Leszek RÓŻAŃSKI, Krzysztof ZIOPAJA
POZNAN UNIVERSITY OF TECHNOLOGY, FACULTY OF MECHANICAL ENGINEERING AND MANAGEMENT
3 Piotrowo St., 60-965 Poznań
POZNAN UNIVERSITY OF TECHNOLOGY, FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING
5 Piotrowo St., 60-965 Poznań

Detection of material defects in reinforced concrete slab using active thermography

Abstract

In order to validate the practical usage of passive and active infrared thermography for bridge inspection, a number of experimental studies have been conducted. Concrete slab of dimension of 60×60×10 cm made of concrete of strength class C35/45 was the object of research. Steel bars type B500SP with a diameter of ∅10 and ∅12 mm were used as reinforcement of analyzed slab. Four structure discontinuities imitating damages were implemented inside the slab. Using various methods of thermal excitation, the sensitivity of the slab response using infrared cameras was investigated. The paper presents the results of experiment and FEM simulation.

Keywords: active IR (pulsed or step heating) thermography, damage detection, non-destructive testing.

1. Introduction

The active or passive infrared thermography is common NDT technique used to detect delaminations and voids in concrete. A complete description of the theoretical and physical basics of infrared thermography with its practical applications can be found in Polish monographs [3,5,7]. The characteristics of thermography in non-destructive tests of composite materials for special applications can be also found in [6].

A thorough review of the state-of-the-art regarding the use of active infrared thermography for identification of damages in reinforced concrete structures is presented in [2].

In the [1] study, impulse thermography was used to detect voids in four concrete slabs with dimensions of 100×100×30 cm. Voids, imitate damages, were simulated by inclusion of polystyrene cuboids or by integration of gas concrete parts with a size of 10×10×5 cm. The damage position to the plate surface was 6 and 10 cm. The study took into account the influence of various factors, such as material properties varied by concrete age, pore content, aggregate type and reinforcement.

From the point of view of our scientific interests, the key problem to solve is to develop such a methodology of infrared thermography, which could be applied to the inspection of bridges. Similar topics are in the scope of interest of group of scientist under the direction of Vaghefi et. al [8]. The first preliminary results of our research were presented at the QIRT 2016 Conference [4]. We assumed that for now we focus our attention on the investigation of concrete structures. Several laboratory tests on a reinforced concrete slab were performed to investigate the possibility of voids detecting, identifying of their location, the effect of heat exchanger conditions and the possibility of digital processing of recorded thermograms. Additionally, some numerical simulations in Abaqus/Standard have also been performed.

2. Laboratory tests

The study focused on the analysis of the concrete slab of dimensions of 60×60×10 cm that was made of concrete of strength class C35/45, used during execution of the real supports of one of the new-built viaduct in Poznan. Reinforcement mesh was made of steel bars type B500SP with a diameter of ∅10 and ∅12 mm in a spacing of 15.0 cm. View of the panel formwork and the configuration of the bars grid and “defects” in slab before concreting are shown in Figure 1.

Inside the plate four discontinuities imitating damages were implemented. Internal voids (Void1÷Void4) were made in the form of plastic boxes with dimensions of 7.0×4.7×1.9 cm. They were placed in the plate so that they were about 1.5 to 3.0 cm below the top (measuring) surface. The above mentioned damages layout is shown in Figure 2.

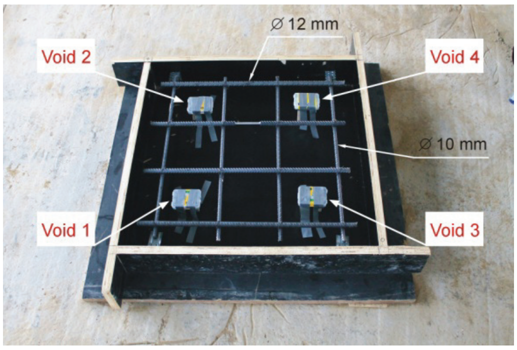

Fig. 1. View of formwork, reinforcement mesh layout and defects before concreting

The study was divided into three independent tests, differing in the form of thermal excitation and registration methods. Basic technical parameters of the test are summarized in Table 1. Methodology of research (in Tests 1 and 2) relied on the heat flow forcing using a long, constant (rectangular) heat pulse and on recording the plate surface temperature distribution during the heating and cooling process.

