Principle component thermography for defect detection in reinforced concrete structures

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Abstract

Non-destructive Testing (NDT) is an important tool to increase the service life of critical structures. Compared to other NDT methods, Infrared Thermography (IRT) is an attractive method because it is a non-contact technique, and it has full-field defect imaging capability. Typically, two problems are relevant in the domain of NDT of structures. The first problem deals with the detection of defects, while the second problem is based on estimating the defect parameters like size and depth.

This paper aims at enhancing the capability of defect detection of IRT in reinforced concrete structures. Cooling down thermography can be used to identify subsurface structural deficiencies. Defect detection and quantification is rarely a straightforward procedure because of all the signal degradation sources. Pre-processing by traditional image enhancement techniques may help to increase defect/non-defect contrast. However, more sophisticated techniques are often required. In this paper, detection of defects was performed using active thermography technique called Principle component thermography (PCT).

Principal Component Analysis (PCA) is a statistical analysis tool used for identifying patterns in data and expressing the data in a way to highlight the similarities and differences in patterns. PCA applied to the data in the form of thermogram sequence is called PCT. Results of the PCT are empirical orthogonal functions (EOF) constructed from a set of orthogonal statistical modes that provide the strongest projection for the analysed data.

The results of the research conducted by using PCT proved that proposed approach significantly enhances the defective area contrast against the background in the field of reinforced concrete.

Keywords: Nondestructive testing, Infrared thermography, Principle component analysis, Reinforced concrete, defect detection

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Introduction

Although concrete is one of the most versatile and durable construction materials, premature deterioration presents a significant challenge to the individuals responsible for the inspection and maintenance of concrete elements [1]. On the other hand, advances in signal processing, combined with the development of efficient numerical algorithms have made it practical to implement imaging technology into non-destructive testing (NDT) of reinforced concrete structures, among others. With infrared thermography (IRT), the temperature distribution at the surface of any structural element can be recorded as an image, called a thermogram. The use of IRT as a means of structural health monitoring has significantly increased in recent years, due in large part to the advancement of IR cameras and the considerable reduction in their cost [1]. Even though in the inspection of metals, infrared thermography (IRT) is an accepted practice, in the inspection of reinforced and prestressed concrete, the use of active IRT is relatively new. The slow development of IRT for concrete is because, unlike metals and ceramics, concrete is highly inhomogeneous composite material on a macroscopic level with varying composition and different raw materials. In addition, compared to metals, concrete has low thermal conductivity and is thermally inert which means that it takes a lot of energy to manipulate its temperature change, i.e. initiate heat flow in order to use active IRT to detect and/or characterise defects in concrete structures. One has to also consider the dimensions of concrete structures as well as defects occurring in such structures when using IRT [2], [3].
IRT investigation techniques are based on the fundamental principle that subsurface anomalies in reinforced concrete, such as voids caused by corrosion of reinforcing steel, or voids caused by poor concrete consolidation called honeycombing, or pooling fluids such as water infiltration, in a material affect heat flow through that material. These changes in heat flow cause localized differences in surface temperature. Thus, by measuring surface temperatures under conditions of heat flow into or out of the material, one can determine the presence and location of any subsurface anomalies [4].
The only precondition for detection is that defects within the object under examination lead to a sufficient variation of temperature compared to the bulk material [5]. It is well known that IRT has certain limitations when low thermal conductivity materials comprising deep defects are being tested, but at the same time IRT was proven useful when used in conjunction with NDT methods that enable detection of deeper defects [6].
The technique of passive IRT, has been used in civil engineering for the last 50 years. The method has been applied to the identification of internal voids, delaminations, and cracks in concrete structures such as bridge decks highway pavements parking garages, pipelines and other applications [6]–[9]. The main advantage of passive thermography is that it is both a cheap and an environment-friendly technique which provides a perfectly even heating. Disadvantages are the relatively low available heating power and the dependence to weather conditions, to surface orientation, and to the colour of the concrete, as the sun mainly heats in visible light. It has been proven that IRT testing is possible with direct sunlight on the surfaces in question; furthermore, one needs to achieve transient conditions while testing. If transient conditions are not achieved, it was proved difficult, if not impossible to determine the existence of defects in concrete [11].
Bridge decks receive significant attention historically because the decks typically require repair sometime during the service life of a bridge, frequently due to corrosion-induced delaminations [10]. On the other hand application of the IRT for the inspection scenario when concrete bridge components are in shaded conditions that typically exists below a bridge are very difficult if one applies passive IRT. Therefore, active IRT techniques are more and more applied in detecting damages in materials and structures that are not exposed to direct sunlight.
The active IRT depends on establishing a thermal gradient in the material under test where the energy is imported into the target through the use of an artificial external heat source such that significant heat transfer occurs within the material [29].
Most notable of the disadvantages of IRT is its restricted depth of penetration, which limits its application to relatively thin components, and depth of concrete cover. This restriction stems from a combination of reasons, but is fundamentally rooted in an exponential rate of attenuation

