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ANALYSIS OF THERMODYNAMIC BALANCE IN THE CONSERVATION-MAINTENANCE PROCESS ON BRONZE MONUMENTS EXPOSED IN THE OPEN: THE CASE OF FRANCESCO MESSINA'S "CAVALLO MORENTE"

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ABSTRACT

Correlation between information deduced from a model (aimed to define the importance that theoretical and direct solar radiation has in the global heating dynamics of a structure) and data obtained in situ carried out by thermographic investigations (properly organised in time and operating ways), gave, in various circumstances, significant results for the definition of the zones of maximum thermal stress on objects exposed to open air. The detection of these zones of preferential deterioration, in fact, is basic to accomplish the risk-check of the structure and then to properly plan and define a conservation project that includes the restoration and maintenance activities.

INTRODUCTION

Francesco Messina's *Cavallo Morente*, a monumental bronze work, 4,60 meters high and 5,50 m. long, was realised by a fusion and finished with an artificial varnishing under the supervision of the artist at the Battaglia foundry in Milan. On November 5th 1966 it was placed in the garden in front of the façade of RAI headquarters in Viale Mazzini, Rome.

In the last few years the work, in contact with the urban highly polluted atmosphere of the town, had shown clear degradation signs, characterised by a manifest chromatic alteration of the surfaces, due to the formation of heterogeneous and especially disfiguring corrosion patinas constituted by carbon encrustations, and by a high concentration of geodetic lines, effect of the rain water flowing, that give to the metal a typical "striped" aspect.

It is nowadays certain that contemporary bronze sculptures, if exposed outside, reveal, in a short period, serious degradation problems and these are sometimes harder to solve than on the ancient ones because environmental conditions act in a very strong manner on the deterioration processes of their constituent materials.

The *Istituto Centrale per il Restauro* deals with bronze restoration since its establishment in 1939, and recently has addressed its activity also towards the conservation of contemporary works such as Arnaldo Pomodoro's *La Sfera Grande* (Ministero degli Esteri) and Antoine Bourdelle**'s** *Ercole Arciere* (Galleria Nazionale d'Arte Moderna).

For this reason the restoration of the *Cavallo Morente* represented a further opportunity to deepen the study of the most important problems, more and more urgent in the recent years, which regard the intervention modes aimed to restoration, protection and maintenance of these artefacts.

The conservation project has been developed on the basis of a methodological criterion whose preliminary phase was aimed to the recognition and cognitive-diagnosis of the sculpture conservation conditions, in relationship with its structural characteristics, its construction techniques, the analysis of the interaction mechanisms between environmental factors and corrosion processes.

The team, constituted by the Institute scientific personnel of the Institute, accomplished the diagnostic investigations and correlated the gathered data so that a treatment and maintenance programs could be established.

Visual Investigation – The Point of View of Realisation Techniques

The metal surface reveals an evident un-homogeneity, characterised prevalently by smooth and compact zones alternate with thinly heterogeneous areas, formed by microhillocks, with a fairly high degree of porosity. These are mainly concentrated on the surfaces of the back, the sides and the belly and are typical of the gaseous bubble deriving from fusion proceeding.

The whole surface appeared characterised by the manufacturing signs of the wax model realised for the fusion. They appear in the form of thin folds on the bronze surface, and they had been left purposefully, as documented by the artist.

The basement is not a pure support element but was conceives and realised as integral part of the work. It was worked with a lightly undulated trend, with some subsidence where holes have been created for the drainage of the rain water. Also the holes, present in the nostrils and in the fauces, had probably the function to avoid stagnations due to the rain. The realization date and the name of the foundry appear along the outside border.

Visual Investigation – The Conservation State

The expository environment of the *Cavallo Morente* is characterised by risk factors related to the high level of damp of the zone, adjacent at the Tiber River, to the high rate of surrounding atmospheric pollution and to conditions more specifically bound to the area immediately neighbouring the monument. In fact the building façades are almost totally constituted by glass windows, an so they produce an unavoidable reflective effect which enlarges the solar radiation; moreover the relative damp of the area is further increased by the constant spraying of the gardens where the work is placed. Such a situation interacts with the morphological and structural aspects of the work of art.

Therefore the monument conservation state revealed a manifest particularity in the surface degradation level, which is differentiated in relationship with orientation and inclination of the various parts. The southward side had its surfaces more exposed to the direct solar radiation and to the rain beating and so it appeared considerably more damaged than westbound one.

The original features of the artificial patina, wanted by the artist, were changed. It was preserved only in a few circumscribed zones, cause most of it was lost, replaced by alteration phenomena much differentiated for morphology and composition.

In several places of the surface were located formations of red iron oxides, caused by the corrosion of internal structural elements realised in iron-coal league.

On the head, the mane and the tail, there are little cracks, which in some points concern the whole metal thickness, with clear signs of water pouring coming from inside the monument in the form of condensate. Water, in fact, enters inside the statue through the holes in the nostrils and in the fauces, and does not find vent because of the drainage system ineffectiveness. So it remains in the lower zone provoking condensate phenomena

In the basement, because of the drainage hole obstruction, a heterogeneous alteration state could be observed. It was characterised, in the depressed areas of metal surface, by a total absence of patina, consequence of the water stay, and the presence of calcareous deposits.

All the work surfaces were covered by particulate deposits and sandy dusts coming from the atmospheric precipitations.

