermal insulation of building envelopes. Defects like voids in concrete or masonry, delaminations at interfaces of composites which have different density, heat capacity and/or heat conductivity in comparison to the bulk material can be localized and characterized.

Infrared thermography, due to its non-contact character that allows for quick 2D surface mapping, represents a powerful tool for non-destructive evaluation (NDE) of materials and structures. Notwithstanding this, Infrared thermography is still not completely exploited.

In contrast to the conventional use where natural temperature gradients are utilized, the NDT-applications take an active approach. A heat pulse is applied and the surface temperature is monitored and analysed. Typically, the temperature distribution at the surface at the time of maximum contrast is used for the detection of any defects [3].

The most important condition for infrared thermography to provide useful results is that a temperature difference or thermal contrast ΔT, exists between the feature of interest, e.g. people on a scene or an internal flaw on a specimen; and its surroundings. A second condition is to have the appropriate thermal imaging equipment to produce thermal images or thermograms. It is necessary to count with an experienced thermographer to interpret thermographic results.

2. IR THERMOGRAPHY IN CIVIL ENGINEERING STRUCTURES

Examples are inspections of bridge decks [4] and of paving in general [5]. For locating delaminations at bridge decks, an ASTM standard, published in 2007 with the title Standard Test Method for Detecting Delaminations in Bridge Decks Using Infrared Thermography [6], exists. The method is intended for use on exposed and overlaid concrete bridge decks, asphalt or concrete overlays as thick as 100 mm. The standard has no Precision and Bias statement and should not be used for acceptance or rejection of a material because comparative data is not available. According to the test procedure, bridge deck should be dry for a minimum of 24 hours prior to the test and the temperature difference must be at least 0.5 °C between the delaminated or deboned area and the adjacent solid concrete.

2.1 LOCATION OF VOIDS IN CONCRETE

To investigate the detectability of voids in concrete, two concrete test specimens were built as demonstrated in ***Figure 1***, having a size of 1.8 x 2.0 x 0.25 m. Before concreting, voids, simulated by polystyrene cuboids with different sizes were positioned by polyamide threads in the wooden formwork.

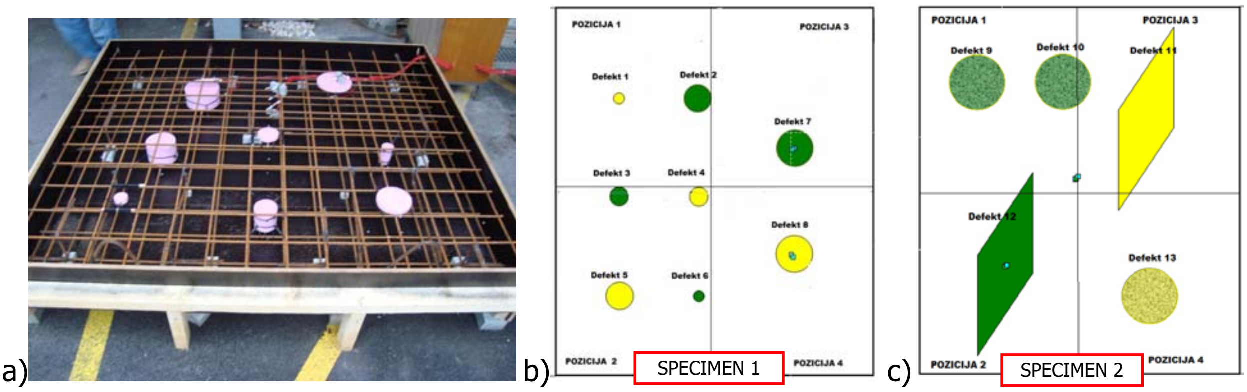

Figure 1 *Concrete test specimen including polystyrene cuboids with different sizes at different depths, a) photo before concreting, b) and c) schemes of the specimens*

Thermal imaging was performed according to ASTM D 4788-03 [6] in the summer period, between the 18.00 and 22.00 hours with the periodic imaging every hour. During the day both specimens were exposed to direct insolation while the shades moved over the specimens when the sun was setting. The day was sunny, and there was no rain for at least a week before the thermal imaging.

