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Thermographic inspection of cracks in the mixed materials statue: Ratto delle Sabine

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Abstract

This work describes a simple use of active Infrared Thermography developed to detect the level of weathering of a statue with respect to cracks observed on the surface. The statue "*Ratto delle Sabine*" of Giambologna is exposed in the Galleria of the Accademia in Florence-Italy and was the object onto which the methodology of analysis was used. Radiographic analyses indicated that the statue was originally made out of composite materials (mainly wood and tissue at the inner part and raw clay at the outer part). This artefact is a model which was originally not conceived to last for a long time and nowadays shows severe cracks. Thermal investigations have been done in laboratory and in field to evaluate the level of weathering of the statue, in particular related to the previously mentioned cracks. The main purpose of this study was to find a way to detect and/or demonstrate eventual interconnections between the different cracks and to evaluate the state of weathering of the statue. The methodology is based on insufflating hot air locally into the cracks of the statue during a short time, monitoring at the same time the surface temperature evolution near to the place of inflow and observing if the hot air emerges at the opposite side.

To assess the eventual danger of this methodology of blowing in hot air locally, preliminary tests were made in laboratory using samples composed out of different combinations of materials (raw clay, wood, tissue, etc.) similar to the ones composing the statue. Such tests have shown that a heating time of a few minutes was sufficient to highlight the leaking of warm air from the inflow opening to the back side and this without an excessive temperature increase of the surface near the infiltration point. This was done respecting the conservation restrictions and rules for the these materials. Results in lab and field demonstrated the potential efficiency of the method to monitor the conservation state of this fragile artefact. In this specific application the method allowed to identify four critical points in the "*Ratto delle Sabine*" model.

Keywords: Active and passive infrared thermography, Ratto delle Sabine model, Cracks, Cultural heritage weathering

Introduction

In order to preserve the "*Ratto delle Sabine*" model the Ministero dei Beni e delle Attività Culturali e del Turismo commissioned the restoration of this work of art. Before intervening, numerous analyses were performed by different scientists to study this particular statue. One of them foresaw the use of infrared thermography.

During the last decades, the Infrared Thermography (IRT) has evolved into a powerful non-destructive tool to study the state of Cultural Heritage artefacts and monuments. IRT is applied following two different approaches: "passive thermography" when only the naturally occurring temperature variations in the object need to be analysed and "active thermography", when an external stimulus is needed to produce relevant thermal contrasts. To highlight the presence of anomalies or the different thermal behaviour of the materials (evidencing for example cracks or detachments), both techniques require differences in temperatures of at least a few degrees.

Infrared thermography (IRT) has been widely applied to study buildings [1,2], monuments [3,4] and frescoes [3,5-9] and to analyze other artefacts such as paintings (wooden paintings and canvas) [9-14] or sculptures [15-18].

The "*Ratto delle Sabine*" (Figure 1) is one of the oldest preserved models at a 1:1 scale, constructed by Giambologna between 1579 and 1580. It was used as model for the realization of the final marble statue and,

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Figure 1 The model statue of The "Ratto delle Sabine" of Giambologna.

therefore, it represents an interesting opportunity to investigate the sculptural capacities of Giambologna.

The radiographic analysis[a] [19] and the visual inspection of the surface during restoration[b] [20] showed that the model is composed mainly by raw clay in the outer part and by several different materials in the inner part. In particular the radiographic inspection [19] showed the presence of a core composed of various wooden elements differing in type and dimensions, in most cases joined together by nails in metal. In other parts of the "*Ratto delle Sabine*" model the bonds seem to be made by means of joints and/or bandages. In the construction of some parts of the artefact (stomach and head of the Romano warrior) materials have been used which are lighter (e.g. cloth) than raw clay. This was probably done in order to make the work lighter and less subject to withdrawal during the solidification of the entire statue [20].

The different physical properties (in particular the specific weight) of the materials, related to the use in the model caused the formation of several cracks of the raw clay, a material which delaminates easily thereby increasing the rupture risk [20].

