CULTURAL HERITAGE

Series of History, Analysis, Conservation, Valorisation of the Cultural Heritage

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The Series Cultural Heritage collects scientific contributions concerning the protection, the restoration, the enhancement and the management of Cultural Heritage both in general and in specific aspects. This purpose is pursued through both theoretical and operational contributions about the knowledge of cultural heritage, able to propose conservation and valorization actions, to suggest management strategies, and recommend adequate dissemination channels. The series collects essays on landscape and urban structures; on historic gardens and parks; on the archaeological heritage and on that which has been reduced to a state of ruin; on historical architecture and that belonging to the so-called "modern movement"; on the widespread heritage with traditional characteristics (rural, mountainous, vernacular).

On the cover:
Brescia Cathedral, picture by AIPnD ETS©

Proceedings of AIPnD art'23

14th International Conference on non-destructive investigations and microanalysis for the diagnostics and conservation of cultural and environmental heritage

Brescia (Italy) - 2023, November 28th/30th

edited by
Monica Volinia, Antonello Tamburrino

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Introduction

Emanuele Romeo*

Politecnico di Torino, Italy
*Editor in chief of the series Cultural Heritage

The series Cultural Heritage collects scientific contributions concerning the protection, the restoration, the enhancement and the management of Cultural Heritage – with a focus on architectural and landscape heritage – both in general and in specific aspects. Theoretical and methodological books alternate reasearch ones, more pertinent to the practical sphere, i.e. regarding conservation and enhancement actions. Further goal of the series is to suggest prevention and maintenance strategies, even through proper channels of dissemination.

The AIPnD ETS - Italian Society for Non-destructive Testing by deciding to publish the proceedings of *art'23 - 14th International Conference on non-destructive investigations and microanalysis for the diagnostics and conservation of cultural and environmental heritage*, enriches the series of new knowledge, providing readers, researchers, scholars with interesting insights into the value, above all material, of architectural heritage.

The publication of the proceedings represents a new specific field until now never dealt with in this series, bringing out strongly the need, if we talk about cultural heritage, to work through the cooperation of different disciplines and different actors: universities, research institutions, specialized companies, professionals, who work together to the preservation of the Heritage, by proposing innovative prevention actions aimed at a more compatible management than in past decades.

The first conference, organized by AIPnD held in 1983, was the result of the far-sighted vision of Giuseppe Nardoni, who wanted to broaden the Association's fields of interest just to include further actors than industry. Since then, the conferences have become even more international, held every 3 years and itinerant, as shown by the last edition in Argentina. This year, a lucky coincidence, art'23 will take place in Italy, and in particular in Brescia, city birthplace of AIPnD and, together with the city of Bergamo, the Italian Capital of Culture 2023.

The Conference and all the contributes in this volume attest the international nature of the event, thanks to the presence of high profiled scientific and organizing committees, of universities and research institutes, but also a connection with the guest country, Italy, due to the sponsors and to the honor committee.

The volume opens with the greetings of President Ezio Tuberosa followed by five Plenary Lectures offering an overview of research on assets with high artistic and historical value in specific territorial realities such as Brescia, Turin, Genoa and Paris, and a Technical Sponsor Lecture on the state of the art and development of radiographic techniques, aimed at the conservation of cultural heritage.

The book is composed by four different sections, and each section concerns Cultural Heritage in the broadest meaning of the expression, i.e. applications on both movable and immovable assets: Non-destructive Testing in Cultural Heritage; Microanalysis and Conservation of Cultural Heritage; Monitoring of Cultural Heritage; Environmental Control and Protection.

The authors of the contributes belong both to research institutions (University, Enea, CNR) but also to companies operating in both public and private field: this represents the significant and innovative multidisciplinary AIPnD way of researching and working. Thus, an interesting international comparison emerges as the result of a combination of academic and practical research, without neglecting specific case studies related to contingent experiences and sites. The cross-reading of the essays highlights the spillovers that scientific and academic activities have in the operational field, where, for example, evidence that what has not yet been standardized is employed through protocols increasingly channeled within scientific boundaries, even if sometimes dissonant from market needs.