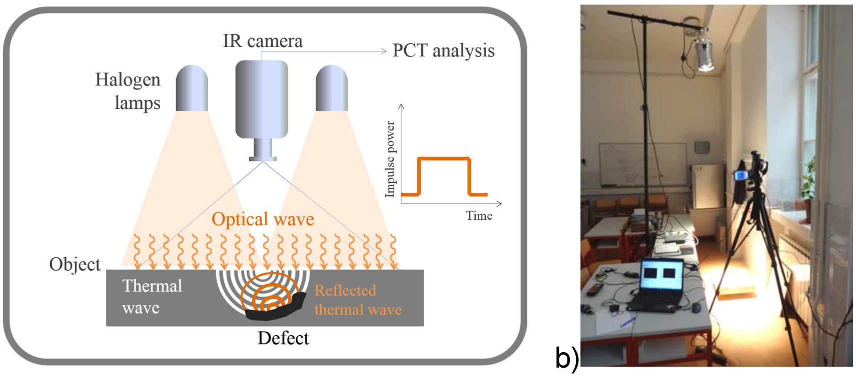
of defect signature with depth – a consequence of the dependence of IRT on processes of heat conduction to convey information about internal structural anomalies [12]. The practical consequence is that defect signatures tend to be subtle, often amounting to temperature changes of tenths of a degree or less. From the standpoint of remote IR detection, this amounts to a difficult technical challenge.
There are several post-processing techniques developed in the field of metals and composites in order to enhance the contrast between defect and sound area. In civil engineering, two of the active techniques, impulse-thermography (IT) and pulse phase thermography (PPT), have proved to be very useful for the investigation of structures close to the surface [13], while lock-in was also by few research groups [14]. On the other hand, the use of the principle component thermography (PCT), as the IRT post-processing technique in concrete structures is scarce.

Principle component thermography

Principal Component Analysis (PCA) is a statistical analysis tool used for identifying patterns in data and expressing the data in a way to highlight the similarities and differences in patterns. For oscillatory signals, the sine and cosine functions comprising the Fourier transform are an intuitive basis, and the projection is expected to be strong, as in case of PPT. In the case of pulsed thermographic inspection however, the temperature response signals tend to be monotonic and, consequently, the case for an oscillatory basis is not obvious [12]. The pattern matching of the data becomes very difficult when data dimension is very high. In such situations PCA comes in handy for analysing and graphically representing of such data.
The method of empirical orthogonal functions (EOF) offers an appealing alternative for these situations. Instead of relying on a prescribed set of basic functions it constructs a set of orthogonal statistical modes that provide the strongest projection for the data.
Once the patterns are found, data is compressed by reducing its dimensions without much loss of information [15]. PCA applied to the data in the form of thermogram sequence is called PCT. The image data captured by the IR cameras consist of undesirable signals and noise along with the IR image data. These image sequences are processed in order to eliminate the undesirable signals and enhance the useful IR information. The PCT used for processing IR sequences is based on thermal contrast evaluation in time, while the PCT analysis is based on the 2nd order statistics of IR image data. The thermograms sequence containing the information about the specimen is processed using singular value decomposition (SVD) based PCT. In the context of thermal response data, the first two functions normally provide an adequate description of the relevant systematic spatial variations, which amounts to a remarkably compact representation [12]. Each orthogonal function is associated with a characteristic time behaviour. Detailed description on the conversion of 3D image matrix into 2D matrix is described in [12], [15], [16]. As mentioned earlier, results of the PCT are empirical orthogonal functions (EOF) constructed from a set of orthogonal statistical modes that provide the strongest projection for the data.