In exposition places (ex. museums, galleries, etc.), where the environmental conditions need to be controlled within small ranges to avoid thermal stress to the artworks [21], the use of passive thermography is often unsuccessful because the work of arts do not show relevant differences in the surface temperature distribution. In these cases an active approach of the thermography is required to make relevant thermal contrasts of the defects like cracks visible.

In order to analyse the eventual interconnection between the cracks previously identified by other investigations (radiography and visual inspection) of the "*Ratto delle Sabine*" model, a more localized methodology of active infrared thermography was set up. This would lead to the understanding of which specific parts of the model are more at risk of further damage and prevent any potential falling down of parts of the statue due to gravity.

In this case the usual heating (halogen lamps, thermoconvectors, etc.) used in active infrared thermography is not suitable, because heating of the entire surface would be required, causing an important temperature increase of the parts of the artefact not affected by cracks and risking to increase the temperature over the acceptable limits (Table 1). Furthermore, such thermographic measurements on one side allow to highlight the presence of anomalies of the statue, but on the other side are not able to discover or demonstrate the interconnections between the cracks.

For these reasons and considering also the historical and artistic importance of the artefact, a more localized heating methodology has been considered, allowing on one side to visualize the connected cracks and on the other side to reduce potential damages directly related to excessive heating of the whole statue.

Table 1 Wood thermo-hygrometric values

		T (°C)	ΔT (°C)	RH (%)	ΔRH (%)
UNI 10829 - 1999	wood	19 - 24	±1,5	45 - 60	±4
Thomson		15-25	±5	50-60	

Optimal thermo-hygrometric variables by UNI 10829 – 1999 and Thomson (Aghemo et.al. [23]).

Method

In order to highlight connections between crack's by means of infrared thermography in museum environments where the artefacts are most of the time in thermal equilibrium an active approach is necessary to create temperature differences of a few degrees.

The fact that different materials are used in the composition of the "*Ratto delle Sabine*" model made our study very demanding because of the different thermophysics properties (thermal inertia and conductivity) of these materials. The radiographic survey campaigns showed that the inner structure of the model is composed out of organic materials, in particular wooden elements (of different dimensions and types) with metal joints in some parts, while in other parts the junctions are made out of lighter materials, like straw, or by means of dovetail and/or bonding with bandages. The external parts are completely out of raw clay, which is a very fragile material and delaminates easily.

For the reasons described above, this statue of Giambologna is a peculiar case of an artefact composed out of internal materials that could be subject to more degradation than the outer parts.

It is known that the organic material, wood in this case, needs well controlled environmental conditions for a good conservation, above all relative humidity (RH). Indeed, humidity affects the equilibrium moisture content of the wood. The temperature variations, influencing the RH variations, have a secondary effect on the wood behaviour, but not necessarily less important. Moreover wood is a material characterized by a long response time to the thermo-hygrometric variation of the environment. Table 1 shows the indications for safe daily temperature variations of ±1,5°C and ±5°C suggested by UNI 10829 – 1999 and Thomson respectively [22,23].

Taking into account these temperature limits for wood, it was decided to heat the places where the cracks were visible only for a short time in order to show the interconnections between the cracks, but avoiding at the same time temperature increases higher than ±5°C as indicated by Thomson.

The method consisted in introducing warm air (about 50°C) directly in the cracks considered critical, in particular from the static point of view, and checking by thermal camera the corresponding outflow of the warm air flow at the opposite side of the infiltration point. The heating system used was a conventional thermal convective portable device with a power of 1200 W. In order to heat only localized parts corresponding to the crack a soft plastic tube covered with an aluminum foil and directly connected to the thermal convective device was used. The aluminum foil avoids the influence of the surrounding radiation on the heating process. The thermal measurements were performed with at AVIO TVS 700 thermal camera operating in a spectral range (8–12 μm), with a microbolometer detector (320x240 pixel) – not cooled. The temperature range of the camera was set to (−20; + 400) °C with a thermal sensitivity of 0,07°C (at 30°C). Because the "*Ratto delle Sabine*" model is mainly composed out of raw clay and wood the emissivity value inserted in the thermal camera was 0,9.