The interdisciplinary perspective is ensured by the presence of different knowledge and skills all aimed at the experimentation and application of techniques and technologies at the service of Cultural Heritage; while the international panorama of studies and research increasingly enriches the field of diagnostic investigations with new experiences, through specific protocols of understanding between research bodies and territorial realities.

And, in addiction to these protocols, there are the educational spin-offs: from Bachelor's and Master's degree courses in the Faculties of Architecture and Engineering, to Level III courses and Master's degrees, without neglecting the collaboration with public and private educational and research bodies operating in the same territory.

In fact, AIPnD ETS (founded in 1979) is a nonprofit scientific, cultural and professional organization; and the promotion of scientific and technical knowledge and technological development of non-destructive testing is one of the main purposes of the Association, which is realized through dissemination activities, creation of educational materials, training courses in view of the certification examinations, required and/or necessary to operate in certain fields and, specifically, in the field of Cultural Heritage.

As an example, I would like to cite the Laboratory of non-Destructive Diagnostics (founded in 1992) of the Politecnico di Torino, one of the main actors of the art'23 Conference. The Laboratory purpose is the knowledge of the architectural and environmental heritage in its technological and technical aspects, through the use of non-destructive investigation techniques including infrared thermography, endoscopy and resistography, used for the analysis of the state of conservation and the search for defects or alterations "under the skin", or not detectable at a direct visual analysis.

I would like to conclude by saying that the authoritativeness of the organizers and of the editors (Monica Volinia, Marco Giachino, Dario Foppoli and Antonello Tamburrino) has granted the high profile of this book, while the specific skills of all the contributors have enriched the scientific community with new insights into the cultural and material value of architectural, historical, artistic and environmental heritage, by contributing fully and correctly to the dissemination of the research carried out and the results obtained. Mission, this, which for years has been the main objective of the Cultural Heritage series, also thanks to the attention of WriteUp Publishing House in choosing and selecting which studies and research to publish, together with the Scientific Board.

President’s Greetings

Ezio Tuberosa

President of AIPnD ETS - Italian Society for non-Destructive Testing

Welcome to the 14th art’23 Conference in Brescia.

Italy is the so called “Belpaese”, preserving an unparalleled cultural heritage: in spite of this, it was not easy to choose the conference venue - but in 2023 Brescia and Bergamo are the Italian Capitals of Culture, so here we are.

Art in its broadest meaning covers every human activity, carried out individually or collectively, leading to forms of creativity and expression that are based on technical devices, innate or acquired skills and behavioral norms deriving from study and experience.

Therefore, art is a language, that is, the ability to transmit emotions and messages. However, there is no single artistic language nor a single unequivocal code of interpretation, nor even a term equivalent to “art” exists in most spoken languages.

In its most sublime meaning, art is the aesthetic expression of interiority and of the human soul. It reflects the opinions, the feelings and the thoughts of the artist in the social, moral, cultural, ethical or religious context of his/her historical period.

Art can also be considered a profession of ancient tradition, carried out in observance of a few rules, even if requiring a lot of love for what is created. Today art is widely considered as way to universal communication, and therefore can be the means to transmit a message of equality and peace among peoples: nothing further, unfortunately, from what is happening now in the world.

Thanks, so, to all the “professionals”, to all the “experts”, to all the “lovers” of this wonderful and indecipherable word “ART”, and thanks to the Italian Association of non-Destructive Testing, to the whole Board, who have made it possible to create yet another this wonderful event once again.

Benvenuti a Brescia alla 14° Conferenza di art’23.

L’Italia, il “Belpaese” che conserva un patrimonio culturale senza eguali, non ha facilitato la scelta della sede della conferenza, ma quest’anno Brescia e Bergamo sono le Capitali Italiane della Cultura, allora eccoci qui.

L'arte nel suo significato più ampio copre ogni attività umana, svolta singolarmente o collettivamente, porta a forme di creatività e di espressione che poggiano su accorgimenti tecnici, abilità innate o acquisite e norme comportamentali derivanti dallo studio e dall'esperienza.