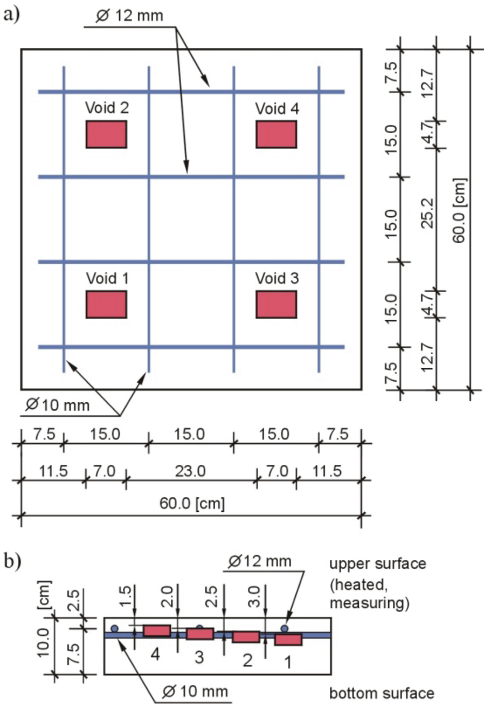

Fig. 2. Geometry of the reinforced concrete (RC) plate: a) reinforcing bars and “defects” layout, b) schematic position of voids in plate

Tab. 1. Basis parameters of the step-heating thermography tests

No.	IR camera	Thermal excitation	Time [min]		Distance to the IR camera [m]	Moment of measurement
			heating	self-cooling		
TEST 1	FLIR T620	Halogen lamps 2x150W	5	13	0.60	During the heating and cooling phase
TEST 2	FLIR X6540 SC	Halogen lamps 2x150W	5	15	0.75	During the heating and cooling phase
TEST 3	FLIR T620	Hot air	18	60	2.40	During the self-cooling process

The heat source was composed of two halogen infrared radiators 2x150 W. In both tests lamp exposure time was about 5 minutes. Lamps were positioned symmetrically about 25 cm above the plate surface. Due to the possibility of camera positioning and the type of lens it was assumed that each of the four defects will be stimulated and analyzed separately. In test 1, the measurement area had dimensions of 25×18 cm, while in test 2 12.7×10.1 cm.

The value of the surface emissivity coefficient was assumed a priori, according to the commonly reported data in the literature, ε=0.95. It is well known that the signal which generates IR camera during measurement depends on the emissivity of the surface of the test object and affects the determination of the temperature. At this stage of our research, the issue of emissivity is not analyzed because it is important for us to detect the slightest difference in temperature distribution rather than determining the exact temperature value.

In the TEST 1 thermograph type FLIR T620 (FPA detector 640×480, thermal resolution NETD - 0.05°K, spatial resolution 0.68 mrad, image frequency 30 Hz, spectral range 7.8÷14 μm) for acquisition of thermal imaging was used to carry out the measurements. During the test the environmental conditions were as follows: ambient temperature 22.6°C, relative air humidity 62% and initial temperature of concrete slab about 22.8°C. Due to the location of the heat source and the variable initial temperature of the plate, the heating conditions were not exactly the same for each defect. Additionally, interpretation of thermograms hindered the oval artifacts generated by halogen lamps. Also the variety of the properties of the concrete surface itself (among others roughness, local unevenness, pores, shades, etc.) caused that achievement of homogeneous heating of observed surface was nearly impossible. The advantageous, however, was thattogether with the cooling time the temperature distribution was more uniform, which improved observation on the thermograms features associated with damages.

Analysis of the Test 1 results shows that all simulated damages can be detected by step-heating thermography, wherein the deepest defect (Void 1) requires a longer observation time than others. Better results are visible on the thermograms after several minutes (over 10 minutes) of cooling phase, although temperature fluctuations are higher then. The shallowest defect (Void 4) has already been detected in the heating phase (after about 90 s) and the thermal image for t=9 min shows the best shape and dimensions of defect Void 4 (approx. about 80%). Selected test results using the FLIR T620 IR camera are shown in Fig. 3.

The PRC ANS-Centrum special thermal excitation set, consisting of two halogen lamps with a power of 150 W, was used for the tests. Fastening elements of lamps also enables the registration of the temperature during the heating process. Unfortunately, the low power of the lamps and their size allow the heating of small areas of about 40×30 cm. In future research, infrared radiators, which are cheaper, that generate a lot of energy and are easier to induce heat flow on a larger surface, should be applied.