During the local heating process the increase of the surface temperature around the target crack has been monitored in order to control eventual overheating of the other parts of the structure.

Laboratory experiment

In order to evaluate the effectiveness of the method several trials were first performed in laboratory using samples built with materials (e.g. raw clay, wood, metal nails and straw), characterized by thermo-physical properties close to the ones of the statue.

The laboratory test model was made by using hollow bricks, of which the thermal properties are close to the ones of raw clay of the statue. The holes of these bricks were filled with different combinations of the previously mentioned materials. Filling was done in such a way that a free pathway (average diameter of a few millimetres similar to those previously observed in the "*Ratto delle Sabine*" model) is left to allow for the flow of hot air. Warm air passed through these pathways and allowed us to determine the heating times required for the warming up of the cracks at the outer end whilst avoiding significant and dangerous increases of temperature nearby the inlet of the hot air inflow. Before manufacturing the laboratory samples the characteristics of the free paths (depth and length) to be copied were defined in the field by comparing the radiographic results and the cracking framework, obtained from other studies made within the restoration project.

The bricks simulated the raw clay envelope of the "*Ratto delle Sabine*" model because both are composed out of the same material: clay (thermal conductivity 0.383 [$Wm^{-1}K^{-1}$] specific heat 2190 [$JKg^{-1}K^{-1}$] and density 1.29 [Kgm^{-3}] [24]). The only difference is the procedure of drying: the brick is dried in a furnace (between 800°C and 1200°C [25]) whilst the statue envelope was left to dry at environmental conditions under the natural heating of the sun. Therefore we can consider that the brick simulates the statue envelope in terms of thermo-physical properties.

The results reported in this paper are related to the samples with following dimensions : 15x31.5x4.5 cm. Two types of filling were used: mixed materials (wood, straw, raw clay) and raw clay only. In this way, the two extreme scenarios existing in- situ are simulated. In fact, on one side the raw clay only sample simulates the more superficial cracks of the statue whilst the sample composed of mixed materials simulates the cracks

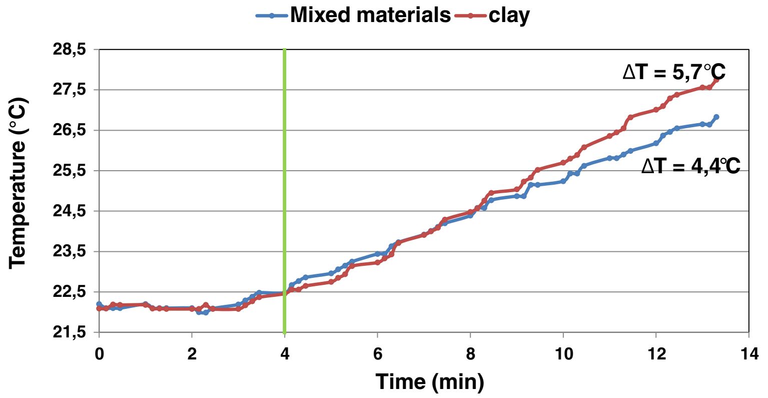

Figure 2 Temperature increase of the samples surface. Temperature increase of the samples surface, for raw clay sample (red line) and mixed materials sample (blue line).

crossing the parts of the structure composed mainly out of organic materials. The free paths in these samples were realized at a depth less than 2 cm from the surface.

Results

Laboratory tests

The first step was to demonstrate in laboratory the applicability of the methodology on samples and to define the limits to be respected before performing the measures in-situ in order to avoid damage to the materials composing the "*Ratto delle Sabine*" model.

First, the minimum heating time was established observing the temperature near the inflow hole during the procedure. The Figure 2 shows the increase of the surface temperature around the inflow hole during the heating time in the samples composed by mixed materials (blue line) and by raw clay only (red line).

As it is not possible to measure exactly on the surface of the hole due to the physical presence of the pipe connecting the brick with the heating device, the heating of the material was evaluated by following the hottest spots near the holes. These spots, taken as reference points, were found to be at about one cm from the input hole.