Pertanto, l'arte è un linguaggio, ossia la capacità di trasmettere emozioni e messaggi. Tuttavia non esiste un unico linguaggio artistico e neppure un unico codice inequivocabile di interpretazione, addirittura non esiste neppure un termine equivalente ad "arte" nella maggior parte delle lingue parlate.

Nel suo significato più sublime l'arte è l'espressione estetica dell'interiorità e dell'animo umano. Rispecchia le opinioni, i sentimenti e i pensieri dell'artista nell'ambito sociale, morale, culturale, etico o religioso del suo periodo storico.

L'arte può essere considerata anche una professione di antica tradizione svolta nell'osservanza di poche regole ma richiedente tanto Amore per quello che si crea. Ma l'arte è spesso una forma di comunicazione universale e pertanto può essere il tramite per trasmettere un messaggio di uguaglianza e di pace tra i popoli, nulla di più lontano, purtroppo, da quanto sta accadendo ora nel mondo.

Grazie, allora a tutti i "professionisti" a tutti gli "esperti" a tutti gli "amanti" di questa meravigliosa e indecifrabile parola "ART", grazie anche all'Associazione Italiana delle prove non Distruttive e a tutto il Board, che hanno permesso di realizzare ancora una volta questa meravigliosa manifestazione.

Plenary Lectures

The Winged Victory of Brescia. History, research and enhancement of a great roman bronze

Francesca Morandini

Brescia Musei Foundation (Brescia, Italy)

Abstract

The *Winged Victory* (*Vittoria Alata*) of Brescia is one of the most important Roman bronzes in Italy. Discovered in 1826, it dates back to the 1st century AD. Since the 19th century the statue has undergone multiple conservation interventions. The last one started in 2018 up to 2020, promoted by Brescia Musei Foundation, Municipality of Brescia and realized in cooperation with the Ministry of culture and Opificio delle Pietre Dure of Florence.

The project was defined with a multidisciplinary approach which made it possible to study and compare the data obtained from the restoration with those deriving from scientific analyses, humanistic studies and other specialist research. Since October 2020, the *Winged Victory* has been exhibited in the renovated Capitoline temple in Brescia, where it was discovered. The new display layout is projected following all the guidelines derived from the multidisciplinary research and assuring the highest conservation's standard.

Keywords: Roman bronzes, conservation, *Winged Victory*, bronzes technology, museography, Brescia.

Introduction

Brescia's *Winged Victory* is one of the few surviving large Roman bronzes that was discovered during an archaeological excavation, accompanied by numerous other bronzes items in the same context.

It is a winged female figure, slightly larger than life-size (body height 194.1 cm), whose gestures and posture are incomplete due to the loss of certain features, which were already missing at the time of discovery. Her left foot originally rested on something, perhaps a helmet, and a shield would have been held up by the left leg (slightly bent) and left hand; in her right hand there may have been a stylus, which the goddess had used to engrave an inscription, commemorating it in bronze before the gaze of admiring onlookers [1] (Fig. 1). The statue was found in Brescia during an unprecedented archaeological campaign conducted between 1823 and 1830 by the Ateneo di Scienze Lettere e Arti di Brescia, at the request of the town council. During these investigations the *Capitolium* temple was brought to light (1823-1826), which has three large chambers and numerous furnishings such as altars, marble statues, fragment of decoration, inscriptions.

In 2023, the year in which Brescia together with Bergamo holds the role of Italian Capital of Culture, the city celebrates the 200th anniversary of this exceptional archaeological feat [2].

After many years of interpretations and hypotheses (some of them contrasting) about the *Winged Victory* it became possible to propose some answers and bring numerous aspects into better focus, thanks to a detailed interdisciplinary research project – named *Vittoria Alata 2020* – conceived and conducted by Brescia Council and Brescia Museums Foundation, with the Archaeology, Fine Arts and Landscape Superintendency and the Opificio delle Pietre Dure in Florence, as well as help from numerous private individuals [3].

Fig. 1 The Winged Victory. Archivio fotografico Musei Brescia, credits Fotostudio Rapuzzi.

