Construction and Building Materials 48 (2013) 1261–1265

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

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

Infrared thermographic inspection of murals and characterization of degradation in historic monuments

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HIGHLIGHTS

- IR thermography can unveil in-depth defects in murals.
- IR thermography enables nondestructive assessment of damage in cultural heritage monuments.
- Graduate heating thermography is suitable to characterize degradation of murals from distance and in real time.

ARTICLE INFO

Article history:
Available online 24 August 2012

Keywords:
Non-destructive evaluation
Infrared thermography
Damage assessment
Historic monuments
Murals
Masonries

ABSTRACT

This work presents recent results of infrared thermographic assessment of murals at the "Monastery of Molybdoskepastos" in the Ioannina region (Greece). Infrared thermography is a real-time technique based on monitoring the temperature variation on the surface of materials and structures. This method identifies and interprets differences of surface temperature in the material, enabling the evaluation of damage distribution and accumulation. Infrared thermography is a non-destructive, full field and non-contact technique allowing the characterization of degradation in buildings including historic monuments.

1. Introduction

Monitoring the structural safety of cultural heritage monuments is of great importance. Early assessment of murals, frescoes and masonries condition can prevent irreversible damage and can also provide significant information for the restoration and conservation of the monuments. Non-destructive testing and evaluation techniques are the most suitable for this aim. One of the methods used for real time non-destructive monitoring is Infrared Thermography (IRT). It is a full field, non-contact, fairly portable method and its efficiency in the literature is well documented in the investigation of historic structures. IRT is based on the monitoring of object's surface temperature variation. IR cameras detect infrared radiation emitted by materials and create a thermal image depicting the surface temperature distribution. This thermal distribution is influenced by some physical conditions and material properties such as relative humidity, atmospheric temperature, reflected apparent temperature and material emissivity. The knowledge of materials emissivity is crucial; therefore, many studies on the emissivity of structural materials have been conducted [1–3]. Studies have shown increasing interest in infrared thermography's methodologies. IRT has been successfully used for the damage assessment of historic structures [4,5] and also for the assessment of conservation materials and techniques such as surface cleaning, restoration of masonry by repair mortar and stone consolidation [6–8]. Moreover, infrared thermography has been applied to detect and disclose artificial and in-depth defects such as cork discs, air-filled plastic bags and polystyrene cuboids [9–11], hidden structures like niches and buried openings [12–14], and substrate features as tesserae on a plastered mosaic and sub-surface mural [6–8,15,16]. In addition, one major advantage of thermography applications is the detection of moisture and rising damp in buildings and masonry structures [5,13,17–22]. It should also be mentioned that IRT is a potent tool for damage characterization such as adhesion of frescos, crack mapping [14,16,23,24], insulation deficiencies [20] and can combine well with one-sided ultrasound for assessment of the depth of defects [23–25].

The historic monument (see Fig. 1) studied in this research is situated north of the city of Ioannina (Greece), in the valley of the river Aoos and close to the Albanian borders. It is the monastery of the

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http://dx.doi.org/10.1016/j.conbuildmat.2012.06.062

Fig. 1. The exterior view of the monastery of "Molybdoskepastos".

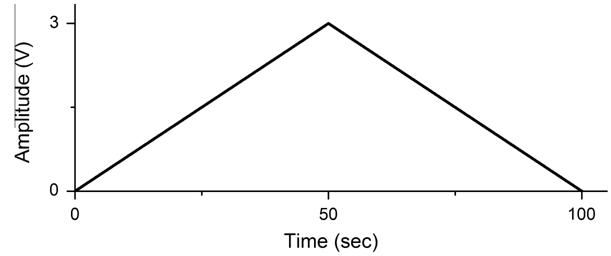

Fig. 2. Thermal excitation rate in graduated heating thermography.

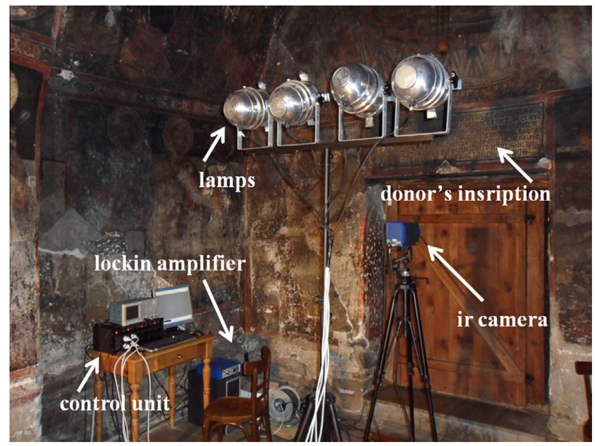

Fig. 3. Experimental setup.