Diagnostic Intervention

On the basis of information obtained by the archival-historical reconnaissance and by the analysis of the macroscopic degradation phenomenology, ascertained by a careful "investigation by sight", it had been possible to set up and define the diagnostic project aimed to design the final interpretative schema, necessary to plan the project aimed to the restorative, conservative and maintenance intervention.

The diagnostic project has been planned to study the features of the realisation techniques and of the conservation state on both the structural point of view and the superficial corrosion processes. It was aimed, in the first phase, to execute not destroying investigations, both in space and time dimension, such as:

- microclimatic monitoring;
- thermographic investigation

On the basis of data acquired in this first phase, one proceeded to the choice of the most significant and/or representative areas for accomplish local and punctual investigations, such as:

- endoscopic tests, aimed to inspect the internal work structure and the support of the basement;
- investigation by ultrasonic technique, aimed to evaluate the fusion throw thickness changes;
- X diffraction testing, infrared, chemical testing for the corrosion patina characterization;
- induced current for the tracking of patina thickness;
- method of Rp polarisation resistance to measure the speed of corrosion of metal surfaces;
- the metallographic and basic analysis of the alloy and the conductibility measures I.A.C.S. (International Annealed Copper Standard) allowed to notice, in general, a significant league homogeneity, constituted by a lead bronze but with several blowings in its interior.

Thermographic investigation

In the planning and pre-operating phase of the conservative intervention on the statue, between the other measurements and control investigations, a **thermographic investigation** was planned and accomplished. It aimed to provide a contribution to the definition of the interpretative model of thermal exchange mechanisms that take place between the bronze structure and the surrounding environment and between the various parts which constitute the structure itself. Such an investigation technique, supplies, in a not destroying and not invasive way, data relating the superficial temperature that are sampled in the time but practically continue in the space and so it allows to design maps of thermal exchange between the structure and the environment. Therefore, among other things, one can identify and determine those parts of the horse structure that, being more submitted to thermal solicitation, constitute the preferential degradation zones, i.e. the so called "risk zones". To such an aim, it is necessary to extrapolate, from the data acquired on field, the typical behavioural model of the artefact under examination.

To define an exhaustive and reliable behavioural model of a structure, it has been noticed the usefulness to develop a theoretical model which allows to define the thermodynamic relationships deriving from the theoretical and direct solar radiation.

Correlation between the mathematical data obtained by such a model and the ones collected on field by thermographic investigations, properly defined in time and ways of execution, has already proved to be fundamental in several cases for the definition of the typical thermodynamic model of handmade articles exposed in open.

The definition of the superficial thermal distribution of a typical day will allow to obtain, by the mathematical modelling, the real thermal deformations and the consequent distribution of the stresses in the structure.

The identification of the preferential decay zones gives the possibility to make a "risk-check" of the object, and so to obtain the information necessary to setup up and define a correct conservation-restoration project including the program of maintenance which must be considered a true and real extent, in the time, of the intervention.

This methodology of diagnostic approach to monumental handmade articles exposed in open has already demonstrated, in the past, its remarkable potentialities while applied to structures of cultural interest such as the *Nettuno* statue realised by Jehan Boulogne called the Giambologna and placed on the homonymous fountain in Piazza del Nettuno (Bologna); the equestrian statue of *Marco Aurelio*, located on Capitolium Square (Rome); the equestrian monuments to *Alessandro and Ranuccio Farnese* realised by Francesco Mochi and located in Piazza de' Cavalli (Piacenza), , the *S. Maria del Fiore Dome* in Florence realised by Filippo Brunelleschi.

The Global Thermal Model – An Operating Example

Dealing with objects exposed in open, one of the main sources of heat radiation is, obviously, the sun. Consequently, it is significant to evaluate the significance that solar radiation has in the global heating dynamics of the structure.

Therefore, while studying the system Marcus Aurelius–Capitolium square (fig.1), it was decided to support the investigations on field (carried out by using thermovision and thermocouples) with the realization, on computer, of a system that could define the theoretical relationship existing between solar dynamics and the bronze monument. Correlation between information deduced from such a model and data obtained on the field gave useful results and constituted a significant instrument for the analysis of the concrete thermal model of the investigated structure.

The thermal characteristics of the constituent material (a poor thermal inertia) and the peculiar conformation of the surroundings (Capitolium Square is placed at the centre of a natural saddle of the hill; while the buildings leave totally exposed the northern side) allowed to presume that conduction-convection phenomena would be significant for the global thermal dynamic of the structure-environment system. Consequently it was decided to realise a schematic model aimed to analyse the phenomenon of solar heating from a purely qualitative point of view. Operatively, given a day and an hour (i.e. the *true local solar time*), the developed system computes the shadows theoretically cast on the Capitolium Square by the surrounding palaces (Capitolium buildings and Aracoeli church) and so allows to visualise the insulation conditions of the equestrian monument.

Correlation between information deduced from such a model and data obtained on the field gave useful results and constituted a significant instrument for the analysis of the concrete thermal model of the investigated structure.

If you consider, for instance, the radiating dynamic computed for a typical day in the second half of August, the theoretical model forecasts a dynamic of the following kind (fig.2):

- in the earlier hours in the morning the structure is completely in the shade, due to the presence of Palazzo Nuovo;
- later, the monument passes to an insulation condition; the sun rays directly hit the rear parts of the structure;
- in late afternoon the structure passes into the shade due to the presence of Palazzo dei Conservatori;
- at sunset, the sun rays hit, almost perpendicularly, the left forward part of the monument.

