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Quantitative analysis of plastered mosaics by means of active infrared thermography

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HIGHLIGHTS

- Different plastered mosaics were investigated by means of cooling down thermography.
- Numerical calculations were also conducted simulating the actual testing scenario.
- Models' thermal response was studied varying their geometry and thermal properties.
- Experimental testing provided results regarding the detection of the hidden mosaics.
- Numerical and experimental data correlation enabled mosaics quantitative analysis.

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ABSTRACT

The aim of this study was to experimentally and numerically demonstrate the potential of cooling down thermography on revealing and quantitatively characterising hidden mosaic layers, located beneath different covering interventions. Images seeing-through the mortar on plastered mosaic surfaces were obtained using the principles of cooling down thermography, while quantitative information regarding the hidden structures were retrieved through the simultaneous conduction of experimental testing and the conduction of numerical parametric studies, evaluating the influence of specific parameters alterations on the plastered mosaics thermal response. Both experimental and numerical testing were performed based on the assumption that infrared thermography will be able to detect the hidden mosaics, presented with temperature variations on the surface, due to the dissimilar thermal diffusion that each layer renders, while quantitative analysis was performed correlating the retrieved numerical and experimental results. The results of this study verified that cooling down thermography can be considered as a valuable appraisal tool for plastered mosaic investigations, as mosaics detection was possible from the experimental measurements. On the other hand, the combination of experimental and numerical results can expand its capabilities for quantification purposes as promising results were produced regarding the estimation of mosaic depth, thickness and thermophysical properties.

1. Introduction

Among the different Non Destructive Testing & Evaluation (NDT&E) techniques, thermal imaging engenders with the responsibility to accurately obtain subsurface features information without compromising the structural integrity of the test object, resulting to the wide use of infrared thermography as an inspection technique in the cultural heritage conservation field [1,2]. For many years, passive thermography was mainly used as a diagnostic tool for moisture detection and monitoring on historic structures [3], while studies have also demonstrated its applicability to structural integrity evaluations of historic buildings [4]. Nevertheless, the thermographic investigation during and/or after a heating process has been proven to show much more potentiality than the conventional passive approach [5,6]. In cases of multilayered structures, where an inhomogeneous regime is presented, active thermal imaging is very well suited to reveal internal features of interest due to the fact that possible variations of the thermal properties in each layer may produce thermal effects, that can be easily monitored after the application of a heat flow into the

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material bulk [7]. Previous studies implementing active thermography for the inspection of plastered mosaics have shown that the combination of a heating stimulation procedure along with data elaboration through advanced signal processing can result to the acquisition of imaging outputs with enhanced resolution. More specifically, Avdelidis et al. [8] and Theodorakeas et al. [9] used Pulsed Phase Thermography (PPT), Thermographic Signal Reconstruction (TSR) and Principal Component Thermography (PCT) in order to qualitatively analyse the raw thermal image sequences derived from pulsed and long pulsed thermographic inspections. Through the application of advanced signal processing, it was possible to clearly identify the hidden mosaic areas underneath plasters of various thickness and composition, while in some instances individual tiles were also detected. Similarly, Mazioud et al. [10] implemented both numerical simulations and experimental testing on laboratory plastered panels evaluating the effectiveness of active thermography to reveal hidden mosaics and detect the joints between the tiles. The above study showed that while mosaic areas can be efficiently detected by means of active thermography, the plaster joints cannot be revealed if adequate processing is not applied for the treatment of the raw data.

Nevertheless, research studies have also demonstrated that the experimental investigation if combined with the development of efficient simulation tools can make it practical to implement active thermal imaging for quantitative purposes as well [11,12]. For instance, Avdelidis and Almond [13] used the difference between temperature distribution above non-defective regions and above inhomogeneities and the temporal monitoring of its variation in order to acquire information about internal features and characteristics such as the estimation of their lateral dimensions. On the other hand, Maierhofer et al. [14] used the results derived from both numerical simulations and experimental testing in order to estimate the depth of internal artificial delaminations in concrete slabs, prepared under laboratory conditions. Similarly, Vijayaraghavan and Sundaravalli [15] assessed wall loss defects on cylindrical Class Fibre Reinforced Polymer (GFRP) pipes, after conducting experimental studies by means of Flash Thermography and numerical calculations through a 2D heat transfer model.