"Assumption of the Virgin", also known as "Molybdoskepastos". This name emerged when the monastery's catholicon was once roofed by lead – "molybdos" – shingles [26–28].

The foundation of the monastery and the establishment of the archbishopric are associated with the name of the emperor "Constantine IV Pogonatos" (AD 668-85) and the tradition is borne out by documentary evidence which may or may not have been invented to supplement the deficiencies of the historians [29]. The catholicon itself has been built in a fairly complex style. It comprises a three-niche church, to the western part of which were progressively added a single-room cross-shaped section then a timber-roofed narthex as well as one chapel upon each of the southern and northern walls of the catholicon, and which are both complete ruins nowadays. The original three niched section, according to the work of researchers, dates from the 11th century; the cross-shaped section from the late 13th or the first two decades of the 14th century; and the narthex on the western side (with many repairs and additions, as it stands nowadays) from the 16th century [30].

The monastery of Molybdoskepastos is stauropegian, which is subjected directly to the Ecumenical Patriarchate. In the 14th century it incorporated a scriptorium; but in the 16th it was at the height of its glory. It was frescoed twice then, in 1521 AD and 1537 AD [31].

There is an interesting donor's inscription over the west door of the church. The text takes up seven lines of script and is dated 1521 AD. Molybdoskepastos has great historical significance and the donor's inscription can give valuable information about the year that the monastery was build or reconstructed.

The aim of this study is the damage assessment of the murals and masonry of the aforementioned Monastery. In order to achieve this goal, infrared thermography inspection, as a non-destructive evaluation method, has been conducted. In the present work, three different IR thermographic approaches were used in order to evaluate the damage of the donor's inscription as well as other parts of the masonry.

2. Experimental study

2.1. Methodology of thermographic investigation

The non-destructive evaluation of a structure using infrared thermography can be achieved by two different approaches, the passive and the active. Active thermography is based on the thermal excitation of the specimen inspected in order to obtain significant temperature differences witnessing the presence of subsurface defects. In this study, three different active thermographic methods have been used to damage characterization of Monastery of Molybdoskepastos's dome and detect in-depth defects on donor's inscription.

The first thermographic method used was the "graduated heating thermography". The increase of surface temperature was monitored during the heating. The heating procedure was achieved using four lamps. The examined surfaces were being heated gradually for 100 s. In the first 50 s the lamps direct current was being increased from 0 to 3 V and in the next 50 s the lamps direct current was being decreased from 3 to 0 V at a constant rate, as it can be seen in Fig. 2. The thermal excitation rate and the duration have been chosen after preliminary experiments on-site, in order to achieve uniform heating of the murals and not to exceed a critical temperature of 50 °C that may cause further damage to the great significance murals of the church [16].

Another method used in this survey was the "Lock-in Thermography" (LT). In this active method, wave generation was performed by periodic deposition of heat on the inspected area through sine-modulated lamp heating while the resulting oscillating temperature field in the stationary regime was recorded remotely through thermal infrared emission. Lock-in thermography is based on the monitoring of the exact time dependence between the recorded temperature signal and the reference signal. The depth of images is inversely proportional to the modulation frequency, so that higher modulation frequencies restrict the analysis in a near surface region [32].

Moreover, the "Pulsed Phase infrared Thermography" (PPT) has been applied. This method combines the advantages of both pulsed infrared thermography and lock-in thermography. In "Pulsed Thermography" (PT) the specimen is heated briefly and then the temperature decay curve is recorded by an infrared camera. The procedure for PPT is based on the Fourier transform. The sequence of infrared images to process which witnesses the temperature decay and follows the initial thermal pulse is obtained as in pulsed thermography. For each pixel, the temporal evolution is extracted from the image sequence. This enables computation of phase images. In pulsed phase thermography the analysis is performed in the transient mode, while in lock-in thermography the signal is recorded in the stationary mode [32].

2.2. Experimental setup

The experimental setup included four lamps (4 × 1 kW) powered with direct current of 0–10 V range for the heating procedure, a control unit for image processing, a lock-in amplifier and two different types of IR cameras. In Fig. 3, the on-site experimental setup can be observed.

In order to achieve the best monitoring of inspected areas structural integrity, two different IR cameras with different bands of infrared spectrum have been used.