Questions and answers on the Winged Victory and the role of the multidisciplinary studies

In 1826, on the evening of July 20th, the archaeological excavation resulted in an unexpected and sensational discovery. Between the outer wall of the temple's western chamber and the hill behind it were found hundreds of objects in bronze, of diverse forms and in varying states of preservation: smooth and molded frames, some gilded, portions of statues, two shoulder belts from equestrian statues, an *applique* depicting a prisoner, 6 portrait-heads, and the *Winged Victory*.

The discovery of this deposit – and above all of the monumental statue – ignited and fueled civic pride so much that the city authorities quickly set up a museum, that was inaugurated in 1830 inside the ancient temple itself (the *Museo Patrio*), which had been partially rebuilt and equipped for this function. News of Brescia's *Winged Victory* spread quickly throughout Europe and the statue was visited and admired by the most illustrious scholars of the 19th century. The *Winged Victory* became the symbol of Brescia's identity, of its heritage and all its inhabitants, and has remained thus up to the present day.

From the year of its discovery, the statue was the subject of numerous studies and conjectures.

During the years the museum's curators have been focused on the conservation's problem and on the structural health of the statue, monitoring the state of the bronze involving specialists in non-invasive diagnostic. In the same time the documentation – graphic, photographic and literature – has been verified and collected with the aim to support with a complete view the ingoing studies.

Fig. 2 The Capitoline temple. Archivio fotografico Musei Brescia, credits Alessandra Chemollo.

The recent project has made possible for the first time a complete and organic study, combining humanistic research with scientific (see below M. Galeotti et al.,) so to give answer to several questions still open. At the time of its discovery, the *Winged Victory* was found with its wings and arms detached; over time this circumstance has inspired a hypothesis that the statue's body originally belonged to a Greek *Aphrodite* of the Hellenistic period, brought to Rome as spoils of war and then transformed into a *Winged Victory* during the imperial era, with the addition of the wings and some changes of posture.

The project *Vittoria Alata 2020* enabled specific controls to be conducted that have disproven these conjectures, as well as pinpointed the chronology and illuminating numerous other aspects of this extraordinary work. The statue's iconographic reference model is the goddess *Victoria in clipeo scribens*, whose origin must derive from the specific Roman habit of giving form to virtues and values, for example Health, Hope and Honor. This deity determined who would be victorious on the battlefield and brought conflict to an end, restoring peace and equilibrium. The iconography first associates *Victoria* with a shield, a trophy acquired and held up in the battlefield, then *Victoria* uses the shield to record the winner's name by means of an inscription.

This iconography is not known before the Julio-Claudian era. By carefully checking known examples, Marcello Barbanera identified the reign of Vespasian as the period when this iconographic model was most used and widespread [4]. After the death of Nero, Vespasian was one of the protagonists of the civil war for the imperial throne. And *Brixia* gave the general crucial assistance in winning his decisive victory in AD 69 between Brescia and Cremona, when he was proclaimed *imperator*.

This chronology also supports the hypothesis, already formulated in the 19th century, that the *Winged Victory* might have been an imperial votive offering placed in *Brixia*'s temple, which was dedicated by Vespasian in AD 73, as recorded by the inscription on the tympanum. The gift of the statue would fit well with the significance and chronology of this decisive episode in Roman history.

Further support for the possibility that it was a gift from Vespasian resulted from the careful cleaning and investigation of the diadem that adorns the *Winged Victory*'s coiffure. Contrary to previous assertions, it is not a wreath of olive, but of myrtle, a crown reserved by the rigid Roman ceremonial of triumph for a victor who had conquered an internal enemy. Hence this detail also reflects the emperor's recognition of the help he received from *Brixia* [5].

Unfortunately, we're not yet able to state where the statue should have been on display; it is most probably that it was in the temple area where it has been discovered, even if we not know whether in the temple itself or in the terrace in open air. We can't even exclude that the *Winged Victory* might has been in the theatre, close to the *Capitolium*, or in another public building in the roman city.

Further confirmation that the work was created as a unified whole, conceived by Roman bronze workers as the *Winged Victory*, came during the course of the conservation treatment, which made visible again the statue's internal surfaces, almost two hundred years after its discovery.