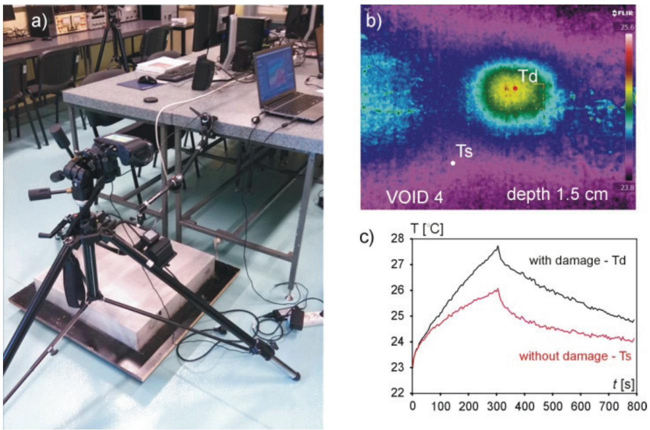

Fig. 3. TEST 1 of step-heating thermography: a) experimental set-up, b) thermogram of defect Void 4 at time 12 min, c) plot of temperature over Void 4 and in surrounding area

In the second stage of the study (TEST 2) thermograph type FLIR X6540SC (FPA 640x480; thermal resolution NETD - 0.025°K) for creating and processing thermal images was used to carry out the measurements. Thanks to better thermal resolution of the IR camera, damage Void 1 (located at a depth of 3.0 cm) has been successfully identified and the size of the defect Void 4 has been estimated to be approximately 90% of its actual size. Using FLIR ResearcheIR software, temperature profiles (as a function of cooling down time) at the places of defects and at the reference points were determined. Selected results are presented in Fig. 4.

In the identification of subsurface damage, the most important problem is to estimate the depth of the defect. The graphs in Fig. 5 clearly show that there is a relationship between the recorded temperature and the magnitude of the damage and its depth. This is demonstrated by two parameters: temperature difference ΔT (Fig. 5a) and a standard thermal contrast *STC* (Fig. 5b). It is known that the position of the maxima of the parameters ΔT and *STC* depend on the size and depth of the defect position. Unfortunately, in this case the depth of the respective defects cannot be clearly determined.

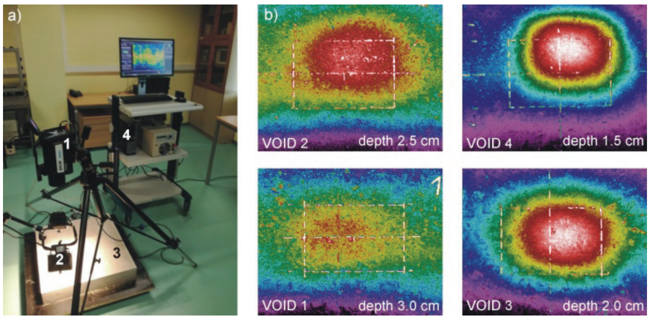

Fig. 4. TEST 2 of step-heating thermography: a) experimental set-up (1 - IR camera, 2 - halogen lamps, 3 – tested concrete plate, 4 - computer), b) thermograms of each defects at time 10 min

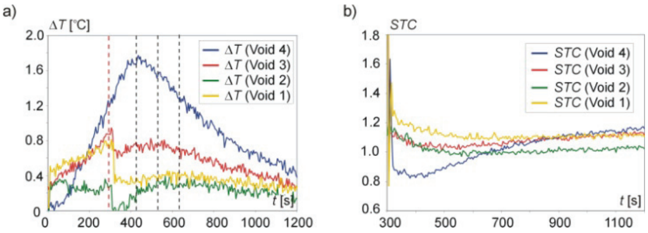

Fig. 5. Results of TEST 2: a) temperature difference (ΔT), b) standard thermal contrast distribution (*STC*)

The third experiment is an attempt to achieve homogeneous heating of the entire surface of tested specimen and make measurements allowing identification of all defects. For this purpose, a box of polystyrene foam (Fig. 6) of dimension 0.6×0.6×0.5 m was built. The box was closed from the top and set on the tested concrete plate. Through a small slot, using an infrared heater (1000 W), a stream of heated air was directed to the interior of the box for the period of 18 minutes.