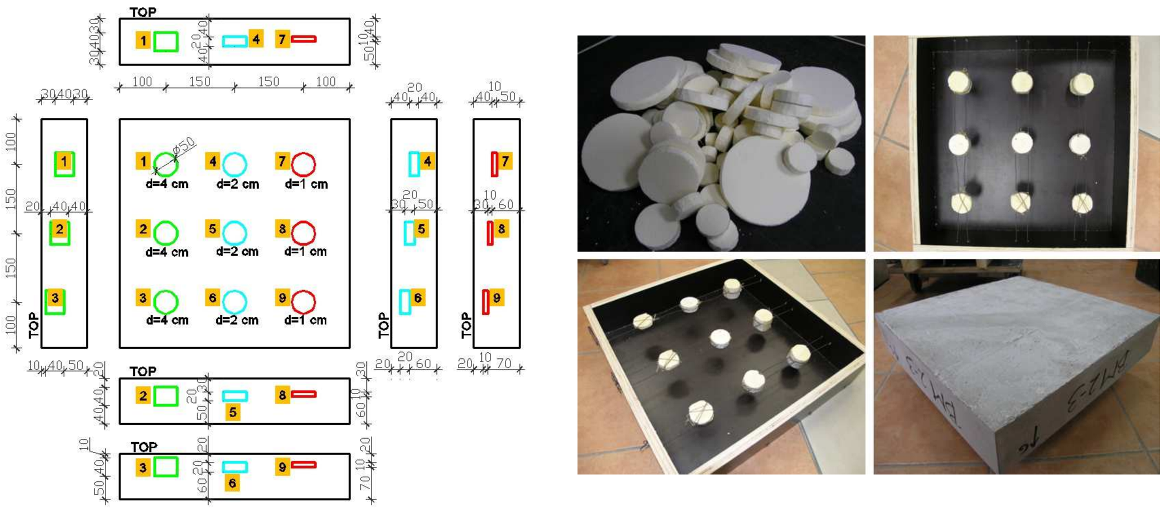
Experimental work

The experimental setup for the performance of IRT measurements is shown in Figure 1. It consists of a thermal excitation unit, an infrared camera and a computer system which enables digital data recording in real time. The research was conducted by using reflecting method (Figure 1), where surface temperature was monitored during 60 minute thermal excitation period, together with the cooling period lasting additional 60 minutes.
Thermal excitation was performed using 1000 W halogen lamp, where heating distances were 1.5; 2.0 and 3.0 m from the surface of concrete specimens, respectively. Within this research specimen size (50×50×10 cm) was defined by the need of transferring the specimens. On the other hand, specimens are large enough to be able to simulate real defects, without the influence of edges or defects between themselves on the temperature field.



a) b)

Figure 1: Thermal excitation of the object under examination using IRT: a) schematic representation, b) photo of the test setup



a) b)

Figure 2: a) Schematics of the specimens BM x-2, dimensions in mm, b) photographs of the concrete test specimens with polystyrene defects

Schematic drawings of the test specimens, with specimens' dimensions, size and location of the embedded defects are shown in Figure 2. The detectability of defects in concrete with active thermography is influenced by their size and depth. Within the presented research, concrete specimens with known defects were prepared. As shown in Figure 2 defect size, embedment depth and thickness were varied in order to determine the influence of geometric properties and depth of defects on the possibility of detection by means of using IRT. Three concrete mixtures have been designed, as shown in Table 1 and Table 2. Concrete mixtures were made with dolomite aggregates D_{max}=16 mm, with the composition as shown in Table 1.