In fact, to recompose the original shape of the statue, an internal support capable of supporting the detached arms and wings was inserted into the body few years after the opening of the *Museo*. The body of the statue was filled with various materials in order to make this structure stable and, for conservation reasons, this device was removed during the recent restoration.

The technological study revealed that the *Winged Victory* was made using the indirect molding lost-wax casting technique. The body is made up of about thirty separate parts that were subsequently welded together.

The various sections of the statue were made using as the "principal" model a cast of an already existing work, probably a 4th century BC Greek statue of Aphrodite. Signs of this process are discernible especially in the head and body which show the elegant features and proportions of the original figure, although with some formal inconsistencies and functional adaptations dictated mostly by production requirements and present above all in the rendering of the drapery.

The study also demonstrated that the openings on the back for attachment of the wings were created in the wax model. Although they have been improperly modified in recent times, they are of ancient origin, as are the two underlying protrusions that served to keep the large wings in place [6]. These details are of particular importance for the statue's interpretation and allow to reject the proposal that the wings were added later. The work's originality, conceived and created by Roman bronze casters as a *Winged Victory* writing on a shield, appears also to be confirmed by the results of recent analyses carried out on the composition of the alloys (see below M. Galeotti et al.,). With regard to identification of the statue's place of production, examination of some fragments of mold material that were fortunately found in crevices in the internal cavity revealed that this might possibly have come from the Brescia area, given its geological characteristics. This information reopens the prospect that the *Winged Victory* may have been made by craft workshops in ancient *Brixia* itself, which had in the past been suggested and now seems more likely [7].

The conservation work brought to light further traces of gilding, on the right hand and the big toe of the right foot – which had never been observed before because they were hidden beneath layers of various substances. The rectangular patch revealed on the right hand was clearly gilded using the technique of application of gold leaf, allowing us to imagine e very different aspect of the statue, more polychrome than we see it today.

The new museum exhibition layout design

A relevant part of the project concerned the adaptation of one of the chambers of the *Capitolium* temple in Brescia as the location for its display at the end of the restauration works.

In the past the *Winged Victory* had generally been on show in the *Capitolium*, except for a period when it was inserted in the archaeological itinerary in the Museum of Santa Giulia (1998-2018), and on several other occasions when it was moved for security reasons (for example during the two world wars) and for conservation treatments.

The selection of the statue's current location resulted from of a joint evaluation made by the institutions concerned with the conservation and enhancement of Brescia's archaeological heritage [8].

The design related to this choice was entrusted to the architect Juan Navarro Baldeweg, whose work embodies and interprets its various aspects, ancient and contemporary [9]. The *Winged Victory* has been placed in the eastern chamber of the *Capitolium* (in which the original flooring in *opus sectile* was less extensively preserved), in order to keep it near where it was found, in an appropriate setting that enhances its form and evokes its *aura*, so that instead of viewing the statue as a museum exhibit, visitors experience it as an integral part of a public monument. The handling of the Victory was planned with great care, given the statue's delicacy and the presence of a new internal support. Every detail of the design project is according the guidelines that emerged by analysis of the state of conservation and by the possible threatens elements. The room is a very calibrated balance between visual necessities and conservation standards and hosts several devices for monitoring in real time the temperature and relative humidity conditions of the outmost importance for the preservation of every archaeological bronze.

Fig. 3 The *Winged Victory* in the *Capitolium*. Archivio fotografico Musei Brescia. Credits Alessandra Chemollo.

Although it is not known in which chamber it originally stood, nevertheless the size of that chosen seems appropriate for the solemn and visible location that the work presumably had in ancient times. The possibilities offered by the space available, to be able to raise the statue sufficiently from the ground and have 360-degree vision of it, allow a new and more complete appreciation of the work, also outlined by studies conducted in parallel with the conservation treatment [10].

The statue is accompanied by many other notable bronze items that were found with it, consisting of numerous smooth and molded frames, as well as functional elements of architectural ornaments. Some are in a horizontal showcase, while most of the frames are mounted on the wall, outlining geometrical surfaces similar to the ancient ones they would have framed, for example marble slabs or inscriptions. This selection of the group of bronzes evokes especially both the context of discovery and an abstract, hypothetical context of origin, maintaining the visual dialogue between the statue and part of the deposit it belonged to.