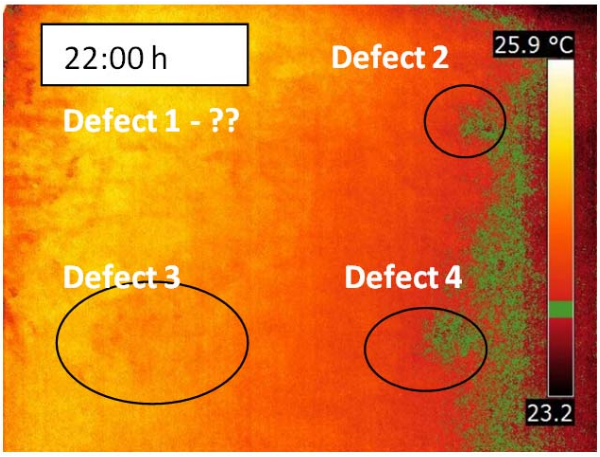

Figure 2 *Thermogram of specimen 1, defects 1 to 4, at 22.00 hours*

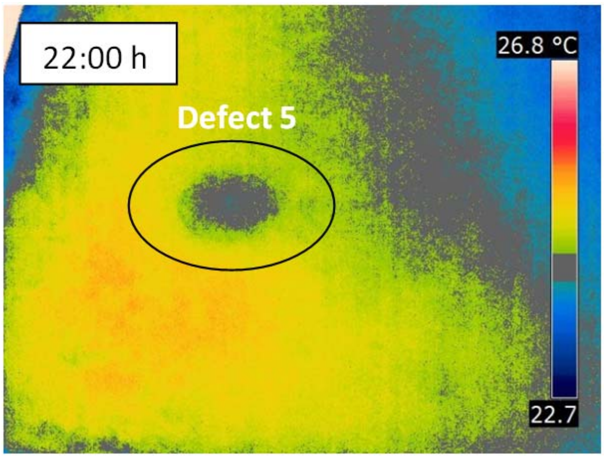

Figure 3 *Thermogram of specimen 1, defect 5, at 22.00 hours*

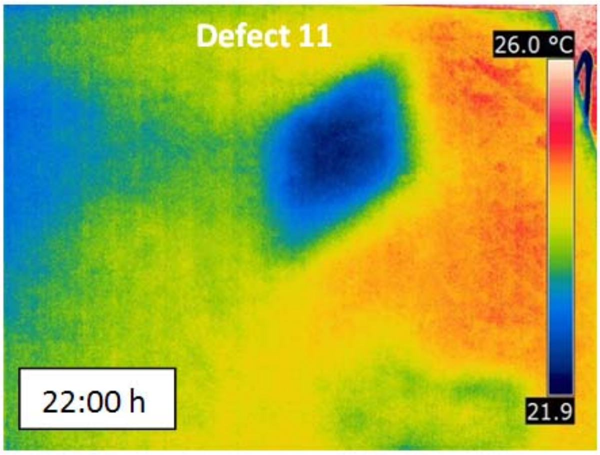

Figure 4 *Thermogram of specimen 2, defect 11, at 22.00 hours*

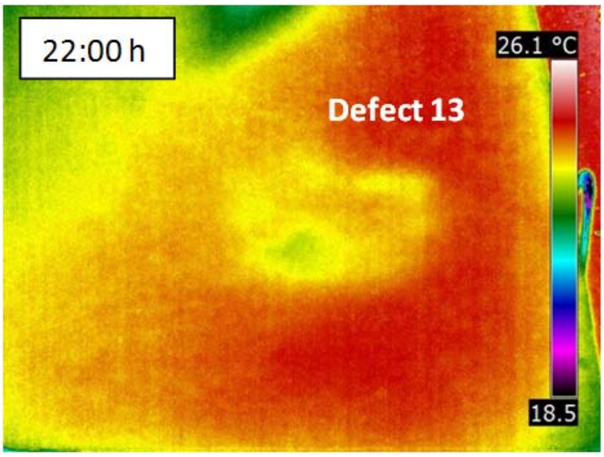

Figure 5 *Thermogram of specimen 2, defect 13, at 22.00 hours*

In ***Figures 2 to 5*** selected thermograms of the measurement cycle are shown. In every image, the temperature is scaled to the respective minimum and maximum to obtain the best possible contrast. It can be seen that the small voids (Defect No. 1 to 4) are not visible or just barely visible. Defects which are covered by 3 - 4.5 cm of concrete as well as the shallow larger voids (Defects No. 5, 11 and 13) are visible with maximum contrast at the at the end of thermal imaging process, 3 hours after the time shade has covered the sample and 2 hours after the sunset.

Some problems of using infrared thermography for non-destructive testing according to standardised ASTM D 4788-03 method were identified.

Relatively low thermal conductivities of used materials and large dimensions of most civil engineering structures contribute to difficulties in achieving homogenous cooling of the monitored surface. In the case of reinforced concrete, it is interesting to detect defects at the depth of cover concrete. By using the passive thermography, defects in the construction elements that are not exposed to direct sunlight cannot be located. Therefore, engineers seek to determine whether voids and delaminations in such reinforced concrete elements can be detected through the use of active infrared thermography. Also, by using active thermography techniques, quantitative measurements of defect depth and dimensions can be conducted.