It can be noted (Figure 2) that the temperature rise was only 0,5°C for both samples after a heating time of 3–4 minutes (green line), supporting the assumption that the temperature rise of the material around the hole does not exceed 5°C indicated by Thomson as a good conservation limit.

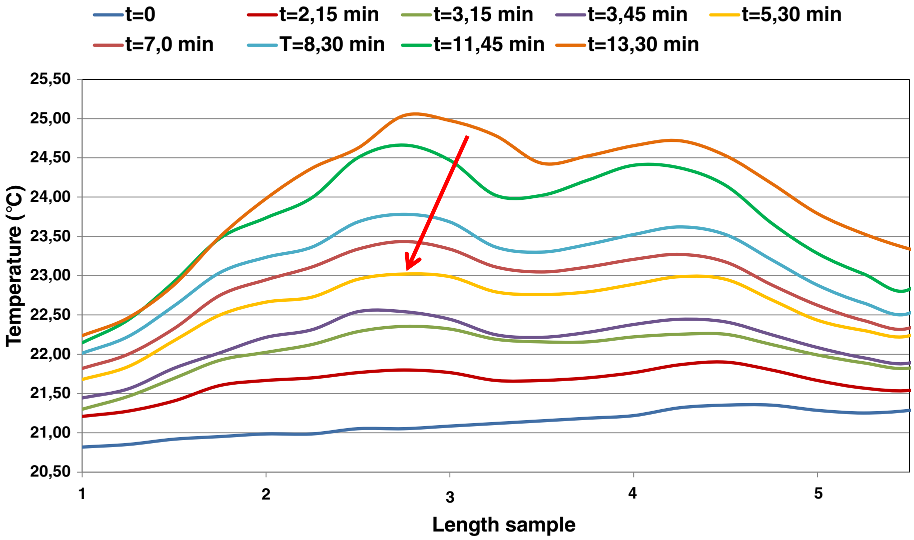

Figure 3 The surface temperature increase at the back side of the inflow hole (mixed materials sample). The different curves indicate the increase vs time of the surface temperature at the back side. It can be observed that during the heating of 13,3 minutes the temperature increases with 3,7°C and after 3–4 min the temperature increases of about 3°C (red arrow).

Table 2 Thermo-hygrometric values by UNI 10829 -1999

		T (°C)	ΔT (°C)	RH (%)	ΔRH (%)
UNI 10829 - 1999	fabrics, upholstery, silk etc.	19-24	±1,5	30 - 50	±6
	chinaware, ceramics, stoneware, earthenware etc.	NR[1]	—	NR[1]	±10
	metals, metal alloys, coins, bronzes etc.	NR[1]	—	NR[1]	<50

Optimal thermo-hygrometric variables for different materials composing the "*Ratto delle Sabine*" model.
[1] NR: Not relevant.

The very low value of the temperature at the inflow hole was explained by the heat loss of the warm air inside the pipe (40 cm long) and by the shielding of the pipe at the entry the hole making the heat spreading inside the specimen rather than on its surface.

As consequence, a heating time limit of 3–4 minutes was assumed. The Figure 3 shows the temperature increase at the back corresponding to the outflow in the samples with mixed materials. It can be noted in this figure that a heating time of 3–4 minutes was enough to observe a temperature increase of about 3°C (red arrow). This limited increase of temperature confirmed the applicability of the methods also for a real case and the applicability of this thermographic technique by means of a localised active approach.

Moreover, Table 2 indicates that there are no particular temperature restrictions for a good conservation to apply the methodology in the raw clay samples and that the applied time of heating on the parts of statue constituted by raw clay only depends mainly on the path that the warm air has to cover across the connected cracks. The Figure 4, which represents the temperature increase at the back caused by the air leaking across the crack in presence of raw clay only material, shows that also in the case of raw clay samples a heating time of about 3 minutes (red arrow) is enough to highlight the escape of hot air at the opposite side of the inflow point. In fact the Figure 4 shows that the temperature rise at back side is about 3°C. This is optimal to perform the thermographic measurements.

We can assume for both samples that the temperature increase of the materials near the point of outflow is less than 3°C, because of their thermal inertia.