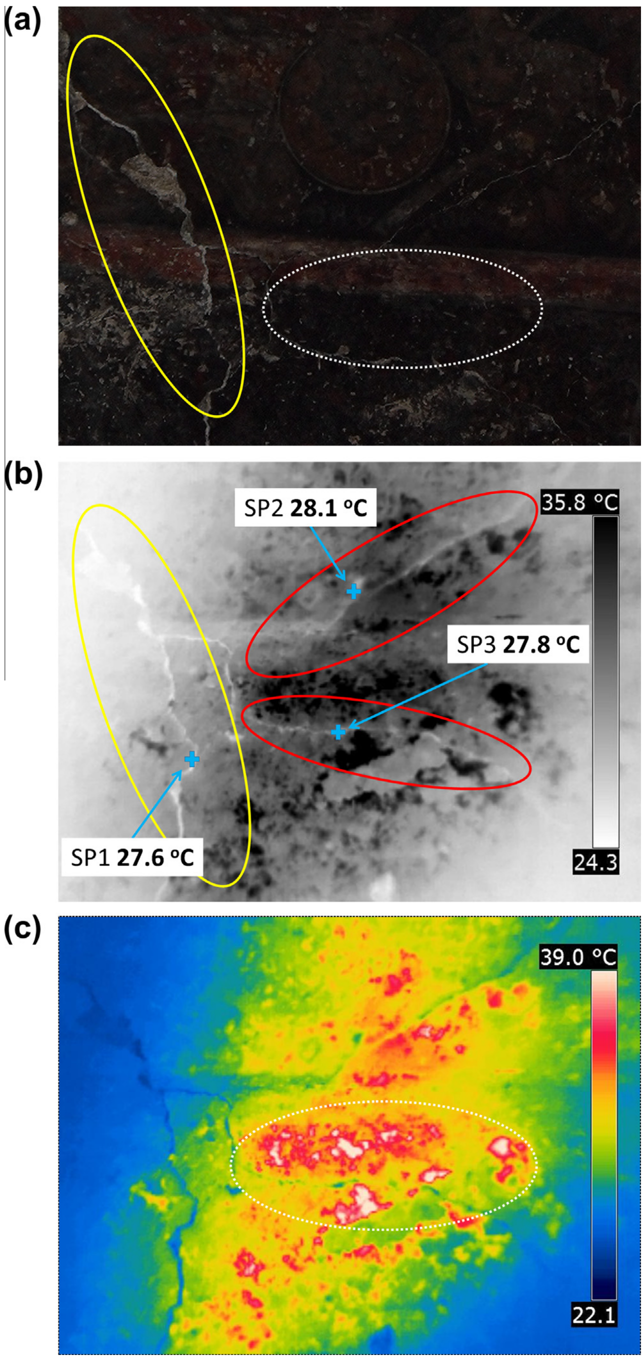

Fig. 4. (a) Murals on roof of the "Monastery of Molybdoskepastos", (b) thermograph of the dome indicating cracks and (c) IR image of the dome indicating delaminations.

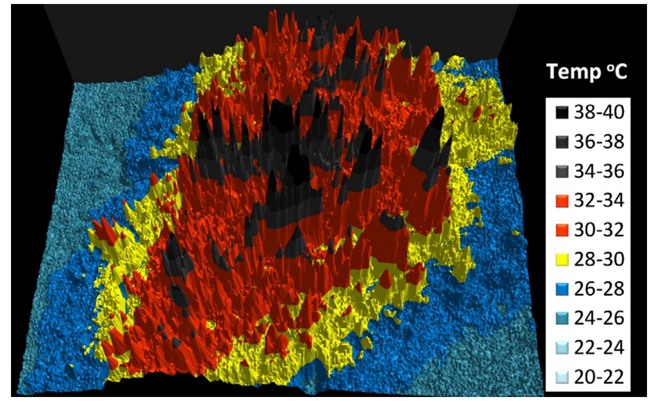

Fig. 5. Three dimension (3D) temperature mapping of the dome.

Fig. 6. The donor's inscription.

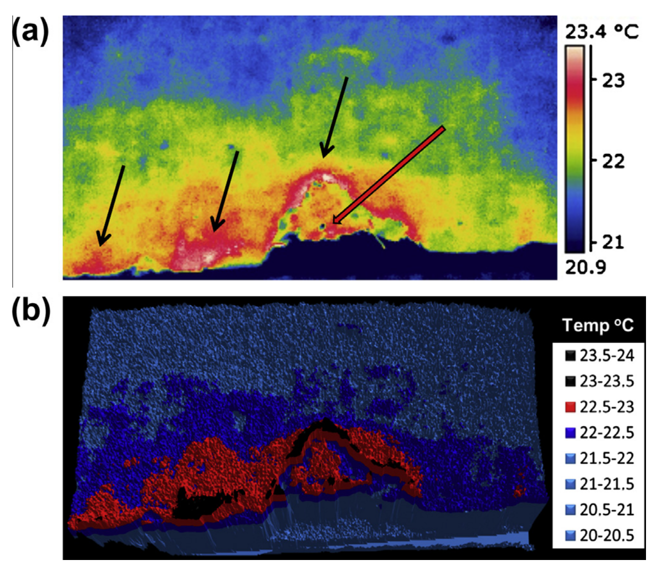

Fig. 7. (a) Thermographic image depicting part of the donor's inscription and (b) 3D temperature mapping of the donor's inscription.

