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Determination of the applicability and limits of void and delamination detection in concrete structures using infrared thermography

Patricia Cotič [a], Dejan Kolarič [b], Violeta Bokan Bosiljkov [b], Vlatko Bosiljkov [b], Zvonko Jagličić [a,b,*]

[a] Institute of Mathematics, Physics and Mechanics, Jadranska 19, 1000 Ljubljana, Slovenia
[b] Faculty of Civil and Geodetic Engineering, University of Ljubljana, Jamova 2, 1000 Ljubljana, Slovenia

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ABSTRACT

Based on the results of the infrared thermography of 51 artificially created defects – voids and delaminations – in concrete, it was shown that it is possible to detect defects at depths that are equal or less than the defect size *D* using the thermal contrast method. By applying the phase contrast method, an increase of 50% in the maximum depth for a given defect size *D* was achieved. Delaminations containing thin air gaps were detected with the same success as much larger voids of the same cross section.

1. Introduction

In thermographic testing or *infrared thermography* or just *thermography* [1], the surface temperature is measured in order to obtain information about the interior of the observed object. It can be used as a non-destructive testing method in many different fields, e.g. in medicine, agriculture, the environment, and thermo-fluid dynamics, as well as for the inspection of industrial and civil engineering materials [2–5]. In *passive thermography* [6], differences in the surface temperature of the investigated object can be observed without using an external stimulus. In civil engineering this method is often used when searching for thermal bridges or leakages in floor heating systems. However, for the inspection of more deeply lying defects, *active thermography* [6], in which the inspected structure is heated prior to or during the measurement of the surface temperature, is more commonly used. Among several available active thermography techniques [1], square pulse thermography is usually used in civil engineering. Here, the specimen is uniformly heated using an IR radiator or a fan heater for several minutes up to one hour of *heating time*. After the heating, the specimen's time-dependent surface temperature is measured during the *recording time*, which can take up to one hour or even longer.

Commonly used civil engineering materials (e.g. concrete, brick, and plaster) have low thermal diffusivities. For this reason much longer heating and recording times are needed for thermographic inspection compared to metals and composites. However, due to the frequently large size of inspected specimens, it is practically impossible to ensure homogenous heating over a period of time. Apart from this, the fact that building materials often have a non-homogeneous structure, including voids, cracks, and reinforcement, means that the use of active thermography in civil engineering has been much less widely reported than in other related fields such as the aerospace industry and mechanical engineering. A few papers have, however, been published about the use of thermography for the investigation of historic structures [7–12], as well as plastered mosaics [13–15]. Maierhofer et al. [3] reported about the detection of voids having different sizes beneath the surface of a concrete test specimen. Additional basic research involving the quantitative analysis of experimental and numerical pulsed thermography data has also been performed on concrete specimens with artificially created defects [16–18]. Recently, there has been interest in the combining of thermographic results with the results obtained from, for example, ground penetrating radar and ultrasound for the detection of cracks, voids, and delamination [19–21]. In such cases the availability of data about the sensitivity of each particular NDT method is of great importance for defect characterization. In the case of

* Corresponding author at: Institute of Mathematics, Physics and Mechanics, Jadranska 19, 1000 Ljubljana, Slovenia.
E-mail addresses: patricia.cotic@imfm.si (P. Cotič), dejkolaric@gmail.com (D. Kolarič), Violeta.Bokan-Bosiljkov@fgg.uni-lj.si (V.B. Bosiljkov), Vlatko.Bosiljkov@fgg.uni-lj.si (V. Bosiljkov), zvonko.jaglicic@fgg.uni-lj.si (Z. Jagličić).

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square pulse thermography, as well as other test methods, detectability limits need to be defined for defects of particular sizes, which are located beneath certain depths of concrete cover.

Two different computational methods can be used for the evaluation of thermographic data [6]: (a) the method based on thermal contrast $C(t)$, where the time dependence of the difference between the surface temperature above the defect $T(t)$ and the reference temperature $T_{ref}(t)$ (usually the average temperature of the surrounding sound area) $C(t)=T(t)-T_{ref}(t)$ is observed over the recording time, and (b) the method based on pulsed phase thermography, where Fourier transforms of $T(t)$ and $T_{ref}(t)$ are first calculated and then the difference – a phase contrast $-\Delta\phi(f)$ of the phases of the Fourier transforms is observed as a function of frequency. In the case of a typical defect, such as a void in a medium with a higher thermal conductivity (e.g. concrete), a maximum can be observed in the time dependence of the thermal contrast $C(t)$, as well as in the phase contrast $\Delta\phi(f)$. The values of the time t_{max} and the frequency f_{max}, when $C(t)$ and $\Delta\phi(t)$ reach their highest values, depend, respectively, on the depth of the defect z_{def}, as well as on its geometry, and the material properties. A method for the quantitative estimation of defect depth as a function of t_{max} and $C(t_{max})$ has been proposed by Balageas et al. for carbon–epoxy composites [22]. However, the successful use of this method, which is based on the use of relatively short heating pulses, depends strongly on the physical properties of both the specimen and the defect, and cannot be applied in the case of specimens made of concrete. On the other hand, Arndt et al. [18] introduced an equation which is based on the maximum phase contrast $z_{def}=k_{PC}\sqrt{\frac{\alpha}{f_{max}}}$, where α is the thermal diffusivity of the inspected material, and k_{PC} is a correlation factor which has to be determined for the actual conditions and usually has values that are close to 1.