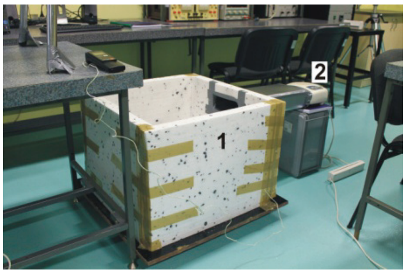

Fig. 6. Experimental set-up for step-heating thermography - TEST3: (1 – Styrofoam box without cover yet, 2 – infrared heater)

During the heating process, the plate surface temperature increased from 21.9°C to 24.5°C (average) and the air temperature at the interface between the plate reached maximum 27.2°C. The IR camera was set at a distance of 2.4 m which allowed us to observe about 90% of the plate area. The cooling process of plate was recorded for a period of 60 min. Although all four damages were detected (see Fig. 7), the worse optical resolution did not allow for a more accurate interpretation of the results.

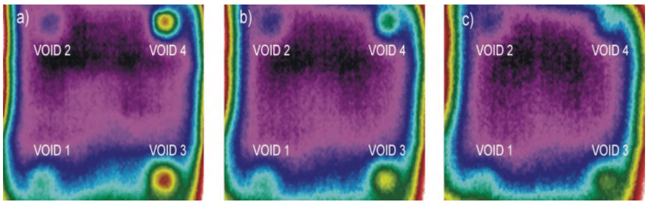

Fig. 7. TEST 3 selected thermograms at time: a) *t*=30 sec, b) *t*=5 min, c) *t*=9 min

Summarizing the results of experiments it can be deduced, that the ability to detect defects depends on many factors including the magnitude of the defect itself, its depth, the nature of the thermal excitation (time, power, spectrum, direction), the metrological parameters of the camera (mainly thermal resolution and geometric resolution). Possibility of detecting also depends on the thermo-physical properties of the material, properties of the test surface (such emissivity) and environmental conditions of measurement (the influence of wind, rain, sunlight). In spite of experience, the research is still in the process of seeking answers about the possibility of using active infrared thermography as a tool to help assess the technical condition of bridges. In this context, laboratory tests are used to verify the assumptions for detecting of specific defects in reinforced concrete elements and optimal selection of equipment.

Moreover, it was found that the radiation reflection of the halogen projectors do not interfere noticeably the process of recording the progress of heating of the concrete slab. This is because:

- the radiation spectrum sent by the NXS 150/0103 halogen projectors (150 W each) is approximately in the wavelength range of 0.3 to 3 µm, outside the spectral sensitivity of the FLIR T620 and only in a small range of the spectral sensitivity of the FLIR X6540SC,
- the concrete slab, with a very rough surface, has a small reflection coefficient (about 0.05), which means that only 5% of the radiation is reflected from the surface,
- the radiation is reflected from the slab evenly in all directions (diffused), due to its roughness and the fact, that the projectors are equipped with a quasi diffusion reflector, that creates a directional-diffuse (mixed) stream of heat energy.

3. Numerical analysis

Numerical analyzes were used to verify the FEM model of plate and to compare obtained FE results with the results from the laboratory tests, with particular emphasis on the thermal excitation and measurement. For these purposes, numerical model of concrete slab with a grid (mesh) of steel bars in Abaqus/Standard was prepared. It almost exactly corresponds to the geometry of the experimental plate. The numerical model consists of 16 layers of elements of different thickness. The total number of 8-nodes continuum diffusive heat transfer elements DC3D8 is 90000. What are the advantages of numerical analyses? First, they allowed to verify of thermal parameters of model materials and heat flow phenomena. Second, they allowed to perform wide ranged verification of the capabilities and limitations of detecting various defects. They also allowed us to determine the influence of plate reinforcement on defect detection. A few interesting results are presented in Figure 8. Visible on graphs 8a,b regular disturbances in temperature distribution are the effect of thermal wave reflection at the interface of the reinforcement mesh and concrete plate (effect not obtained in laboratory tests).