Such a behaviour is extremely discontinuous; moreover, the danger is still greater due to the fact that bronze, having a rather low thermal inertia, follows rapidly the thermal stresses of the environment.

Examining the charts of the thermocouples data recorded during the same period (fig.3), it is immediately possible to observe that the curves can be easily explained by the described theoretical considerations. In fact:

- the area that reaches the highest temperature value is the croup (thermocouple 4);
- the left-hand side (thermocouple 1) is always warmer than the right-hand one (thermocouple 7), except in the earlier hours in the morning;
- the rear end (thermocouple 2) is heated more rapidly than the front one (thermocouple 6), but its cooling off is also faster;
- the horse's chest (thermocouple 6) has a peak at sunset, when the temperature of all the other thermocouples is decreasing.

In addition to these observations, the thermocouples charts give other information which cannot be directly compared with the described theoretical model:

- during the night the basement is warmer than the bronze statue;
- the daily variations of a single thermocouple cannot be superimposed over each other.

The first observation can also be confirmed by thermovision which completes the information by showing that the structure, during the night, has a thermal gradient which is inversely proportional to the level above the ground (fig.4). This is due to the fact that the basement has a higher thermal inertia than the bronze statue. Then, because of the season and the hour of the recording, the basement temperature is higher than the statue one and consequently it radiates heat towards the monument causing a temperature increase in the areas that are geometrically more exposed to its influence. Then the marble basement should be considered a basic component of the structure-environment system. Therefore for a complete and exhaustive thermodynamic model, it will be necessary to study the basement thermal variations and their influence on the monument.

The second observation confirms, on one side, the great influence of the sun direct radiation on the thermal dynamics of the structure: in fact, the tendency of the examined points is to follow the described behaviour. But, on the other hand, it demonstrates that other thermal processes (connected with evaporation, convection, etc.) can give an important contribution in the design of the structure “risk maps”.

Francesco Messina’s “Cavallo Morente” – Operating Methodology

Thermographic investigation has been oriented to collect data that could be useful to define the bronze structure (fig.5) from the point of view of his relationship with the environment and that could be correlate with the possible un-homogeneities due to subsurface and/or realisation-technique and/or composition and/or conservation state differences.

It has been carried out with the system *"AGEMA Thermovision mod. 489"* sensible to I.R. in the *8 - 13 micron* band; the instrument thermal resolution is in the order of *0.08 °C.*

Two kinds of lenses were used: the focal and the geometric resolution of the 7° one were 99 mm and 1.1 mrad, while the values for the 20° lens were 33 mm and 3.4 mrad.

The investigation has been accomplished in a single campaign of acquisition, during the Spring-Summer seasonal transient. in the course of this survey sample-recordings have been executed, from fixed position, in the whole daily cycle.

Besides the thermographic investigation, a recording of thermo-hygrometric size values has been carried out; the measurements were sampled in time and space and were executed both in the preliminary phase and while the investigation was in act.

Thermographic recordings were executed from two fixed positions, identified in fig.6 by the letters *A* and *B*. A dolly furniture was used so that one could manage, in a easily way, the distance, the angle and the optimum positioning of recording place as well as the speed in changing the prospect in analysis. That has allowed to detect the thermal distribution, on the two lateral prospects, on surfaces sufficiently extended and in a timeframe sufficiently short so that the survey could be considered practically an instantaneous one under the point of view of the structure thermal change.

The *A* recording place had an average scanner-surface distance of about 5 m. and was meant to investigate the left-side prospect. From such a position, in the first scanning, a 20° lens was used so that one could record, in axis, areas of 1.6x1.6 sq.m. Then, more detailed recordings were executed, from the same distance, using the 7° lens, so that areas of 0.54x0.54 sq.m. could be detected, always in axis.

The *B* recording place had an average scanner-surface distance of about 15 m. and was meant to investigate the right-side prospect. From such a position, in the first scanning, a 20° lens was used so that one could record, in axis, areas of 4.8x4.8 sq.m., so that one could detect the thermal surface distribution on the whole side. Then, more detailed recordings were executed, from the same distance, using the 7° lens, so that areas of 1.6x1.6 sq.m. could be detected, always in axis.

The analysis and the processing of the thermal maps, recorded by telethermograph, have been executed in digital form by a specific management software. So, between the other things, one could differentiate quantitatively the various issued energy levels and generally achieve a further thermal space analysis.

Thermographic surveys were carried out from 7:30 p.m. up to 9:15 p.m. (summer-time) in May 31st 2000 and from 9:30 a.m. up to 10:45 a.m. (summer-time) in June 3rd 2000.

In fact, investigation was accomplished in two different environmental situations that is when the bronze structure was going:

- to enter the “shadow zone” in the phase of thermal decrease of the structure (night phase).
- to leave the “shadow zone” in the phase of thermal increase of the environment (ante meridiem phase).

Comparisons between the behaviour of the bronze structure, or of some part of its, in the two different environmental conditions demonstrate themselves useful to confirm hypotheses formulated by the analysis accomplished in the single situation.

Concluding Considerations

The processing of the thermograms, acquired in a time sampled way and in the different phases of daily cycle (i.e. environmental thermal increase and decrease), has allowed to acquire data on the thermal behaviour of the structure as a whole (that is horse and basement), in relationship with natural thermal solicitation, induced mainly by solar, direct and secondary, radiation.