In this work, the limits for the detection of voids and delaminations in concrete specimens will be defined. The smallest size of a defect that can be detected by thermography at a particular depth is determined using the thermal or phase contrast method. Based on a 3-dimensional numerical simulation of the thermal transfer occurring in concrete specimens containing a void, and the experimental results, the relationship between the depth of the defect and t_{max} or f_{max} is determined. In this way it should be possible to predict the depth of a defect from the results of the thermographic testing of concrete structures.

2. Materials and methods

2.1. Experimental part

2.1.1. Samples

In order to determine the parameters which affect the detection of voids and delaminations, four concrete test specimens were prepared, using the same concrete mixture. Three of them, measuring 50 cm × 50 cm × 15 cm, were prepared at the University of Ljubljana (UL), and were used in part of our previous study [20]. Up to five defects (having either a rectangular prismatic shape, or a cylindrical shape), having different sizes and different amounts of concrete cover, were created artificially inside each of these three specimens, thus simulating voids. The rectangular prisms, which had dimensions of $D\times D\times s$ and are shown in Fig. 1, were made mostly from polystyrene[1] in order to simplify the preparation of the test specimens. They were covered on both sides with concrete (D had values of either 6 or 8 cm, whereas the thickness of the prisms was of the same order as D, but varied slightly with respect to the concrete cover). Some smaller cylindrical air voids, which had diameters of D=3.6 cm, 2.4 cm, and 1.2 cm, were drilled out from the back of the specimen.

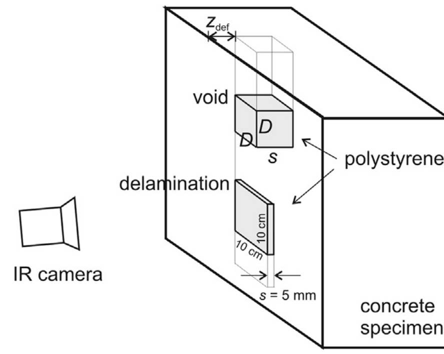

Fig. 1. Sketch of a rectangular prism (forming a void-like defect) and a plate (forming a delamination-like defect) with the marked size D and depth z_{def}.

The fourth concrete test specimen, which had somewhat larger dimensions (150 cm × 150 cm × 30 cm), was prepared at BAM in Berlin. It had a total of 35 artificially created defects, which differed in their shape and size, and in the material used to make them (polystyrene, air, polyacrylamide, wood, water, and metal). The comparative investigations were focused only on the polystyrene and air-filled defects of rectangular prismatic shape, which had dimensions of $D\times D\times s$, as described above (D was 8 cm), and on simulated voids. Thin acrylic glass[2] plates, which formed delamination-like defects and had plan dimensions of 10 cm × 10 cm, and a thickness of s=5 mm, as shown in Fig. 1, were also taken into account.

In our previous study [20], as well as in the present study, no significant differences were observed between the time evolution of the surface temperature above the polystyrene and air-filled defects. Thus both the polystyrene and the air-filled defects are hereinafter referred to as "*air voids*", whereas the acrylic defects are referred to as "*delaminations*". The term "*size of the defect D*" refers to the length of one side of the plan shape of a rectangular prism or a delamination, and, similarly, to the diameter of the cylindrically shaped defects. The concrete cover on top of the void or delamination is denoted by the term "*depth of the defect*" z_{def} (Fig. 1). The properties of all the defects which were taken into account in the case of this study are summarized in Table 1.

2.1.2. Measurements

For the measurements which were performed at UL, a FLIR A320 IR camera with a thermal sensitivity of 50 mK (at 30 °C), a spatial resolution of 1.36 mrad, and a focal plane array with a resolution of 320 × 240 pixels and a spectral range of 7.5–13 μm, was used. At BAM, an INRATEC VarioCAM hr IR camera with a thermal sensitivity of 50 mK (at 30 °C), a spatial resolution of 0.8 mrad, and a focal plane array with a resolution of 640 × 480 pixels and a spectral range of 8–12 μm, was used. In both cases, IR radiators were applied for heating the specimens. At UL, two 1.2 kW stationary heaters were used, whereas at BAM, a 7.2 kW strip-shaped radiator was moved slowly in front of the specimen to make the heating as homogenous as possible. After a

[1] Polystyrene was chosen for simulating most of the air voids since its thermal properties are similar to those of air. Only two rectangular prisms were filled with air.

[2] Acrylic glass was selected for simulating delaminations since the thickness of this kind of defect could be more easily controlled than in the case of polystyrene. The thermal conductivity of acrylic glass is considerably higher than that of air or polystyrene, but is still low compared to that of concrete.