In conclusion the experiments performed in laboratory confirmed the possibility to apply the methodology in-situ without any risk for the statue of "*Ratto delle Sabine*" model. These measurements will permit a first evaluation of the state of weathering of the different cracks, visible on the surface of the statue.

In field measures

Several examples of thermal images recorded in field on the "*Ratto delle Sabine*" model after the application of the localised heating methodology on different points are shown, demonstrating the efficiency of the methodology.

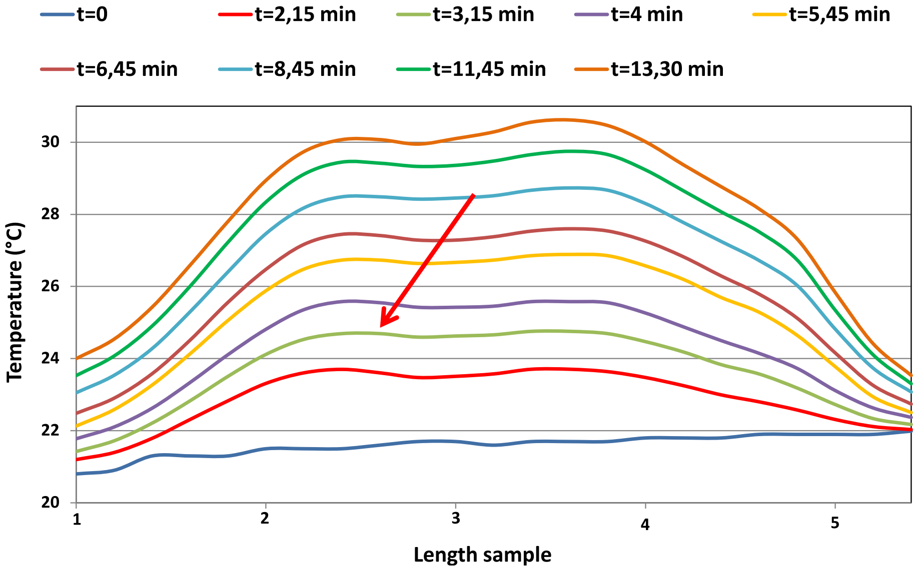

Figure 4 The surface temperature increase at the back side of the inflow hole (raw clay sample). After 13,3 minutes the temperature increases with 8,6°C and a heating of 3–4 minutes are enough to increase temperature of about 4°C (red arrow).