In general, on the bronze equestrian statue, thermal behaviour differences have been highlighted. They can be put in relationship not only with the conductive and convective exchanges due to the conditions to the contour, but also with subsurface and/or realisation-technic and/or conservation differences, with the geometrical conformation of the various elements which constitute the structure, and with the reflexion, transmission and absorption features of superficial layer.

It has been noticed also the necessity of examining in detail this study by realising an interpretative model dealing with the direct and theoretical solar radiation. Such a model, inserted in the diagnostic program from the beginning and now in the developing phase, could be useful to execute a risk-check of the bronze structure during its seasonal cycles.

Specifically, on the basis of the accomplished surveys and as far as concerning the considered day, it appears plausible to suppose that an important role, in the thermal dynamics of the bronze structure, is played by the presence, in the thigh, the leg, the left rear leg hock, of fillings and/or thickenings of the fusion throw and/or pivots. Such elements have a relatively high thermal inertia and so constitute a kind of thermal accumulator. In fact their thermal changes, in the daily cycle, are lower, both in amplitude and speed, than the ones recorded for the environment and for the statue considered as a whole.

In short, from the data obtained through the thermogram exam, taking into account what already said, it was possible to establish what follows:

Environmental thermal increase phase (see the thermograms in fig. 7):

- in correspondence to the head, the neck, the withers, the shoulder, the chest, the crupper, the outsider part of the tail, the fore legs and rear right leg, a positive thermal gradient higher than the other parts of the equestrian statue has been noticed, because such areas turn out more subject to the environmental thermal solicitations induced prevalently by solar radiation phenomena and convective events;

- the left hind leg, attached to the basement, has a lower isothermal level and shows a negative gradient from the thigh to the hoof. That, as we have already said, can be correlated to subsurface un-homogeneities (fillings and/or thickenings of the fusion throw and/or pivots);
- the other parts of the structure turn out to have an intermediate isothermal level.

In the environmental thermal decrease phase (see the thermograms in fig. 8) one registers a inversion of phase in the behaviour of the thermal structure elements of which over, even if the thermal difference between the parts more subject to the environmental solicitations (in this phase, due principally to convective phenomena) tends considerably to reduce itself.

Generally one highlights that, at this moment of the daily cycle, on some parts of the structure a phase inversion is determined. In fact those structure zones that during the thermal increase phase (a.m.) had come more quickly at a higher thermal level, in the decrease phase undergo a phase inversion and move at a thermal less high level, that is they get cold more quickly.

As said before, the further widening of the thermodynamic study will be able to provide useful indications for the work maintenance program purposes.

Programmed Maintenance Project

The conservative project expects, through the study of the state of conservation of the work after the restoration intervention, the setting and the definition of a maintenance program that should be considered as an extent, in the future, of the restoration intervention. This program is developed on the basis of the observations collected by the restorers during their periodical controls and of the data obtained by diagnostic campaigns accomplished at fixed cadence in an intervention systematization aimed to monitoring the conservation state.

Observations, accomplished 12 months after the end of the restoration intervention, have allowed to notice a located phenomenon of superficial alteration of the final protective layer, the so called “sacrifice layer”, constituted by the microcrystalline wax.

This phenomenon was concerning well circumscribed surface areas, that have modest dimensions and are principally concentrated on the right-side, that is, the more exposed one. Some areas had limited detachments of the most superficial wax layer, the other ones had wax whitening. These last were concentrated in few points, where the wax had been deposited with bigger thickness because of depressions or roughnesses of the surface (the wax has been applied in two subsequent layers at a distance of a few days; the aim was to ensure the maximum protection to the acrylic layer in direct contact with the bronze surfaces, and in fact it was turning out unchanged). This phenomenon has been observed only from the beginning of the winter, as in the previous inspections (September-October 2001) was not yet present, and has modified very slowly in the time, with a modest increase in the interested areas, as detected up to the last inspections in November 2003. Instead, since the first observations, it had been discovered a clear phenomenon of particulate deposition, due to atmospheric pollution and sand deriving from rainy precipitations, of remarkable consistency and especially covering effect.

The observation on the work conservation status and on the conditions in which the phenomenon of microcrystalline wax deterioration took place, has proved the strict correlation between the thermal exchange behaviour of the bronze monument and the expository environment (fig.9). On the methodological basis activated for the study of the mechanisms of interaction considered the provoking cause of the corrosive processes, the graphic surveys of the zones interested by the deterioration and their characterization have been accomplished. Then the graphics were compared with the thermograpic investigations performed before restoration. From the exam of these data, a punctual correspondence has emerged between the zones interested by the wax deterioration and the areas interested by the highest thermal solicitation values (i.e. the higher speed of thermal exchange with the external environment) (fig.10). Afterwards it has been put in relationship the correspondence of the thermal behaviour with the work structural features in connection with the distribution of the internal metal supports, the fusion throw thickness differences, the distribution of the weights and of the anchorage elements depending on the static monument arrangement. Therefore it has been noticed the necessity of deepening this study, through the elaboration of a interpretative model for the direct and theoretical solar radiation, already scheduled in the preliminary diagnostic campaign to have an extent of the values in the whole seasonal cycle. It will be possible to direct this study towards a conservative methodology systematisation, on the processing of models of the monument behaviour in time dimension.