3. ACTIVE THERMOGRAPHY TESTING PROCEDURES

If a thermal gradient between the scene and the object of interest exist, the target can be inspected using the passive approach. However, when the object or feature of interest is in equilibrium with the rest of the scene, it is possible to create a thermal contrast on the surface using a thermal source; this is known as the active approach in infrared thermography. Energy brought to the object of interest will cause the change of thermal gradient compared to the bulk material thus witnessing the presence of subsurface anomalies.

3.1. PULSED THERMOGRAPHY

Pulsed thermography (PT) is one of the most common thermal stimulation methods used in thermography for nondestructive testing. One reason for this is the quickness of the inspection, in which a short thermal stimulation pulse lasting from a few milliseconds for high-conductivity material, such as metal, to a few seconds for low conductivity specimens, such as plastics, is used. Basically, PT consists of heating the specimen briefly and then recording the temperature decay curve, ***Figure 6.***

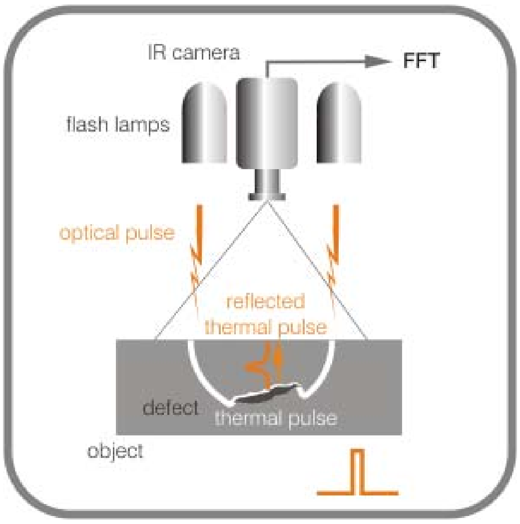

Figure 6 *Schematics of the pulse thermography test procedure*

Qualitatively, the phenomenon is as follows, the temperature of the material changes rapidly after the initial thermal pulse because the thermal front propagates by diffusion under the surface and also because of radiation and convection losses. The presence of a subsurface defect modifies the diffusion rate so that when observing the surface temperature, a different temperature with respect to the surrounding sound area appears over a subsurface defect once the thermal front has reached it. As for the detection depth, it is limited since thermography for nondestructive testing is a “border technique”, but often, anomalies such as cracks start close to the surface.