Table 1: Concrete mixture compositions

Concrete ID	**Cement type**	**Cement [kg/m^3]**	**w/c ratio**	**Admixture type and amount**
BM 1-2	CEM III 32.5	271	0.70	Air-entraining agent (0.1%)
BM 2-2	CEM I 42.5R	345	0.55	Air entraining plasticizer (0.5%)
BM 3-2	CEM I 52.5N	425	0.40	Superplasticizer (1%) Silica fume (7%)

The concrete mixtures created in this research simulate three types of concrete that can be found in real structures, differing in their compressive strength, air content and also in their thermal properties, Table 2. The testing procedures and measurement methods used to determine properties of concrete (Table 2) are published elsewhere [11].

Table 2: Properties of concrete used for creating specimens

Property tested	Concrete mixture		
	BM 1-2	**BM 2-2**	**BM 3-2**
Concrete density [kg/m^3]	2194.0	2382.7	2545.6
Air content [%]	10.5	4.6	1.4
Compressive strength [MPa]	18.93	40.99	89.05
Thermal conductivity [W/mK]	1.73	2.21	2.80
Thermal diffusivity [m^2/s]	7.996×10^{-7}	9.074×10^{-7}	1.114×10^{-7}
Emissivity	0.928	0.957	0.958

For simulating compaction defects and voids in concrete, defects made of polystyrene foam have been fastened and carefully embedded into fresh concrete specimens in order to obtain the intended depth. All the specimens were tested from both sides, in order to gather data for as much as possible embedment depths.
To perform experiments presented in this paper, 1000 W halogen lamp was used as the thermal excitation source. IR camera FLIR ThermaCAM P640 with spectral range from 7.5 - 13 µm, thermal sensitivity (NETD) 60 mK was used. The IR camera detector is Focal Plane Array (FPA) detector consisted out of 640×480 individual detectors. The IR camera is connected to the computer and the thermal excitation using the active thermography electronic interface. During the pre-processing, using FLIR ThermaCAM^{TM} Researcher Pro 2.9 software, and MatLab a series of more than 700, 2D thermograms were converted into a sequence. Thus an array i.e. 3D matrix was created, where rows and columns are rows and columns of thermogram and the third dimension gives the temperature change of a pixel in time. Before the post-processing, the region of interest (ROI) on the 3D matrix was defined thus omitting the surroundings and concentrating on the specimens alone. Figure 3 presents optimal thermograms taken from the thermogram sequences after step heating (SH) thermography was used to collect sequences of thermograms.

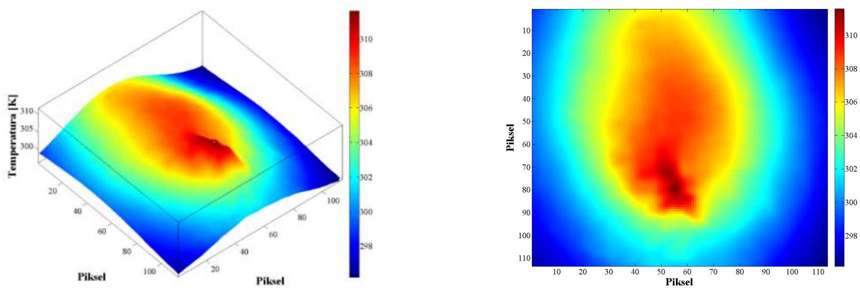


Figure 3: Optimal thermograms of selected specimen configurations, BM 2-2 bottom surface, distance 1.5 m, 3D and 2D representation

It is evident from presented thermograms (Figure 3) that no defects can be located with a sufficient amount of certainty, since the measurements are influenced by uneven heating, and reflectance. Due to the fact that optimal thermograms (Figure 3) cannot be used for location of the defects (especially not for small defects), post-processing of the thermogram sequences was performed where PCT was the technique used for defect detection in concrete specimens.