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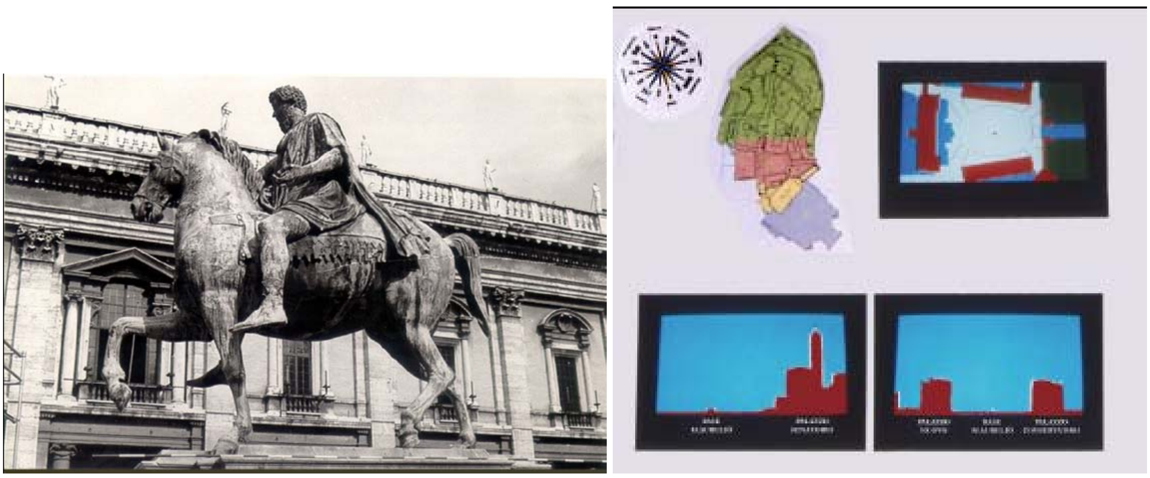


Fig. 1 - Marcus Aurelius equestrian monument and the Capitolium square

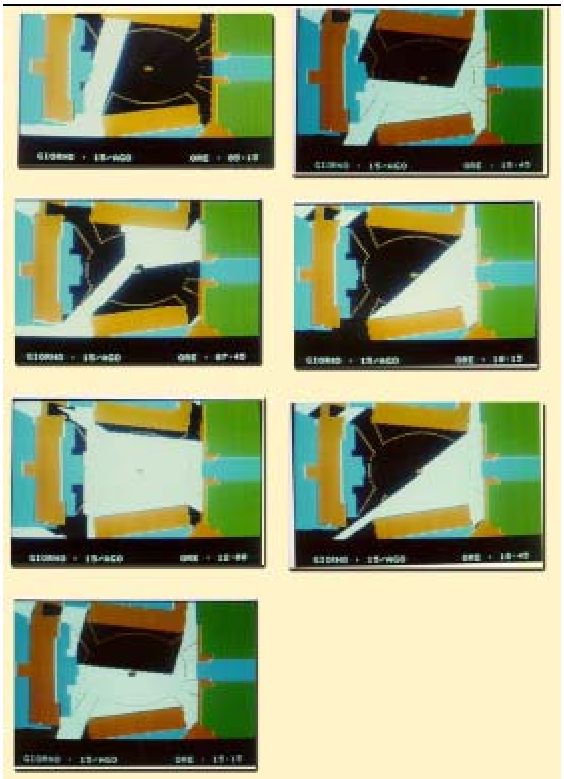


fig.2

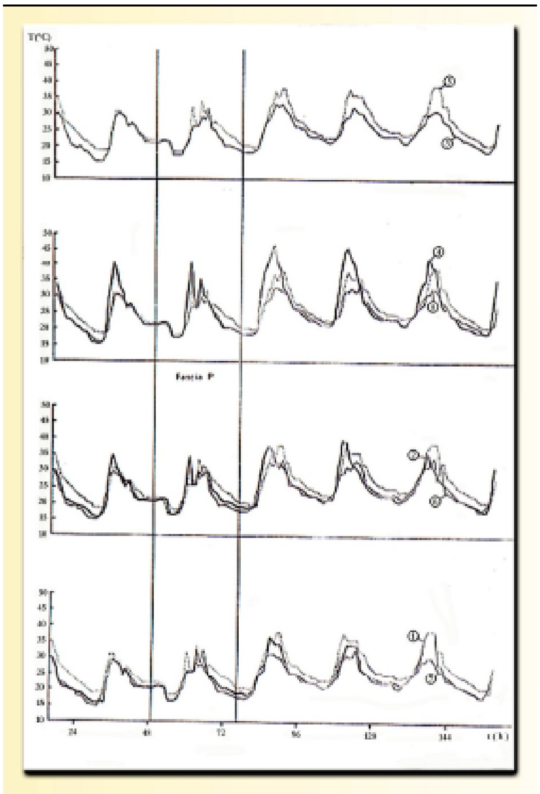


fig.3

Fig. 2 - Dynamic of the theoretical and direct sun radiation as computed for a typical day in the second half of August

Fig. 3 - Thermal values recorded by the thermocouples placed on the equestrian monument in the second half of August

Fig. 4 - Thermogram of the equestrian monument recorded in the environmental thermal decrease phase