The rest of the bronzes, those which would not originally have had an architectural function, are on display in the Roman section of the Santa Giulia Museum, which was reorganized in early 2022.

The formal composition of the exhibition space and the carefully studied, allusive and dynamic lighting offer visitors a unique experience in an abstract atmosphere that make this symbol of archaeological discovery quite contemporary.

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The role of scientific investigation in the conservation project of the Winged Victory of Brescia

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Abstract

The statue of the *Vittoria Alata* (*Winged Victory*), dating back to the 1st century A.D., was discovered in 1826 near the ancient Capitolium temple in Brescia, together with many other Roman bronzes. From 2018 to 2020, a complex intervention was carried out for the study, conservation and enhancement of the *Vittoria*, and to this end various professionals collaborated and interacted - archaeologists, conservators, conservation scientists, engineers, from research institutions and specialized companies. The teamwork has provided invaluable results in terms of advancing the knowledge of the lesser-known aspects of the history and origin of the masterpiece. Scientific investigations supported every single phase of the project so that it was possible to make informed decisions on the intervention and conservation choices. Among the many available diagnostic techniques, those that best met the real needs of the statue were selected, to define a multidisciplinary protocol that made it possible to successfully combine the results of the different investigation methodologies.

Keywords: bronze, structural health, electrochemical analysis, alloy analysis, neutron diffraction, reflectance FTIR.

Introduction

The *Vittoria Alata* of Brescia is one of the most famous Roman bronzes discovered in Italy. The recent conservation project offered a unique opportunity for a thorough investigation of the statue to get insights into the preservation state, manufacturing methods and previous non-documented restoration interventions. The statue was cast in more than 30 main sections made from independent casting, assembled with different techniques [1] (Fig. 1).

For this study, the combination of several methodologies was applied, with the use of non-invasive and micro-invasive techniques, from macro to micro scale. In this paper, we aim at illustrating the protocol that we have set in collaboration with several research groups to cover all the conservation and archaeometric aspects of the work and to make informed decisions on the conservation processes and on the various operational stages of the project (transportation, intervention, and exhibition). To do that, a true multidisciplinary approach was needed, with a continuous exchange of knowledge between the different professionals involved in this complex and multifaceted work (see above Morandini). The conclusions of the humanistic studies were compared with the outcome of the scientific investigation and of the technical studies. After illustrating the general workflow, some still open questions will be specifically addressed, like the dating and the possible later addition of wings to a pre-existing statue [2]. Another point to be understood was the origin of the materials on the surface, whether due to the natural weathering in the burial or to past conservation processes.