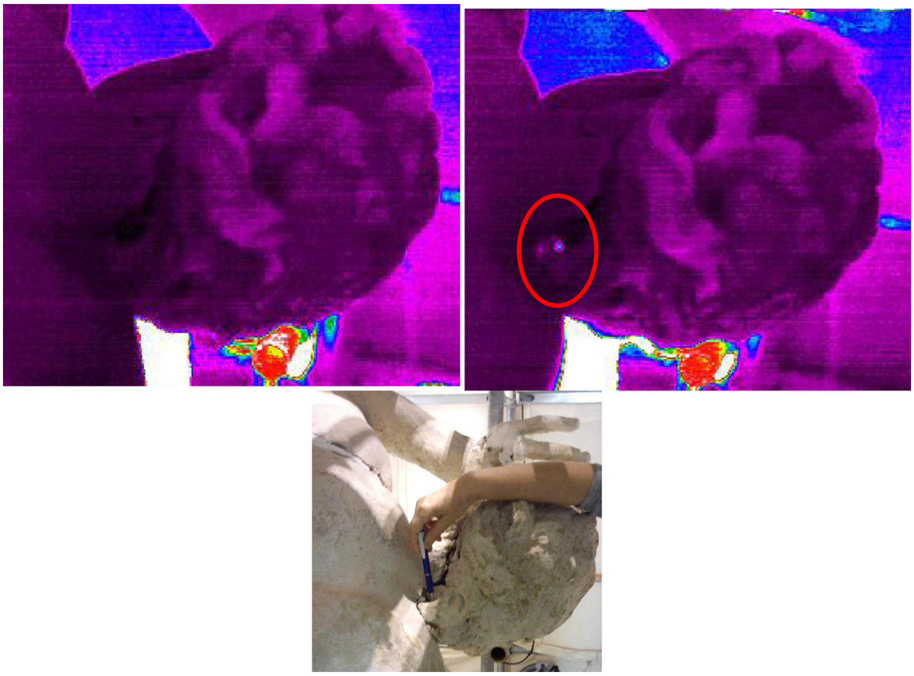

Figure 5 Thermography related to the heating of localised zone in the head of the Sabino warrior. The thermal picture on the left represents the surface temperature at the beginning of heating, the right picture after about 4 minutes. The exit of the warm air showing the connection between the 2 sides of the head is clearly visible (red circle). The inflow point is out of the field of view of the thermal camera.

Figure 5 shows the thermal images performed on the head of the warrior which presented a visible crack on the surface (indicated on the imagine on the bottom of the figure). The outflow of the warm air from the back of the head indicates that a connection of the crack from front to back of the head of the Sabina warrior was present.

On the contrary Figure 6 shows an example of non-connected cracks, demonstrating that they were not harmful for the conservation of this part of the statue. In

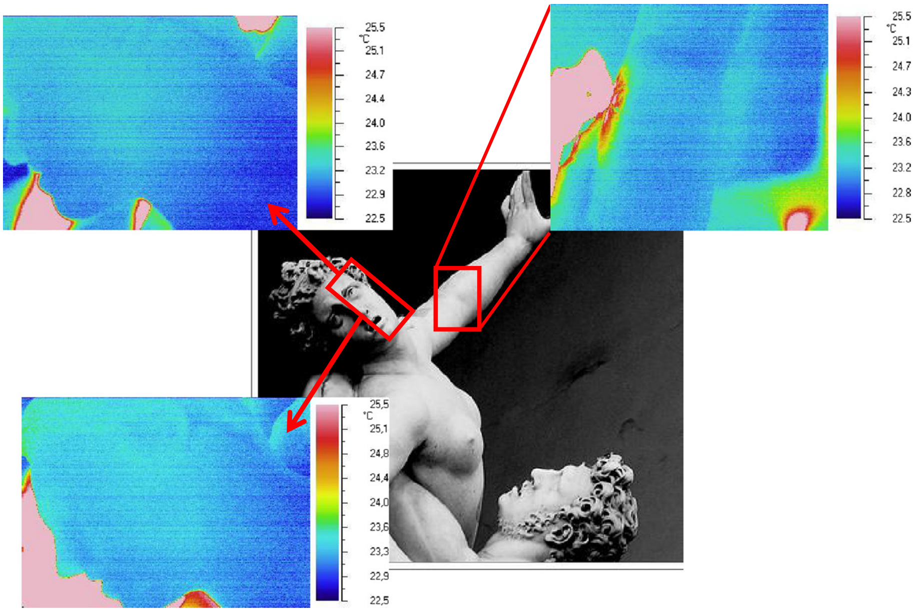

Figure 6 Left arm and head inspection of the Sabina. No connections between the cracks were found.

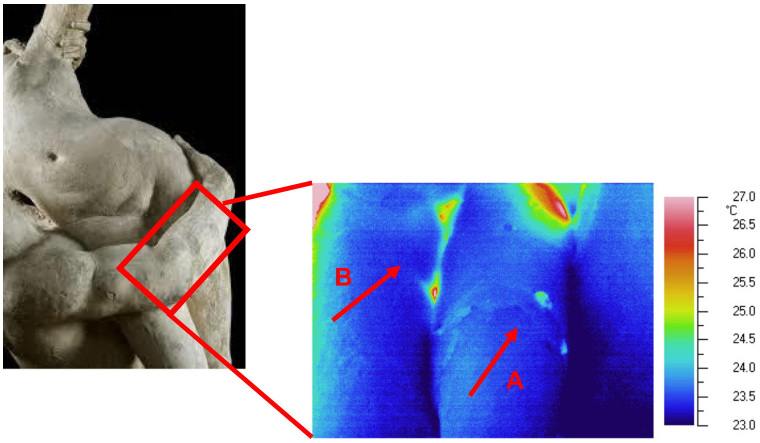

Figure 7 Left leg of the Sabina and right arm of the Romano. Some spots on the Sabina leg (red arrow A) can be seen demonstrating that the inflow crossed the leg coming out on the opposite side. Other connected cracks to the same infiltration point are visible on the thermal image (red arrow B). The inflow of the air was at the opposite side of the points monitored through the thermographic inspection, out of the field of view of the thermal camera.