Fig. 5 - F. Messina's Cavallo morente

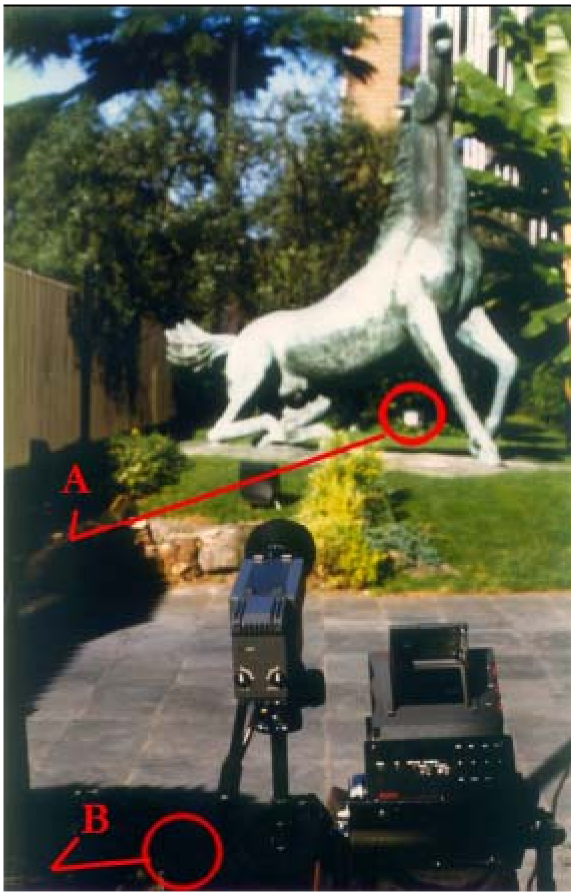


Fig. 6 - The two recording positions

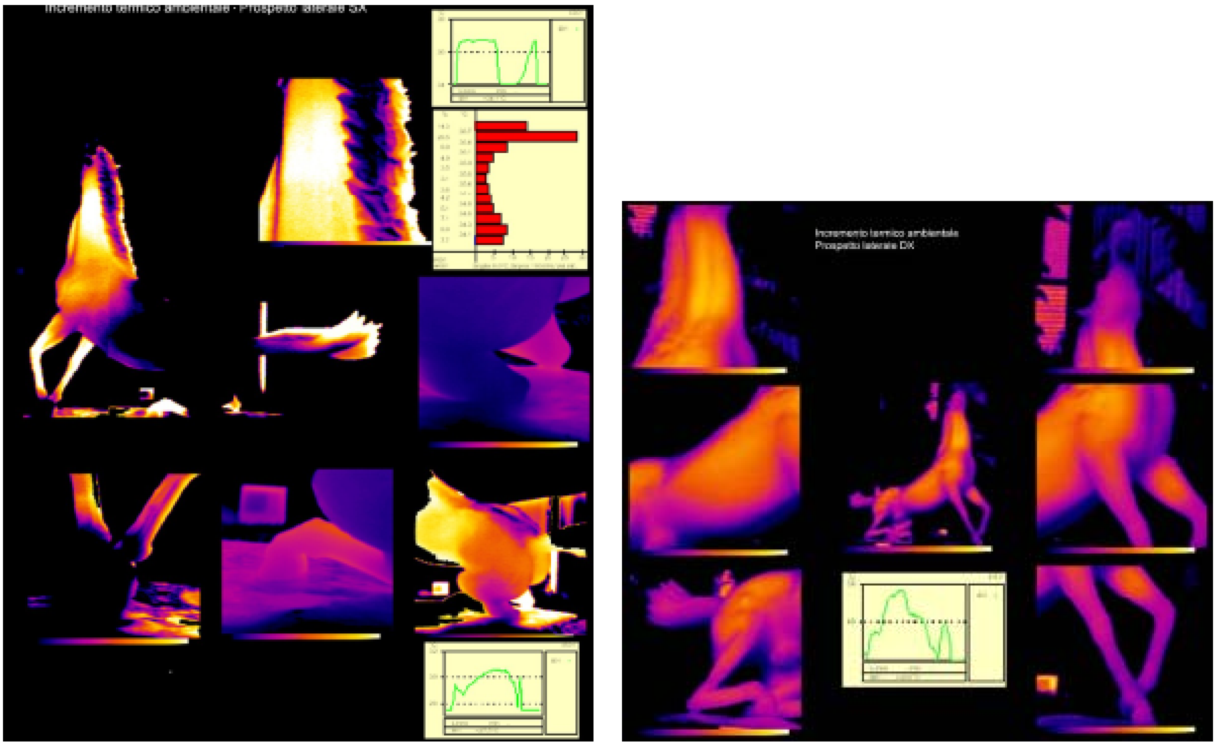


Fig. 7 – Thermograms recorded in the environmental thermal increase phase

