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Original article

Diagnostics of wall paintings: A smart and reliable approach

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ABSTRACT

The object of the work is a character of the *Madonna con Bambino* (XIII–XV century) mural painting (Fontecchio – L'Aquila, Italy). It was analyzed by different nondestructive testing (NDT) techniques: electronic speckle pattern interferometry (ESPI), ultraviolet (UV) imaging and infrared vision. In addition, three micro-samplings were collected on suspected areas after examination of the signal strength variations over the raw thermograms. On the latter, the images' quality was enhanced by applying advanced processing techniques. Micro-samplings were also analyzed by scanning electron microscope (SEM), energy-dispersive X-ray spectroscopy (EDS), Fourier transform infrared (FTIR) and μ-Raman spectroscopy. Splitting, subsurface cracks and under-/over-paintings were detected by this integrated method.

1. Research aims

The paper refers to a historical mural painting partially damaged during the 2009 earthquake in L'Aquila, Italy. This dramatic event drew the attention of people from the EU and abroad. The history and landmarks of restoration of the analyzed object are not well documented. Keeping this point in mind, the state of conservation must be understood before the restoration can start. The paper is focused on filling the gaps with important information for the restorers, considering that part of the documentation has been lost and/or is inaccessible for consultation because of the earthquake. Indeed, several libraries are even now seriously damaged and situated in the no-go areas. The proposed physical and chemical analysis can help, if integrated in the proper way, to retrace the history of the mural painting thanks to scientific congruence.

2. Introduction

The diagnostic analysis of the degradation process of artistic heritage has acquired increased importance regarding its restoration and maintenance. Such studies require the analysis of the materials used and an accurate characterization of the degradation products with the aim of evaluating their effects. Technology advances in recent years offer interesting diagnostic tools and methods, such as Fourier transform infrared (FTIR) spectroscopy [1], scanning electron microscope (SEM) combined with energy-dispersive X-ray spectrometry (EDS) [2], ultraviolet (UV) imaging and near-infrared reflectography (NIRR) [3,4], that are deeply changing the art conservation field.

Structural defects in works of art, such as splitting and cracks, can be detected by speckle interferometry methods. In particular, electronic speckle pattern interferometry (ESPI) technique is very promising for in situ diagnostic campaigns [5]. On the other hand,

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active infrared thermography has been progressively adopted in many areas [6]. Square pulsed thermography (SPT), *i.e.*, active thermography using a long heat stimulation, is very useful for the NDT of works of art given its easiness of implementation (large surfaces can be inspected at once, non-uniformities of the heating sources and other unnatural thermal signals are corrected during the processing stage), its rapidity and the possibility of providing quantitative results (subsurface defect characterization) [7,8]. Nevertheless, processing techniques must be used in order to improve the signal-to-noise ratio (SNR), enhance defect contrast and characterize the defects [9–11]. An integrated multidisciplinary approach is now currently accepted in preservation as the drawbacks of a single diagnostic technique can be partially overcome by integration and because of complementariness [12–14].

The particular case of *Madonna con Bambino* mural painting located in the *Piazza del Popolo* in Fontecchio (L'Aquila, Italy), stands inside a devotional niche placed above a drinking trough at the side of the main square decorated with a beautiful late Gothic fountain, offers a fourfold possibility: to characterize the constituent materials and the production technique, to evaluate the state of conservation, to determine the cause of the degradation, and to reconstruct the history of the restoration because the main information seems to be lost. Indeed, there is no historical information about its realization, and an in-depth study for an exact dating has never been prepared [15].

The combined use of X-ray maps [16] and μ-Raman spectroscopy [17] was very useful and powerful to describe the stratification of the artwork; it can be considered as an innovative approach if correlated to the previous cited nondestructive and micro-destructive testing (NDT) techniques.