Lock-in and pulsed phase thermographic methods conducted with a mid-wavelength infrared camera (MWIR) CEDIP which has a cooled indium antimonide (InSb) detector (3–5 μm). The frame rate for the experiments of this research was 100 Hz. Moreover, thermographic images have a format of 320 (horizontal) × 240 (vertical) pixels. The noise equivalent temperature difference of this camera is under 25 mK and the optical lens which has been used has 50 mm focal length.

In the "graduated heating thermography" method a long wavelength infrared camera (LWIR) Flir T360 has been used. The LWIR camera has a spectral range of 7.5–13 μm and an uncooled microbolometer sensor. The noise equivalent temperature is under 60 mK. In addition, the optical lens which was adapted to this camera has 18 mm focal length.

Furthermore, the under examination murals do not have a specific emissivity value due to the surface heterogeneity, therefore according to the literature a mean value of 0.75 emissivity has been used.

3. Results and discussion

At the monastery of "Molybdoskepastos" non-destructive evaluation was applied for the assessment of damage characterization. IR thermography inspection was preceded by optical observation

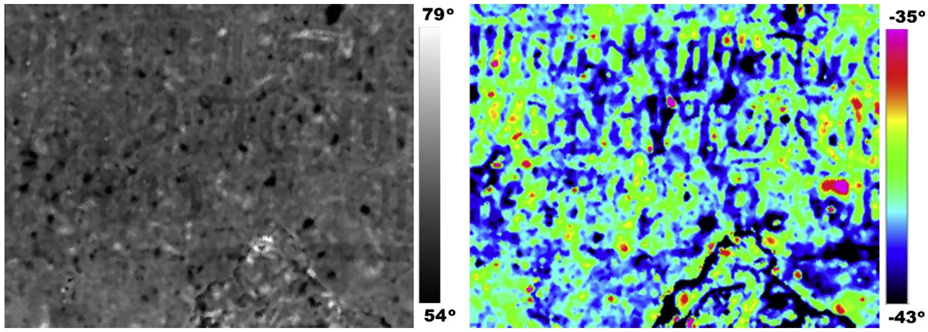

Fig. 8. Lock-in phase images present the substances of the fresco where the donor's inscription is painted.

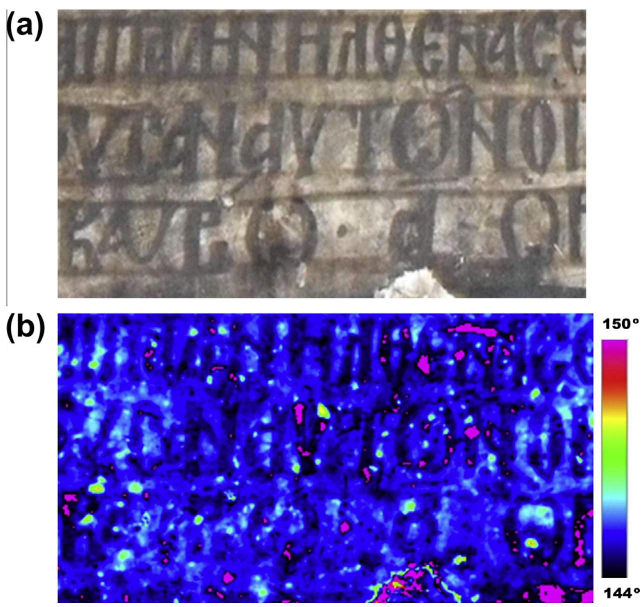

Fig. 9. (a) Digital image of a part of the inscription and (b) pulsed phase image with in-depth defects.

of the monastery indoor space in order to detect specific areas with critical damages and substantial historical importance.