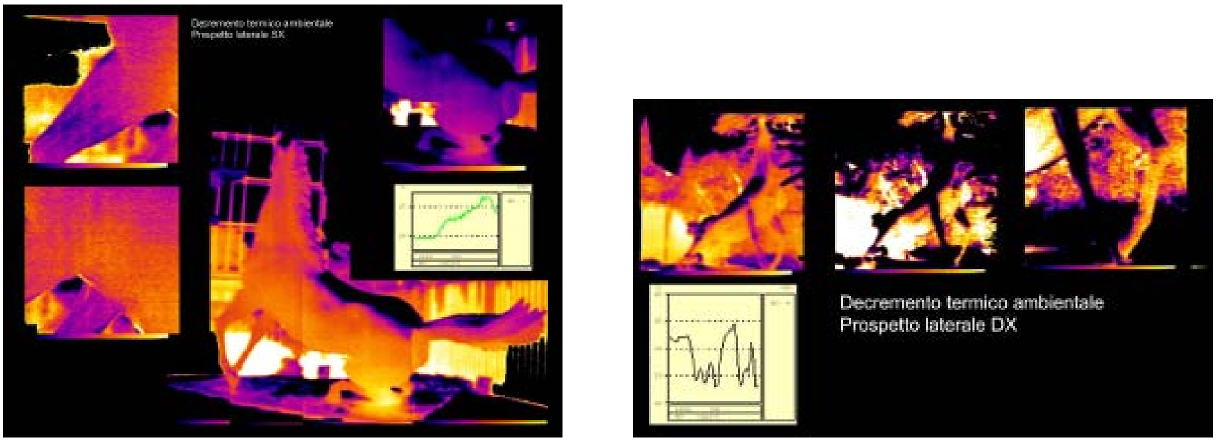


Fig. 8 – Thermograms recorded in the environmental thermal decrease phase

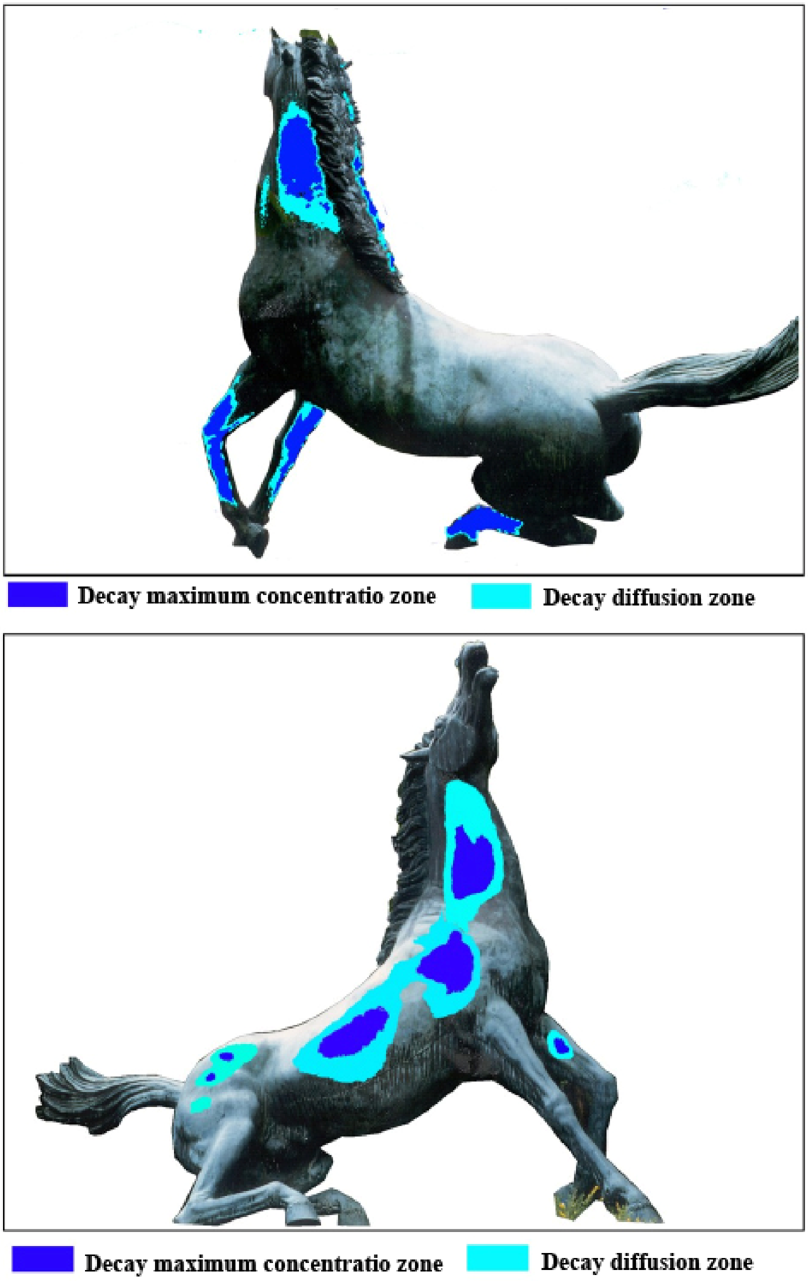
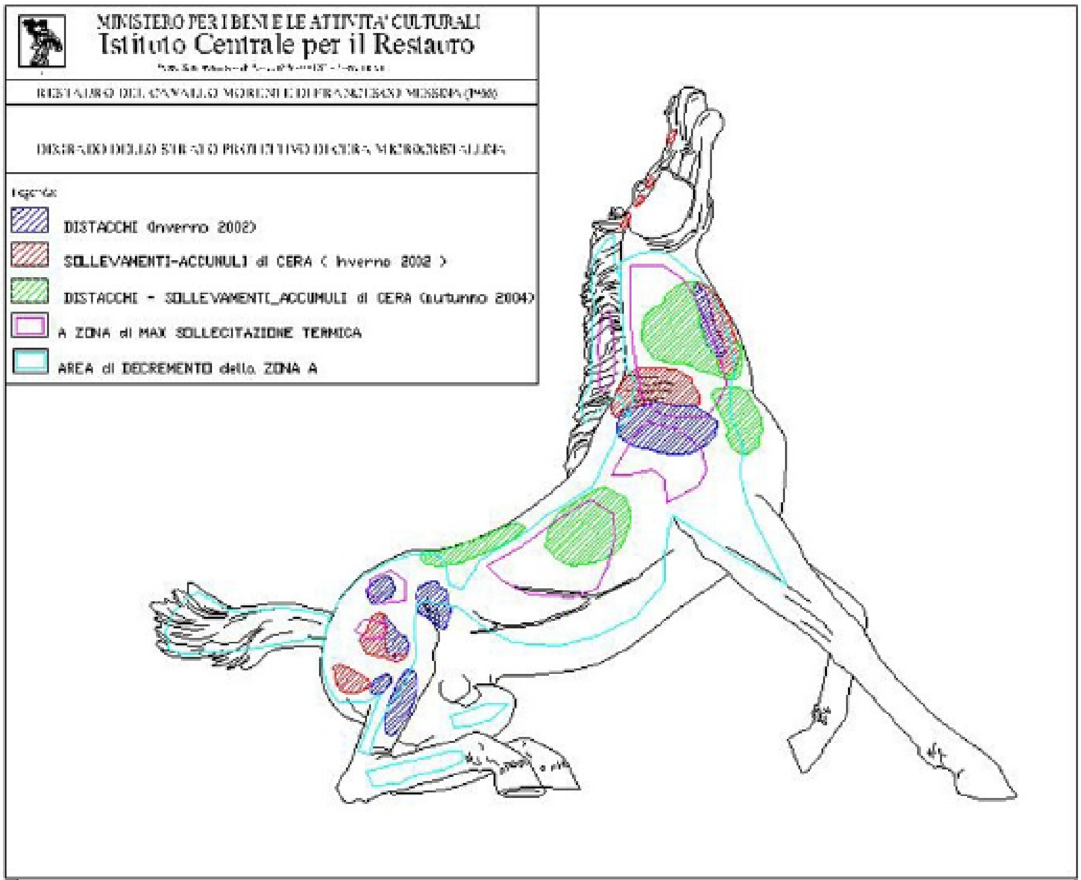


