International Journal of Thermal Sciences 129 (2018) 29–46

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Combined experimental and computational approach for defect detection in precious walls built in indoor environments

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ARTICLE INFO

Keywords:
Numerical simulation
Heat transfer
Infrared thermography
Computational fluid dynamics
Indoor environment
Air heater

ABSTRACT

In thermographic non-destructive evaluation (TNDE), the optimal thermal stimulus to be provided on precious coatings applied on ancient walls confined in indoor environments is a complex problem to solve particularly when low temperatures characterize the room where they were built. In fact, thermal stresses are always the concern of any restorer who is interested in determining both the positions and sizes of superficial and sub-superficial defects. In scientific literature, the use of lamps appears to be dominant, but when large surfaces must be inspected in situ, many problems could arise, such as environmental reflections, emissivity variations, and non-uniform heating, which cause false alarms in defect detections.

In this study, the heating phase was carried out by using a wooden tunnel and an air heater. The main physical and geometrical characteristics of these two objects were optimized in order to stimulate the external coating (called "finishing layer" in this study) as homogeneously as possible. In fact, taking into account the very low temperature of the room which contains the inspected aedicule, the energy deposition (heating phase) is enhanced and the energy dispersion (cooling phase) is reduced (thanks to the tunnel) at the same time. This improves the heat transfer phenomenon along the z axis (*i.e.*, the thickness of the wall).

The detection of the defects was performed via higher-order statistics thermography (HOST) technique, which processes the thermal images resulting from the heating and cooling phases. Bearing in mind the low emissivity value of the canary grass (*i.e.*, the finishing layer), the use of heating sources in front of it must be minimized; otherwise, spurious reflections can be recorded and then processed.

In particular, a computational fluid dynamics (CFD) approach implemented via Comsol Multiphysics® computer program was used to validate the experimental setup. This was applied to a couple of cases in the Baiocco's room subjected to restrictions of the Superintendence for Historical, Architectural, and Environmental Heritage of the Abruzzo region (Italy) owing to its high artistic importance.

The exact position of each defect was modelled after a combined visual-acoustical-thermal inspection. An expert restorer helped us in this task. This study is important because, to the best of our knowledge, the problem discussed above has not been solved yet by the scientific community involved in the field of cultural heritage. The results are first thoroughly discussed and second experimentally validated using a combination between thermocouples and ground penetrating radar (GPR) technique, while advantages and disadvantages of the proposed method are highlighted in view of a future perspective of the present work.

1. Introduction

The evaluation of the optimal thermal stimulus to be provided on ancient structures is of vital importance in particular cases, such as when a thermographic analysis is conducted to detect sub-superficial flaws resulting from an earthquake [1–3]. This goal can be attained under laboratory conditions, by using, for example, sensors placed in specimens with the aim to reproduce *intelligent* artefacts [4,5]. Otherwise, the use of numerical simulations would be an attractive and non-invasive alternative [6,7]. The scenario is much more complicated when real objects having a large area must be analysed in situ under unfavourable indoor environmental conditions. Indeed, the thermal

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https://doi.org/10.1016/j.ijthermalsci.2018.02.026
Received 29 May 2017; Received in revised form 23 December 2017; Accepted 22 February 2018
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stimulus to be applied must be carefully selected in terms of equipment, duration of heating time, heat conveyor, and whether the damaged structure is vertical (*i.e.*, perpendicular to the floor).

In the past, many research groups conducted numerical simulations in indoor environments for various purposes. A brief review of CFD and infrared thermography (IRT) method directly linked to non-destructive detection/art restoration applications is reported herein.

D'Agostino et al. modelled the effect of ventilation strategies on the microclimate of the Crypt of Lecce Cathedral (South Italy) using CFD tools. The research allowed to determine how to improve the indoor conditions in the Crypt controlling the ventilation to preserve the monument [8]. Oetelaar summarizes in Ref. [9] the use of CFD in cultural heritage and classical archaeology to help understand the thermal environment inside ancient Roman baths. Two case studies demonstrate how CFD can provide details previously unattainable, such as temperature distributions, and add to the knowledge base of both archaeology and engineering. Troi et al. performed CFD simulation as well as before and after indoor climate measurements accompanying the change of heating system of the Church in Branzoll/Bronzolo, South Tyrol, Italy. The simulations were proven as innovative technique for cultural heritage preservation which facilitates the application of research knowledge on interrelated decay processes [10].