Results of experimental research

The figures presented in this chapter (Figure 4 - Figure 7) are selected representative EOF's. These figures represent specific specimen configuration, as shown in captions, for the sole purpose to depict trends that occurred during the research. The presented trends can be generalised to other specimen configurations.
Regarding the PCT, it proved to be very useful for detecting small defects. Never the less, it has to be said that one needs to be careful with the interpretation of single EOF, without looking at other EOF's that resulted from the PCT of the thermogram sequence. The characteristic property of the PCT technique is that it can produce EOF's with perfect contrast between defected and sound area, while the following EOF can provide only noise, which can mislead into the conclusion of the defect free area, Figure 4.

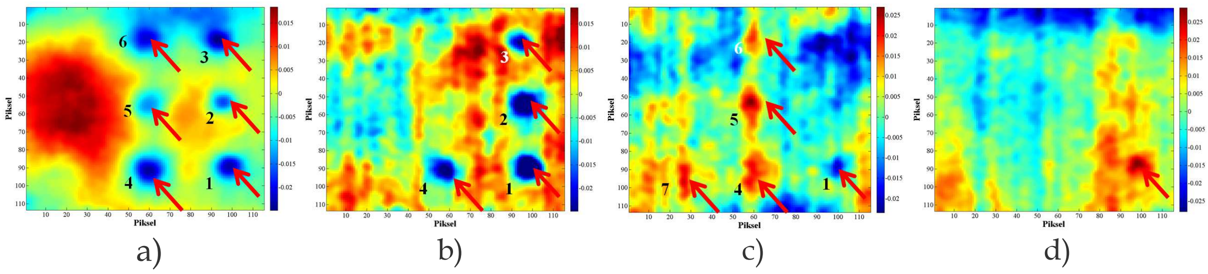


Figure 4: PCT BM 1-2 top surface, distance 1.5 m: a) EOF_2; b) EOF_3; c) EOF_4; d) EOF_6;

Additionally, the reflection is not being removed from certain EOF's by the PCT, which means that EOFs containing reflection from excitation source can be misinterpreted. Nevertheless, reflection can be identified by looking at the sequence of EOFs since the reflection pattern will change significantly in different EOFs while the defects pattern will change only slightly. It was noticed that in case of large defects one can only use first few EOFs while the rest of EOFs produce only noise. Unlike that, when smaller defects are observed one can detect defects in a larger number of EOFs. This proved to be an advantage since by analysing more EOFs, one can rule out the reflections and uneven heating of specimens.

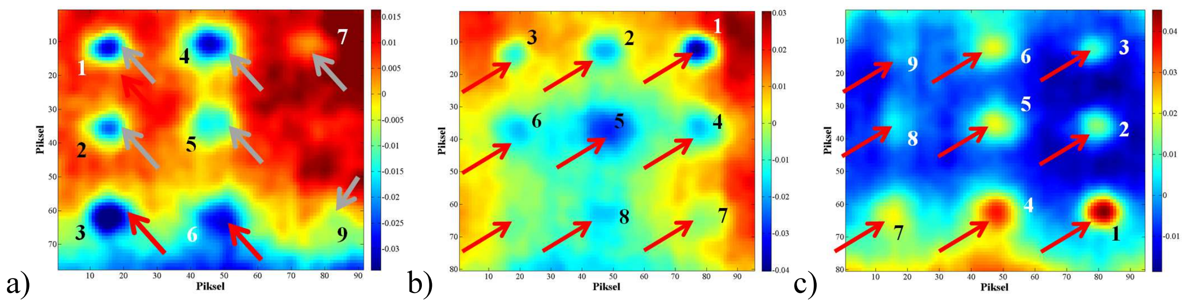


Figure 5: PCT, top surface, distance of 2 m: a) BM 1-2; b) BM 2-2; c) BM 3-2

Concrete quality, measured through its compressive strength, has an influence on detectability of defects when using PCT. This can be explained by the fact that due to the low thermal conductivity, thermal waves could not reach the defect and return back to the surface in the time faster than the duration of thermal excitation of the specimen. On the other hand, due to the high thermal conductivity in case of a concrete of very good quality and dense structure,