3.2. LOCK-IN THERMOGRAPHY

Lock-in thermography (LT) is based on thermal waves generated inside a specimen and detected remotely. Wave generation, for example is performed by periodic deposition of heat on a specimen´s surface while the resulting oscillating temperature field in the stationary regime is recorded remotely through thermal infrared emission, ***Figure 7***.

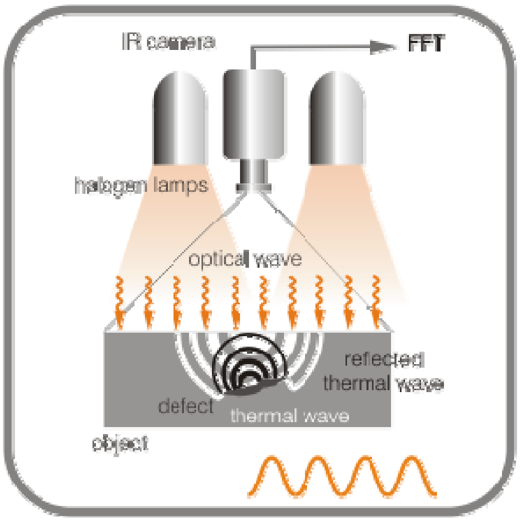

***Figure 7** Schematics of the Lock-in thermography test procedure*

Lock-in refers to the necessity to monitor the exact time dependence between the output signal and the reference input signal, the modulated heating. This is done with a locking amplifier in point-by-point laser heating or by computer in full-field (lamp) deployment so that both phase and magnitude images become available. Phase images are related to the propagation time, and since they are relatively insensitive to local optical surface features such as nonuniform heating. The depth range of images is inversely proportional to the modulation frequency, so that higher modulation frequencies restrict the analysis in a near surface region.

***Table 1** Comparative characteristic of Pulsed and Lock-In Thermography [7]*

	Pulsed Thermography	**Lock-In Thermography**
Heat source	Heat pulse	Periodic thermal waves
Regime	Transitory	Permanent
Advantages	• Fast • A single experience launches a series of thermal waves at several frequencies.	• Little impact of nonuniform heating, environmental reflections, emissivity variations and nonplanar surfaces. • Low power thermal waves. • Depth inversion is straightforward
Disadvantages	• Inversion techniques are complex. • Affected by nonuniform heating.	• Requires a test for every inspected depth. • Slow: a permanent regime has to be reached

4. DEFECT DETECTION

The temperature profile for a non-defective area (a pixel or the mean value of a pixel cluster) is a continuous non-periodical signal that decays approximately as the square root of time, ***Figure 8***. ***Figure 8*** shows actual temperature profiles for a sound area (black continuous line) and for a 1 mm depth defective zone (black dotted line). A semi logarithmic scale is used to increase visibility at the first instants. The sound area temperature decreases until stabilization is reached (ambient temperature). After that moment, temperature changes are negligible.