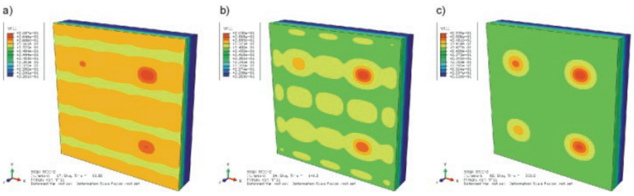

Fig. 8. FEM results of RC plate with temperature distribution NT11 in self-cooling phase: a) at time t=63.5 s, b) at time t=148.5 s, c) at time t=303.5 s

4. Conclusions

The results of current research are promising, but some weaknesses in our assumptions have been revealed. Detection of small defects (subsurface voids) is quite difficult in real structures. Probably using more efficient radiators, in the right amount and power, this will allow uniformly heat the test surface and will improve the detection of defects. The use of FLIR X6540SC IR camera outside the laboratory is inadequate to the possible benefits. Further research should focus on (in addition to the more efficient heat source) in-depth analysis of the relationship between the actual damage and its impact on the measured temperature distribution and possible advanced thermal image processing. Because the estimation of the depth of the defect is a classic inverse problem, a suitable mathematical tool should be developed. Laboratory experiments should be continued on new concrete test specimens with artificial inclusions.

Finally, we conclude that future experiments will focus on:

- construction of more efficient heat sources (respective sets of halogen lamps or infrared radiators),
- an adequate modeling of defects, that will be better reflecting the nature of actual defects (voids, inclusions, cracks, delaminations) of reinforced concrete structures (rational relationship of laboratory tests with NDT diagnostic),
- use of eddy current stimulations in order to better detect reinforcement and its defects,
- implementation of the infrared thermography to assess the technical condition of bridges.

5. References

[1] Maierhofer Ch., Arndt R., Rőlling M.: Influence of concrete properties on the detection of voids with impulse-thermography. Infrared Physics & Technology, 49, pp. 213-217, 2007.

[2] Milovanović B. and Pečur I.B.: Review of active IR thermography for detection and characterization of defects in reinforced concrete. Journal of Imaging, 2(11), 2016.

[3] Minkina W.: Thermovision Measurements – Instruments and Methods. Publishing Office of Czestochowa University of Technology, Częstochowa, 2004. (in Polish).

[4] Różański L., Ziopaja K.: Applicability analysis of active IR thermography and selected signal processing methods for technical conditions assessment of bridge elements. QIRT Conference Open Archives on http://qirt.gel.ulaval.ca/index.php (10.21611/qirt.2016.157), pp. 955-964, 2016.

[5] Suszyński, Z.: Active thermography - models, methods of measurement, thermal imaging processing. Publishing Office of Koszalin University of Technology, Koszalin, 2014. (in Polish).

[6] Świderski, W.: Nondestructive testing of composite materials by IR thermography methods. Monograph, WITU, Zielonka, 2010. (in Polish).

[7] Więcek B., De Mey G.: Infrared thermovision. Fundamentals and applications. PAK Publishing House, Warszawa, 2011. (in Polish).

[8] Vaghefi K., de Melo e Silva H.A., Harris D.K. and Ahlborn T.M.: Application of thermal IR imagery for concrete bridge inspection. PCI Convection and National Bridge Conference, 22-26 October 2011, Salt Lake City, 2011.

Received: 28.10.2016 *Paper reviewed* *Accepted: 02.02.2017*

Leszek RÓŻAŃSKI, PhD

Post doc in Division of Metrology and Measurement Systems Institute of Mechanical Technology, Poznan University of Technology. Head of IR thermography lab. He graduated Automation Control Engineering and Electrical Metrology at the Faculty of Electrical Engineering of the Poznan University of Technology and physics at the Faculty of Mathematics, Physics and Chemistry of the Adam Mickiewicz University. He deals with theory and design of thermal imaging systems, thermal diagnosis and applications of vision systems in metrology of geometrical dimensions.

e-mail: leszek.rozanski@gmail.com

Krzysztof ZIOPAJA, PhD

He received MSc and PhD degree in specialization Civil Engineering on Poznan University of Technology (PUT). Since 2009, he has been employed as Assistant Professor at Department of Bridges and Railway Roads at Institute of Civil Engineering at PUT. Area of scientific activity is associated primarily with non-destructive methods serving to locate defects in material and engineering structures, numerical modeling and simulating the actions of static and dynamic loads, including the flow of heat in solids.

e-mail: krzysztof.ziopaja@put.poznan.pl