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Evaluation of the state of conservation of mosaics: Simulations and thermographic signal processing

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A B S T R A C T

Nondestructive inspection of mosaic structures is not a novelty in the thermographic scene. Interesting works can be retrieved from scientific literature, some of them dedicated to the use of static active configurations and/or the passive approach for the inspection of plastered mosaics or the assessment of mosaic floors. In the present study, a mosaic made by synthetic tesserae of different colors depicting a dove was inspected by active thermography using a static configuration. The mosaic was manufactured with artificial defects positioned at several depths and locations, where some of them, due to their *dynamic* nature, enabled the monitoring of their thermal effects over time. In particular, the mosaic contains: a void into which compressed air can be injected, a sponge insert that can be soaked by a known quantity of water through an external tube, and a sub-superficial recirculation circuit from which a stream of cold or hot water can flow. The variability of the nature of these defects, simulating what happens in a real case, was conveniently modeled by numerical simulation approaches. The latter point was assessed through the aid of a simulation software, while the comparison of the results obtained by numerical analysis with those derived by thermographic testing was also performed.

1. Introduction

The use of numerical simulations grows year by year, enlarging its field of applicability in several sectors. In particular, the numerical study of thermo-physical phenomena linked to engineering problems is of great importance since the prevision of particular interactions between adjacent materials [1–4] guides the subsequent experimental studies [5–8]. Concerning the study of mosaics, that is the focus of the present work, three articles combined the use of numerical simulation along with the application of infrared thermography (IRT) method [9–11]. Nevertheless, in these studies, the inspected mosaics were not manufactured with non-stationary (*i.e.*, *dynamic*) defects, tending in such a manner to simulate what happens in an actual inspection, in situ. In this work, the authors intend to investigate the behavior of both *dynamic* defects which were simulated by insufflating air or water in reserved tubes and static defects that do not change their position both in time and space. One of the most profitable methods to non-destructively inspect mosaics at a structural level is IRT [12], which has also been used in combination with numerical simulations in several investigations [13–16]. Interesting works can be found in scientific literature in which the IRT method was applied for the detection of static defects [9] [17–19], while other interesting works focused on the same artistic objects in order to characterize their state of degradation and/or the provenance of tesserae [20–22]. But, what is the purpose of studying in detail this type of artwork?

The history of mosaic goes back 4000 years and possibly more,

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with the use of terracotta cones pushed point-first into a background to create a decoration. By the eighth century BC, there were pebble floors, where different colored stones were used to create patterns. It was the Greeks, in the fourth century BC, who raised the pebble technique to an art form, through the design of precise geometric patterns and detailed representations of people and animals. By 200 BCE, specially manufactured pieces (*i.e.*, tesserae) started to be used to give extra detail and a range of colors to the work. Using small tesserae, sometimes only a few millimeters in size, meant that mosaics could imitate paintings. Many of the mosaics preserved at, *e.g.*, Pompeii were the work of Greek artists [23]. Therefore, the preservation of these artifacts in the course of time is of fundamental importance, attracting the scientific community's interest.

The present work describes the *reaction* of a mosaic sample that was stimulated by three different thermal effects, two of which were produced internally into the structure by ducts connecting it with the external ambient and simultaneously simulating internal *dynamic* defects, as well as an external one by delivering thermal energy through a halogen lamp. The prediction as well as the temporal monitoring of the thermal evolution of the internal defects was anticipated by numerical analysis, with the aim of monitoring their growth. Static artificial defects were also inserted into the sample and the position and nature of each one (static and *dynamic*) are described in section 3. The numerical results inherent to the *dynamic* defects, graphically illustrate what happens in a real case. Moreover, it should be stated that at this point of the research, the authors focused their attention to the detection and monitoring of the *dynamic* defects, by leaving the detection of the static defects as a second part and a future study.