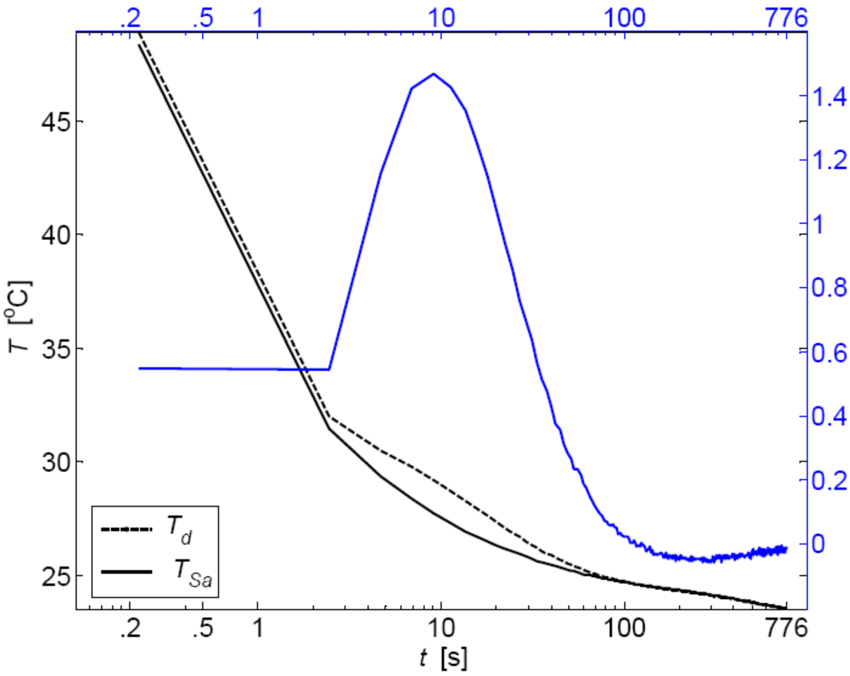

Figure 8 *Defect detection from temperature profiles [2]*

Temperature decay curves for both the defective and the sound areas behave similarly on the first instants after the application of heat since the heat front has not reached the defect yet. However, thermal effusivity *e*, which measures the material ability to exchange heat with its surroundings, is greater for sound material than for air, thus sound material acts better than air as thermal sink. Accordingly, once the thermal front has reached the defective area (air), surface temperature will be higher above the defective zone than above the sound area, from this moment to a given stabilization time.

The defective temperature profile would be inverted if the flaw had a higher thermal effusivity than the specimen material. Several data processing algorithms have been developed for defect characterization, *i.e.* determination of the size, depth and thermal resistance of a defect [8], [9]. Most of these techniques use thermal contrast calculations. The basic definition of thermal contrast is the *Absolute Thermal Contrast*, which measures the difference between defective and non-defective regions [2]:

$$\Delta T = T_d - T_{Sa} \tag{1}$$

Where T_d is the temperature of a defect, and T_{Sa} is the temperature measured at a (non-defective) sound area S_a. Thermal contrast based analysis provide a good indication of defect characteristics (qualitative and quantitative) when working with relatively shallow defect in homogeneous materials and when non-uniformities at the surface are low (or can be corrected).

Non-uniform surface heating is an inherent source of uncertainty on active thermography. Even when a flat surface is inspected, several factors as heating source location, equipment aging, external heating or cooling sources, uneven optical properties of the surface, etc., will induce non-uniformities, ***Figure 9***. Given that defect detection principle is based on temperature differences, non-uniform heating may produce confusion, especially for defect quantification.