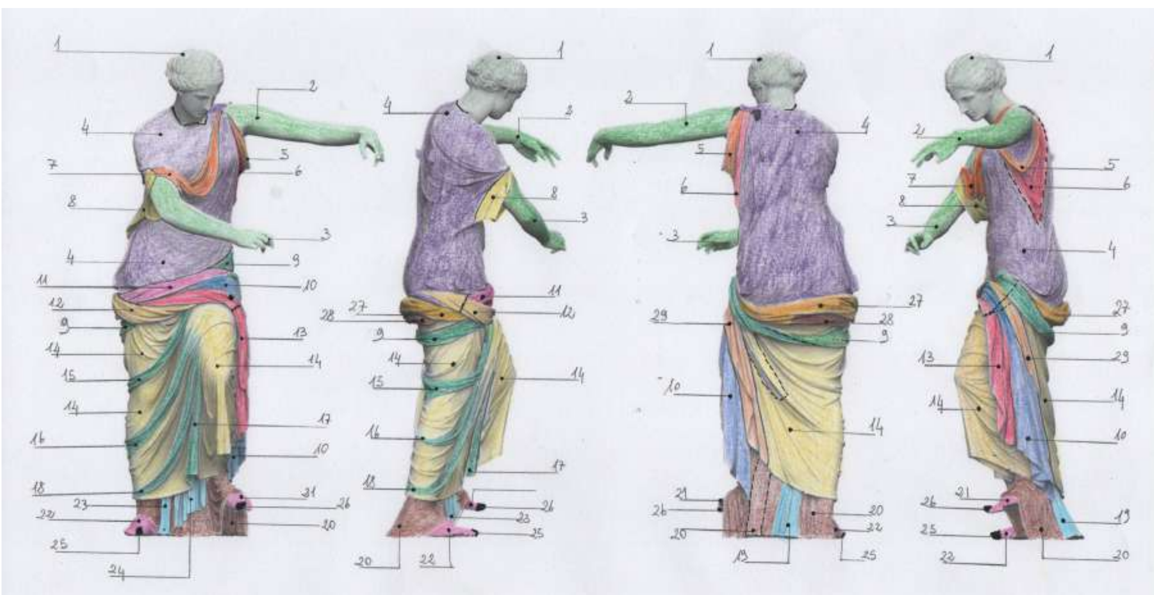

Fig. 1 Possible parts of the statue, as resulted from a visual inspection. Credits @Alessandro Pacini.

The protocol

In the last decades, research has led to broadening the wealth of methodologies for artistic and cultural heritage, making available also to the statuary many of the options that were traditionally used for two-dimensional artworks only. Therefore, given the number of existing possibilities, it is fundamental to set a protocol tailored on the real needs and requirements of the specific case study, choosing a route where the practicalities (timing, budget, feasibility, intactness of the statue) and the expected results match together.

A very important aspect to be investigated was the structural health of the statue, which was tested in different phases of the project (transportation, removal of filling material). Acoustic emission showed that the wings, assembled with a mechanical joint after the excavation, had an impact on the stability and created some tensions upon the daily microclimatic variations that could enlarge existing cracks on the back. During the movement of the statue, acoustic emission showed the rise of critical structural states on the various sections, produced by the change of the axiality and of the statics [3]. The dynamic behaviour of the statue during the removal of the filling materials and the internal support was monitored measuring the vibrations with accelerometers and comparing the response to that obtained with an impact hammer. Possible variations of the dynamic response of the statue to vibrations were also measured before and after the transportation back to Brescia, to verify that the movement had not been detrimental to the structure [4]. Other tests useful to check the presence of weak areas and their possible modifications with movements were X-Ray radiography (see below Lauriola, Radelet) [5] and active thermography [6], which were able to show the extent of cracks barely visible with the naked eye beneath the surface layers of corrosion and encrustations (Fig. 2). Identifying the old damages and assessing the current state of stability was fundamental to the correct planning of the transportation, the choice of the methods for removing the inner material, and the drawing of the new support and the base for the renovated exhibition in the Capitolium of Brescia.

The cleaning of the surface and its protection were central phases of the conservation work. Different approaches for removing old protective coatings were tested and the results were monitored with a portable Fourier Transform InfraRed (FTIR) spectrometer operating in reflection mode. The superficial layers included abundant

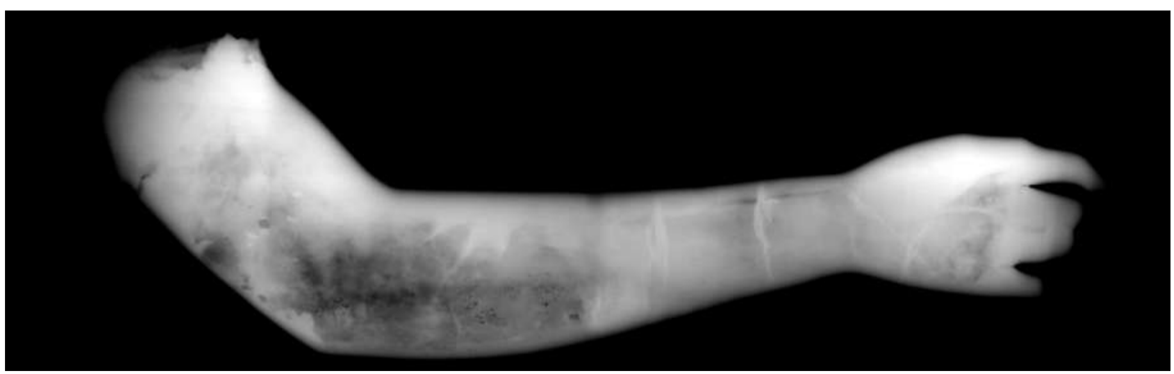

Fig. 2 X-Rays radiography of the arm highlighting a fracture of the bronze.