Among the *dynamic* defects, a sponge insert soaked by a known quantity of water allowed the study of the evaporation effect produced in a porous medium. Fluid flow through porous media, induced by evaporation, is often a two-phase flow (liquid-vapor) including phase changes and sequential evaporation and condensation within partially-saturated complex pore spaces, driven by capillary gradients, gravity, as well as thermal and vapor concentration differences. These flows are relatively slow with velocities in the range of a few millimeters per day. Nevertheless, such a process is highly *dynamic* and may vary considerably in space and time. The prediction must consider the interplay between internal processes (capillary flow to the vaporization surface and vapor diffusion) and ambient conditions (energy input, air temperature and relative humidity). The phase transition inherent to evaporation processes consumes considerable amounts of energy and alters the thermal field at vaporization planes. Variations in evaporative fluxes from heterogeneous wet surfaces may induce a distinct and spatially variable thermal imprint detectable by advanced thermographic techniques [24], and anticipated by numerical simulation [25]. Similarly, the numerical simulation inherent to the degradation of organic and inorganic materials [26,27], as well as the simulation of groundwater flow [28] reflects the second purpose of the authors. This was obtained by using a known quantity of compressed air pumped into a cavity realized by burying a mushroom in the mortar, and a sub-superficial recirculation circuit combined with a submersible pump, respectively.

The novelty of the monitoring over time of *dynamic* defects in mosaics by using the IRT method combined with numerical simulation is undeniable. Its potential use in real cases similar to that presented herein, which could be another perspective of the present research work, is also undeniable.

2. Infrared thermography (IRT) method

IRT is a rapidly growing remote sensing non-destructive (NDT) method; its application premises the combining of a sensor that detects radiation in the infrared portion of the electromagnetic (EM) spectrum and of a computer system (or processor) that displays a two-dimensional image mapping the surface temperature of an object. In the present case, the experimental setup is schematized in Fig. 1.

In contrast with imaging techniques applied to different wave portions of the EM spectrum, where either reflection or absorption is measured, in infrared imaging it is the emission from the sample surface that is directly detected. Thereafter, the signal representing the intensity of the infrared radiation is processed through the computer subsystem to display thermal maps or thermograms. In fact, the computer system performs complex processing beyond the simple intensity-temperature transformation. It applies the necessary corrections to the measurement and it calibrates the sensor to the absolute temperature values. Some examples in which the computer system of the thermal camera directly acts if the proper parameters are inserted by the operator, includes the elimination of false temperature readings due to reflections from the surroundings or due to reflections from the part under test having low surface emissivity values, as well as the compensation for atmospheric absorption.

In the present study, taking into account the defects' depths, active thermographic approach was selected in order to produce a thermal front on the *tessellatum* layer that will enable heat diffusion into the mosaic and subsequently the study of the thermal effects attributed to the presence of the internal artificial defects. The non-steady thermal condition of the mosaic structure was further enhanced by the disruption of its natural equilibrium with the surroundings, due to the bottom-up effects coming from:

a) The recirculation circuit, which provoked the conduction phase,
b) The water ingress in the sponge insert (*i.e.*, a porous media), which subsequently provoked the fluid transmission through the layers,
c) The injected air flow, which provoked the dispersion of the natural gas through the pores of the mortar.

As previously mentioned, the mosaic's stimulation was performed both by *external* (since the energy was delivered on the surface and then propagated itself through the material until it encounters a defect), and by *internal* (because the energy was injected into the sample in order to exclusively stimulate the defects) systems [29]. As it is possible to understand, mechanical oscillations produced by sonic or ultrasonic transducers (*i.e.*, the typical *internal* stress usually applied in the composite materials field), were replaced in this work with the a), b) and c) points. This, in order to reproduce what happens in a real mosaic exposed to outdoor environmental conditions and natural damage hazards.

The thermal camera described in Table 1 was used in this work. It was positioned 1,40 *m* far with respect to the *tessellatum* layer (Fig. 1). In addition, one halogen lamp with a power of 500 W was installed at 0,60 *m*, with an inclination equal to 35° [30]. The lamp irradiated the sample via a long square pulse (LSP) as thermal stimulus.

2.1. Discussion concerning the external factors influencing the thermographic measurements, and techniques for reducing their impact

The way in which the characteristics of the thermal camera, the surrounding environment and the test procedures may influence the results are deeply discussed in Refs. [31,32]. However, in Table 1 the technical characteristics of the thermal camera used are reported, while thereafter a brief summary of the main concepts