fact, the thermal image of the left arm and head of the Sabina obtained after about 3 minutes of heating, indicate that the infiltration points of hot air were not connected with other cracks on the opposite side.

The Figure 7 shows on the back side of the monitored points more connected spots, indicated by red arrows (A and B) on the thermal image, for the same infiltration point.

By applying this methodology thirteen cracks were studied. Only four of the thirteen analysed cracks demonstrated that they were connected from front to back. For the other cracks the heat was dispersed on the surface, following sub-superficial local cracks as shown in Figure 8.

Conclusions

This paper demonstrated by means of laboratory and field application the efficiency of a method based on a active thermography applied locally to detect the weathering of artworks made out of composite materials. Due to the high thermal inertia of these materials all the usual active thermographic techniques (heating procedures based on irradiation or convection of large surfaces) are inadequate. In fact, to obtain a significant result relevant temperature variations need to be induced on the whole surface of the artefact to detect anomalies which are located and hidden deeply inside the structure. This means that the required large temperature increases could reach values which are

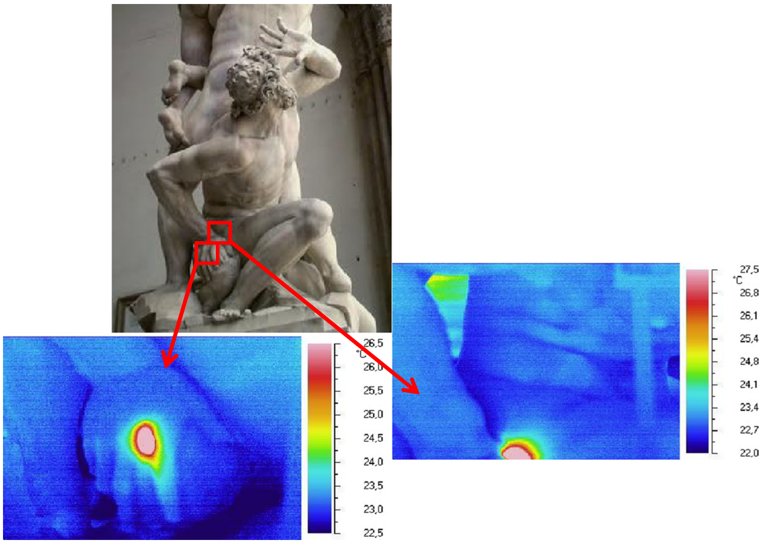

Figure 8 Right hand of the Sabino warrior. In both thermographic images the heat was dispersed around the surface of the cracks, demonstrating a superficial effect.

not allowed due to conservation restrictions. Moreover, these conventional active methods don't allow to highlight particular defects, like the presence of connections between the cracks.

The results of the described particular methodology based on localised thermographic inspection applied to a precious and particular historical artwork, the "*Ratto delle Sabine"* model, highlighted the efficiency of this simple methodology to monitor the state of conservation of frail artefacts and more in general its applicability in the field of Cultural Heritage conservation.

It was also underlined that particular attention has to be given to the levels of heating to avoid dangerous effects and preliminary tests have to be performed in function of the analysed materials, to verify the respect of directives and standards, as was done in the case of the "*Ratto delle Sabine"* model.

Endnotes

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Competing interests

The authors declare that they have no competing interests.

Authors' contributions

All the authors contributed in planning the research activities. MCDT and MG performed the laboratory tests and interpreted the results. MCDT and NL performed the in field data acquisition; both the two authors performed the data interpretation. AD and MCDT wrote the manuscript and revised it critically. All authors read and approved the final manuscript.

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