lateral diffusion on the specimen’s surface is dominant and it masks the thermal wave reflecting from the defect inside the specimen and thus prevents the defect detection. Examples of the test results gained by using the PCT as a post-processing technique for different qualities of concrete are shown in Figure 5.
If one compares the results of the PCT analysis, it can be concluded that, as expected, with the increased distance, the detectability of defects decreases, Figure 6. This is due to significantly reduced energy that is being introduced into the specimen when the heat source distance is 3 m from the specimens. The detectability could be increased from larger distances if more powerful heat source is used.

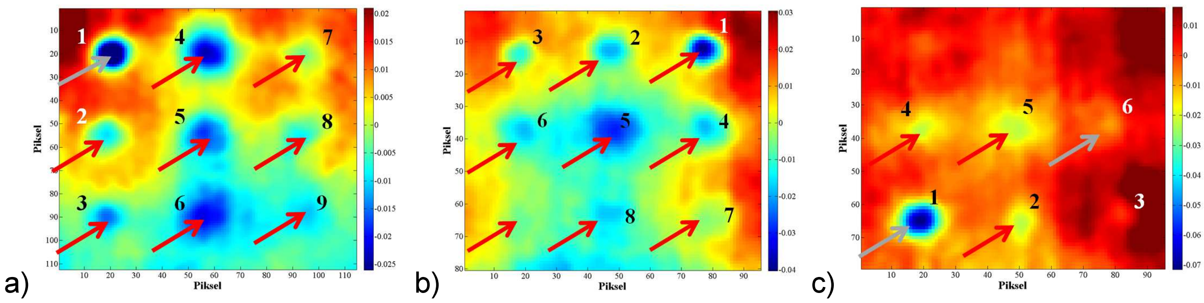


Figure 6: PCT BM 2-2, top surface: a) EOF_2 distance of 1.5 m; b) EOF_2 distance of 2 m; c) EOF_2 distance of 3 m

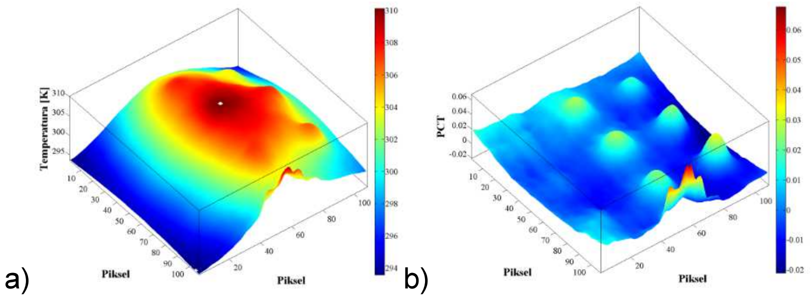


Figure 7: BM 3-2 top surface, distance of 1.5 m: a) Optimal thermogram 3D; b) PCT (EOF_2)

Since the non-uniform surface heating is an inherent source of uncertainty in IRT, one of the most important result of the post-processing using PCT is the fact that EOFs are practically unaffected by non-uniform heating, Figure 7.

Conclusions

Results of the research using the method of active IRT presented in this paper are such that the following can be concluded. Active IRT is a good tool to be used for NDT of concrete structures. It was shown in this paper that can be used for detection of small defects (50 mm) in diameter up to the depth of the concrete cover. The detectability of the defects depends on its depth and the defect thickness. IRT can be used contactless to give direct or processed images of the surface detecting the defects within the structure. Physical and mechanical properties of concrete influence the test results, but it was shown here that with the understanding of characteristics of the measurement system, test configuration, and post-processing technique, it is possible to detect defects using IRT.
PCT post-processing technique is still relatively uninvestigated in terms of detecting the existence of defects by using IRT, especially in the field of concrete structures, since there are

only few research papers published on this topic to the date this paper was finished. Additional research needs to be performed in order to include defect characterization using the PCT.

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