3. State of conservation of the *Madonna con Bambino* mural painting

As can be seen on Fig. 1a, the interpretation of *Madonna con Bambino* mural painting is severely hampered by the loss of part of the decoration. In the first instance, this phenomenon can be attributed to weathering and placer mining (factors partially confirmed in section 5, Results and discussion, and in the enlargement of Fig. 1b), as well as to the effects of the 2009 earthquake that destroyed L'Aquila city and its surroundings, which led to the detachment of painted portions (see the enlargement of Fig. 1a), taking into account the rounded edges of the damage. Moreover, observing the color distribution, it is possible to note some irregular whitening (see the right side of the picture) and color changes (see the dress of the Virgin and the background) probably due to salt crystallization; even if the authors did not get any analytical evidence, this cause of deterioration can be relate to the location of the painting above a fountain (Fig. 1c – left). Indeed, the raising damp effect has been confirmed by a thermogram acquired in passive modality (Fig. 1c – right) in accordance with International standard ISO 6781-1983 (E), named *Thermal Insulation – Qualitative Detection of Thermal Irregularities in Building Envelopes – Infrared Method*. Readers can distinguish the temperature change that follows the usual bottom-up effect, as well as some acts of vandalism in the enlargement of Fig. 1c, in which the edges of the damage are sharps. The inspected part depicting an Angel (Fig. 1b) can be considered in good state of conservation with respect to the remaining one of the painting. In addition, the very pronounced daily variation of environmental parameters beneath the niche is the source of elastic and/or plastic deformation causing surface alterations over time [18]. It is also important to focus the attention on this problem, in order to introduce the reader to the section 5 inherent to the experimental results.

Concerning the moisture levels in walls, it would be inappropriate to differentiate for theoretical reasons between salt loads and water logging, seeing that salt-free water, apart from attracting algae colonies, has little deleterious effect on wall paintings. It should be noted that liquid water – as differentiated from water vapour – will transport any salt in solution to the level at which the water evaporates. Since water vapour does not carry salts, the latter remain at the level of evaporation, where they crystallize. Their volume increases tremendously, as does the pressure they exert on any surrounding material. Salts have another drawback: being hygroscopic, they tend to absorb humidity from the air. A brick containing no salt will remain almost uniformly dry to extremely high humidity ranges; this is the great advantage of brick compared to other wall materials. Whenever the moisture regimen of a wall or the humidity levels of a room are modified, any salt present responds accordingly. This means that while a moist wall is being dried, additional salt crystals will form; moreover, any salt remaining in the wall will reabsorb water from the air whenever relative humidity reaches significant levels. Further damage to wall paintings is, therefore, to be expected even if drying out the wall is successful. In other cases, relative humidity beneath the niche may be so high and surface temperatures so low that condensation will occur throughout the year, leading to proliferating algal growths over wall painting. See for instance the enlargement of a particular area taken from Fig. 1a, *i.e.*, where the red arrow is located.

Determining if the water is being absorbed from the soil, bounded hygroscopically to salts, or condenses on or within the wall painting, is as crucial as knowing the quantities of salt present. Hence, since the success of any attempt to conserve a painting on a moist wall subject to variable salt levels is strictly linked to precise measurement of ambient parameters, a thermohygrometer monitoring campaign was conducted [19]. The choice follows the criterion of maximum variability of climate conditions, *i.e.*, sunny, cloudy, rainy, foggy within 24 hours. A MHB-382SD data logger by Lutron® installed beneath the niche, was used to record temperature (°C) and relative humidity (%) data, that were subsequently processed by Excel® and finally the graphs reported on Fig. 1d and e. The results obtained are a second key clue that confirms our assumption.

In addition, Fig. 1c shows also the infrared thermography experimental setup for inspection of the mural painting, while on Fig. 1f a presumable cross section of mural painting is illustrated.

4. Materials and methods

References for sounder knowledge of each nondestructive (4.1) and micro-destructive (4.2) analytical method used are here reported: (4.1.1) electronic speckle pattern interferometry (ESPI) [20,21], (4.1.2) infrared thermography (IRT) [6,22], (4.1.3) near-infrared reflectography (NIRR) [4,23], (4.1.3) ultraviolet imaging (UV) [3], (4.2.2) Fourier transform infrared (FTIR) spectroscopy [1,24], (4.2.3) optical microscopy [25], (4.2.4) scanning electron microscopy combined with energy-dispersive X-ray spectroscopy (SEM-EDS) [2,26], (4.2.5) micro-Raman spectroscopy [17,27].

The technical information inherent to the various analysis performed is illustrated in the following.

4.1. Nondestructive analytical methods

4.1.1. ESPI

In our system, the light emitted from a helium-neon (He-Ne) laser, with a power of 10 mW and a wavelength of 0.633 μm, is coupled with a gradient index (GRIN) rod micro-lens to a single-mode fibre, and then split by a bi-directional coupler (10:90) into the object and reference illuminating beams. A CCD (charge coupled device) camera, with 510 × 492 pixels, records the speckle image of the object. In this study, the local statistics-based filtering