One of the areas that have been inspected in this survey is the dome of the monastery (Fig. 4a). Considering the fact that the dome is five meters above the floor, it is very difficult an optical inspection to be applied. Therefore, "graduated heating thermography" was used for the damage characterization of this mural. On the photograph (see Fig. 4a) there are many critical and surface cracks, while on the thermograph (Fig. 4b) the severity of the cracks can be observed. The visible crack is indicated with yellow circles in both Fig. 4a and b. Moreover, in Fig. 4b additional cracks which are hardly visible, show up clearly in the thermograph and are pointed out with red circles. In addition, comparing the Fig. 4a and b can be deduced that cracks indicated with red circles are not only surface damages but they are as critical as the cracks with yellow circle. This can be assumed from the same temperature variation illustrated in both types of cracks which is clearly indicated with exact temperatures of the spots in Fig. 4b.

Additionally, the infrared thermography inspection revealed the existence of delaminations and detachments on the mural of the dome. To elucidate this, the accumulated heat in the part of the mural that can be observed in Fig. 4c, indicates that this part of the mural has been detached. This extended detached area is marked with white dot-line circle in Fig. 4a and c. In order to further highlight the remarkable temperature variation in the delaminated area, the three dimension (3D) temperature map was plotted (Fig. 5) from the extracted thermographic data.

Fig. 5 illustrates the distribution of inspected area temperatures in a 3D graph. The *xy* surface in the graph shows the pixels of the thermograph and the *z* axis indicates the temperature of each pixel. The detached area is depicted with grey and black colors which correspond to the temperature range of 34–40 °C.

The thermographic inspection of the mural on the dome resulted that this area requires immediate restoration in order to prevent additional irreversible damage.

Another area of interest that has been examined is the donor's inscription above the west gate of the church. Donor's inscription provides very useful information about the year of church's foundation and further historical details. A part of this inscription has been destroyed as it can be seen in Fig. 6. The inspected area was chosen near the destroyed part of the inscription in order to assess the possible existence of further damage (see in Fig. 6 red circle).

The donor's inscription was evaluated with LWIR and MWIR cameras employing all the aforementioned thermographic methods. Concerning the graduated heating thermography method, the increment of the temperature near the area of the destroyed part of the mural discloses three detached regions (indicated by black arrows) as it can be seen in Fig. 7a. The region indicated with red arrow corresponds to the destroyed area in which has been revealed an older donor's inscription (see Fig. 6). In this region, an increment of temperature can be observed. This is due to the different depth and material type. Therefore, this indication in the thermograph was not considered as subsurface damage or delamination. The experimental data of the thermograph in Fig. 7a was also illustrated in a 3D temperature mapping plot. As can be noticed from the Fig. 7b, the black areas corresponded to the range of 23–24 °C reveal more clearly the presence of delamination and detachments.

The second method that had been applied was the lock-in thermography which has been contacted by a MWIR camera. In Fig. 8 it can be observed an assortment of different shape and geometry patterns due to the phase variation depicting the substances of the fresco used to paint the mural, such as straws, wires and gravel. The implementation of this method has resulted in the better assessment of the fresco's substances.

The mid wavelength infrared band has been used in the third thermographic method. Pulsed phase thermography revealed very interesting results concerning the in-depth defects. Fig. 9 depicts the digital photo and the phase thermographic image of the inscription. According to the IR image (Fig. 9b) the magenta spots correspond to subsurface defects not visible in the digital image (Fig. 9a). These intense variations in the obtained thermographs can be attributed to the historical elements. To elucidate this, in one indoor area of the church, where some murals were partially destroyed, preexistent murals have been revealed. As it can be

Fig. 10. Mural with artificial holes.

observed in Fig. 10, there is presence of holes caused by hagiographers in order to fasten up the new murals. More specifically, the magenta subsurface defects shown in Fig. 9b correspond to a significant variation in phase of about 5 degrees compared to the phase of visible letters. These spots of Fig. 9b have not the same shape or geometry with the holes of Fig. 10 due to the fact that the holes beneath the inscription are partially filled with fresco. In addition, it should be mentioned that the holes was made by hand, therefore their orientation do not follow an exact pattern. Therefore, the PPT has the potential to detect in-depth defects.

4. Conclusions

This study demonstrates that IR thermography is a powerful method enabling nondestructive assessment of damage in cultural heritage monuments. Specifically, this full-field method is suitable to characterize degradation of murals from distance and is a useful tool to draw conclusions in real time about the state of damage in historic monuments. This work led to interesting results about the inscription, enabling the damage evaluation and characterization. Furthermore, the thermographic assessment of the mural on the roof resulted in valuable findings such as critical surface and sub-surface cracks, and extended detached areas causing concern about its structural integrity. However, further work should be done in the identification of in-depth defects applying an addition NDE method such as ultrasonic to compare and establish these findings.

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