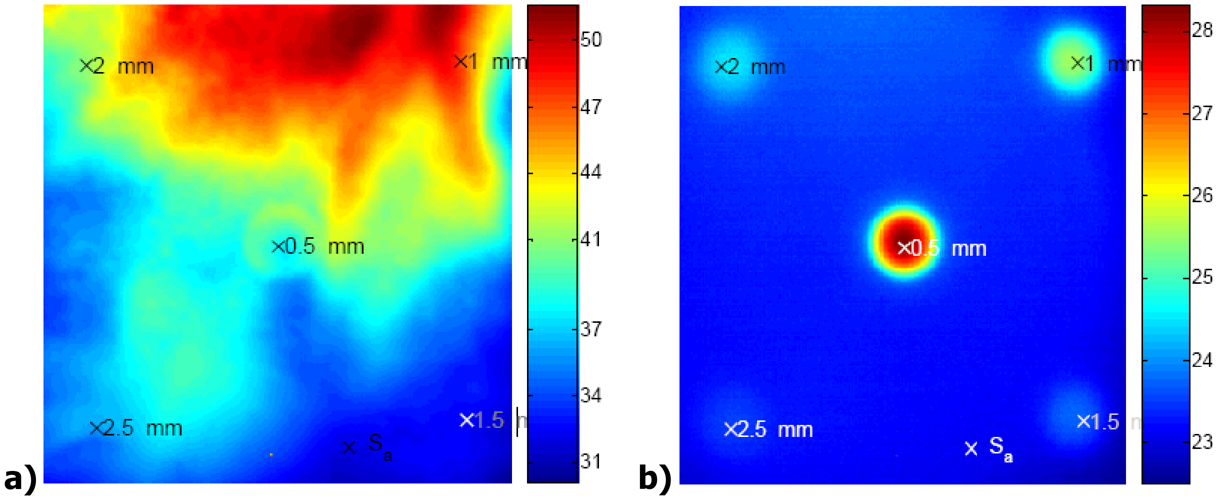

Figure 9 *Impact of non-uniform heating. Thermograms at (a) t=6.3 ms; and (b) t=25 ms after thermal excitation of aluminum specimen, showing defect locations [2].*

By using active infrared thermography and appropriate post processing techniques, detection of near-surface inhomogeneities and common subsurface defects in typical structural elements is possible. The quantitative determination of their geometrical parameters and defect depth is the main objective for the practical problems like:

- locating and quantifying voids and honeycombing in concrete
- locating delaminations of plaster at concrete and masonry
- locating delaminations and voids behind tiles on concrete embedded in mortar
- assessment of bonding of carbon fibre reinforced laminates glued on concrete
- identifying poorly grouted ducts

5. CONCLUSIONS

By using passive infrared thermography, defects in concrete structures can be inspected using only an infrared camera. This method, however, strongly depends on weather conditions since it requires the presence of sunlight or an increase in air temperature, it cannot be used, then, when it is overcast or raining. The most important result from presented research is that simulated defects can be detected by using passive infrared thermography under certain conditions and only few of the existing defects are visible.

There is a need to develop new quantitative non-destructive testing techniques for delaminations defects in concrete structures. Some techniques already in use in the field of aerospace industries and mechanical engineering can be applied to civil engineering problems respecting the differences in thermal properties and the homogeneities of materials. The purpose of this paper was to present new active techniques of infrared thermography that could be used for detection of near-surface inhomogeneities and common subsurface defects in typical structural elements.

6. REFERENCES

[1] Biennial Quantitative Infrared Thermography (QUIRT) conference; 1992 – 2010.

[2] Maldague, X.: „Theory and practice of infrared technology for non-destructive testing", John Wiley and Sons, New York, 2001.

[3] Wiggenhauser, H.: „Active IR-applications in civil engineering", Infrared Physics & Technology 43, pp. 233–238, 2002.

[4] Bjegovic D., Mikulic D., Sekulic D.: "Non-destructive methods for monitoring of reinforcing steel in concrete", In: Forde MC, editor. Proceedings of 9th international conference on structural faults and repair, London: Engineering Technics Press; 2001. CDROM.

[5] Stimolo M.: "Praktische Anwendung der Thermografie im Straßenbau und fur Abdichtungssysteme", DGZfP - Berichtsband 77, Thermografie-Kolloquium, Stuttgart, 2001 [in German].

[6] ASTM D 4788-03; Standard Test Method for Detecting Delaminations in Bridge Decks Using Infrared Thermography; 2007.

[7] Ibarra Castanedo, C.: "Quantitative subsurface defect evaluation by pulsed phase Thermography: Depth retrieval with the phase", PhD Thesis, Faculté Des Sciences et de Génie Université Laval, Québec, 2005.

[8] Krapez J. C., Cielo P.: "Thermographic Nondestructive Evaluation: Data Inversion Procedures, I: 1D Analysis," *Research in Nondestructive Evaluation*, 3(2):81-100, 1991.

[9] Krapez J. C., Maldague X., Cielo P.: "Thermographic Nondestructive Evaluation: Data Inversion Procedures, II: 2D Analysis and Experimental Results," *Research in Nondestructive Evaluation*, 3(2): 101-124, 1991.

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