Fig. 9 –Correlation between thematic maps



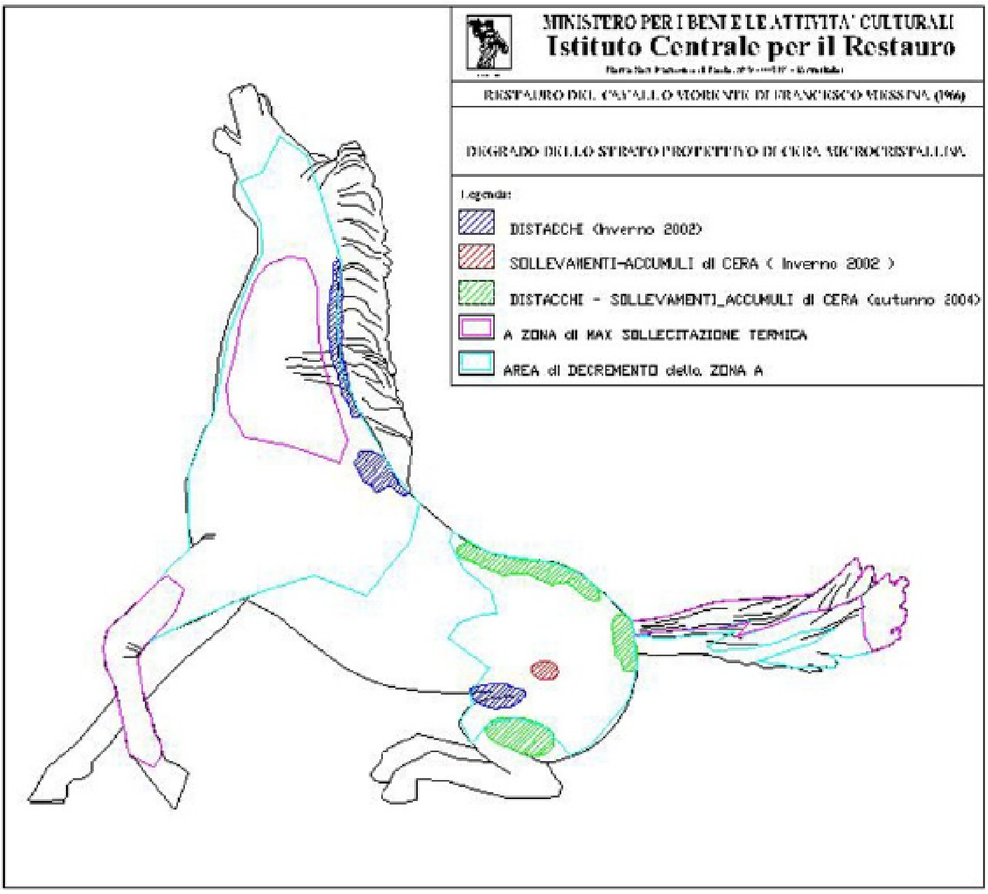


Fig.10.- Analysis of the protective layer decay compared with the results of the thermographic survey

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