Studies using IRT method to monitor thermal indoor conditions are few, and this motivated the research presented herein. In particular, the mock target IRT, which is a novel technique for in situ measurement of indoor air temperature, was introduced in Ref. [11]. The technique was based on the use of mock targets with appropriate hygrothermal properties. The physics of the examined concept were introduced by employing analytical predictions and numerical analysis using FE simulations performed in Comsol Multiphysics® computer program. Instead, a comparative study of in situ measurement methods of a building wall thermal resistance using IRT was performed in Ref. [12]. Indoor climatic conditions of ancient buildings were also monitored by numerical simulations and thermographic measurements in Ref. [13], while a diagnosis of insulated building walls using passive IRT and numerical simulations was studied by Monchau et al. in Ref. [14]. In their study, the best indoor conditions for the preservation of frescoes and the appropriate schedule for the number of visitors were analysed. The accuracy of two IRT techniques for airflow temperature measurements was evaluated in Ref. [15] during a benchmark test case of natural convection over a horizontal heated plate. In addition, the visualization and measurement of air temperature using IRT were also attained in Ref. [16]. The air temperature was indirectly measured using a low thermal mass screen in conjunction with IRT. A new dimensionless term, called radiation number (Rad), was introduced in a latter work as a measure of the radiation effect compared to convective effect on the measuring screen. Subsequently, a mobile indoor system combined with IRT was used for the acquisition of data required for the quantification of heat loss through a building envelope by conduction, namely temperature values and building geometry [17]. Furthermore, an instrumentation devoted to mapping of indoor ambient conditions by an infrared camera was presented in Ref. [18]. It was used to visualize and quantify the spatial distribution of air temperature, air speed, and mean radiant temperature.

In the present work, the radiative and convective phenomena are the focus of the numerical simulation because an air heater was used during the heating phase [19,20]. The hot air generated was confined inside a heat conveyor (*i.e.*, a tunnel constructed from wood ad hoc) in order to provide a homogeneous thermal stimulus. The heat flux hit two ancient vertical structures built in an indoor environment named Baiocco's room. The heated surfaces were monitored by an infrared camera also during the cooling phase. The post-processing procedure of the raw thermal data allowed the integration of the preventive mapping of the damaged zones performed via finger-tapping test. The numerical simulation demonstrates how the concept of using a heat conveyor when the ambient temperature is extremely low ($\sim 5.5\,^{\circ}C$) must be followed during a thermographic campaign performed in indoor environments. A knowledge of the main thermal parameters of the layered vertical structure under inspection [21], as well as an estimate of the detached and fissured areas can help to understand the optimal thermal flux to be provided on the surface in order to reach the depths to be detected and subsequently analysed. In fact, the core of this paper is the numerical simulation of a particular indoor environment containing cultural heritage objects which are typically irregular and, therefore, require special caution to safeguard the conservation.

In a second experimental campaign conducted in a period of time in which the same environmental parameters were present into the inspected room, the evolution of the temperature in time was also monitored by applying on the surface of the full-centred arch six temperature sensors on strategic positions included in the numerical model. In addition, the surface was also analysed by applying the ground penetrating radar (GPR) technique. In this way, the good agreement between numerical and experimental scenarios was confirmed; the scientific approach initially proposed was then validated in section 5.

2. Materials

On the internal walls of the central hall of the Baiocco's room located in the historical centre of the city of L'Aquila (Italy), there are two aediculae that harmonize the building architecture. They have two different perimeter shapes: one resembles a rectangular portal and the other a full-centred arch. From a visual examination, such aediculae are damaged by cracks on the external finishing layer. Taking into account some collapses occurred near to the analysed areas, it was possible to determine the stratigraphy of the wall. In Fig. 1, the inspected aediculae are shown.

Often confused with *marmorino*, the finishing layer was accomplished following an exceptional and fine hand crafting of the walls. The same can be observed for the floors.

Since the past, the need to find a cheaper material that could replace marble started the search for new combinations of artificial materials. One of the most important examples is represented by the *scagliola*, which is widely used since the 1700s to imitate marble. The perfection achieved with this decorative art material, as well as the excellent state of preservation that still exist after centuries, explains the preference of gypsum over other cement products.

The term *scagliola* conventionally means a mixture of cooked gypsum with a solution of animal glue mixed with pigments and binders of various types. A document dating back to 1984 and kept in the municipal archive of Carpi (Italy) explains in detail the method of *scagliola* production. It describes a mixture of hemihydrates gypsum

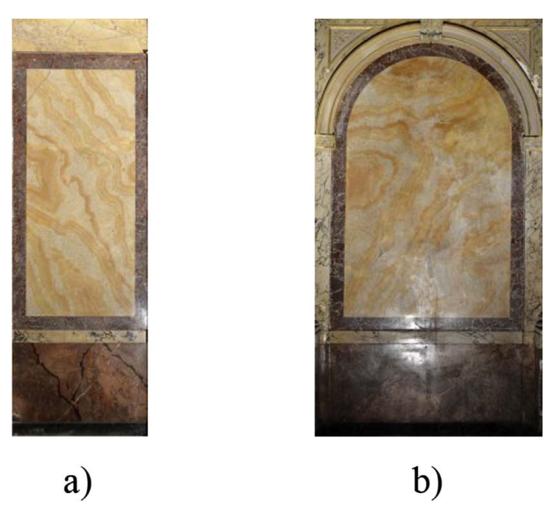

Fig. 1. a) Rectangular portal and b) full-centred arch.

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