Based on the aforesaid, the main objective of this study was to investigate and assess the reliability and suitability of active thermography based on the cooling down thermographic principles [16,17], in order to test multilayered structures and identify hidden mosaic artefacts beneath layers of plaster. Moreover, the combination and comparison of results derived from experimental testing and numerical simulations were investigated, with the goal to quantitatively characterise the subsurface features of interest (mosaic layers) and provide a complete set of information regarding their location, thickness and the determination of their thermal properties.

2. Materials and methods

For this study, five (5) assorted panels – 3 mosaic samples consisted of either marble or glass with sheet of gold tesserae, covered with different plasters and two blank samples with just plaster and no tiles underneath them were prepared in the laboratory, simulating different cases of covering interventions. The cross section of an investigated panel is shown in Fig. 1b, while the description of all mosaic samples is presented in Table 1.

The experimental setup for the performance of cooling down thermographic investigations is presented in Fig. 2. In particular for the Cooling Down Thermography (CDT) approach, the inspected specimens were heated with the use of an external 1500 W heat source (infrared lamp of INFRATECH type), placed at the distance of 40 cm from the inspected surfaces. The thermal excitation process was performed for 90 min, while the monitoring of the transient cooling phase was performed for 60 min, through the aid of an infrared camera placed always vertical to the surface of the panels. The thermographic system used for this study (ThermaCAM SC640) was operating in the wavelength region from 7.5 to 13.5 μm and it was a focal plane array with an image resolution of 640 × 480 pixels. For the monitoring of the cooling down process, thermal images were recorded sequentially with a time step of 30 s.

The concept of the measurements performed in the present study, was based on the assumption that infrared thermography will be able to detect the hidden mosaics, presented with temperature variations on the surface, due to the dissimilar thermal diffusion that each layer renders. Thus, each individual measurement was performed by comparing the thermal behaviour of the covered mosaic with respect to the behaviour of the corresponding in terms of plastering reference sample. As a result, the sets of samples studied were as follow: M1–M5, M2–M5, and M4–M6.

For the conduction of quantitative analyses, the transient curves (surface temperature decay as a function of time) from areas above the plastered mosaic and above the blank sample were compared and the produced thermal contrast curves were further plotted as a function of time. The purpose of ΔT vs. time plotting was to monitor how this quantity changes as a function of time and to identify the maximum ΔT_{max} and the maximum time of this occurrence t_{max}. In order to compute the above quantity, two different options were investigated in the sequential analysis of the cooling down process, selecting initially a single pixel above the plastered mosaic and a single pixel above the mosaic-free surface. Additionally, the same analysis was repeated after computing the average temperature values on the two aforementioned areas. As the first option raises the crucial issue of how the control points should be selected (the feature of interest occupies a large volume of pixels in the thermal image), four different points were selected – two on each sample surface-accommodated in diametrically opposed positions between them (pixels T1 and T4 were selected at the centre of each panel, whilst pixels T2 and T3 were selected near the bottom edges, Fig. 1a). By selecting two different control spot analysis procedures, the aim was to evaluate the influence of the heating process non uniformity on quantitative information retrieval.

Along with the experimental testing, parametric studies were conducted in a simulation environment, modelling transient thermal regimes. Through numerical simulations, the aim was to evaluate the mosaic detectability by altering parameters such as the covering intervention thickness, the mosaic layer thickness and the thermophysical properties of the hidden mosaic. The above parametric studies were implemented through the aid of ThermoCalc-3D™ heat transfer model [18], calculating the thermal response of the covered mosaics after the application of a heat flux. This commercial software was developed based on solving heat conduction problems by means of an implicit finite element numerical scheme and simulates thermal non destructive testing scenarios where transient temperature signals over subsurface features are of prime interest. It is intended for calculating three-dimensional (3D) temperature distributions in thermally isotropic and/or anisotropic layered solids that may contain subsurface features. An advantage of the aforementioned modelling software package is its ability to model very thin subsurface features in rather thick materials without losing computation accuracy (the thin sheets of gold on glass tiles were included into the model). Along with the main heating or cooling stimulation, both front and rear surfaces are cooled down according to Newton's law (within such approach, both convection and radiant heat exchange mechanisms are combined and described with a particular value of a heat exchange coefficient). The dimensions of the physical models were 40 cm × 33 cm × 4 cm with the half area referring to the blank