organic matter, which was identified as acrylic polymers and natural wax, applied onto the surface during past restoration works. The suitability of different cleaning options was monitored by comparing the reflectance spectra before and after the tests, checking the extent of removal of the organics and the absence of residues of the cleaning means, like cellulose poultice or gels [7].

After the cleaning was completed, it was crucial to know the proneness of the surface to corrosion, in order to choose a better long-term preservation strategy. The evaluation was made non-invasively with qualitative and quantitative electrochemical methods, i.e. electrochemical impedance spectroscopy (EIS) and polarization resistance (Rp) measurements. More test areas with different characteristics were selected for the acquisition of EIS spectra and of linear polarization scans (from which the Rp is calculated). The analysis reported that the various patinas had different protective capacities against corrosion, depending on their thickness and compactness. The average value of Rp, however, was not too far from the typical values of bronze artworks, including more recent ones [8]. The application of a coating of wax sensibly improved the values of Rp on test areas, even though it was not enough to obtain a general reduction on the whole surface, thus suggesting setting a monitoring program of the statue in the long term and the control of the microclimate of the exhibition room rather than relying on coatings only.

Dating, additions and surface layers

Some aspects concerning the origin, dating and construction of the *Vittoria* have been long debated; in particular, the wings were supposed to be a later addition to a pre-existing Venus. Despite numerous past studies [9], an exhaustive study on the origin of the statue was still lacking. The removal of the filling material offered a unique opportunity to reach out to the casting core, a sample of which was used for thermoluminescence dating. The outcome of the measurements shows that the baking of the casting core occurred between 30 and 290 A.D., a timespan that confirms the attribution of the statue to the Roman period rather than to the Greek one [2]. From the mineralogical and diffractometric analyses, the composition of the sandy fraction of the core appears compatible with the soil outcropping in the hills North and East of Brescia, suggesting the possible realization of the statue in a workshop in the city area [10]. The composition of the alloy is another relevant element in addressing the construction phases of the *Vittoria*. Since the presence of corrosion layers may bias quantitative elemental data provided by the application of non-invasive techniques, we have chosen a micro-invasive and multi-technique approach to ensure the reaching of the sound metal and therefore to come to a reliable result on the alloy composition. We combined scanning electron microscopy (SEM) coupled with X-ray microprobe and Time-of-Flight Neutron Diffraction (ToF-ND) to study micro-fragments, and portable X-Ray Fluorescence and Inductively Coupled Plasma-Mass Spectrometry to analyze shavings drilled with tips of less than 1 mm diameter [10, 11] (Fig. 3).

Fig. 3 Taking samples of the alloy with a drilling tip for the analysis of the alloy composition.

The different characteristics of the techniques and of the sample shapes allowed to have information on both the composition and the microstructure, minimize the invasiveness and enlarge the representativeness, limit the effect of the corrosion on the compositional data, obtain quantitative results down to the ppm scale. From merging the data of the four analytical methods, it was concluded that the main composition and the qualitative and quantitative distribution of the traces are consistent with the bronze statuary of the Roman imperial age, with a lead content ranging from about 7 to 12 % (average values obtained with the various methods). The observed variability of the major elements among the different sections agrees with that of other Roman bronzes cast in several pieces. The individual castings were made using the same raw materials as can be inferred by a rather constant level of trace elements. A great variability of the major and trace elements among the different sections is observed, which agrees with the data of other large Roman bronzes cast in several pieces. The compositional consistency of the various portions, together with the visual observation of the technical features, excludes the realization of the statue in not contemporary periods. In addition to the samples, a feather fragment of the right wing (about 3.0 cm × 3.5 cm) could be brought to the neutron center for analysis with ToF-ND and neutron radiography. Owing to the penetration power of neutrons into the bronze, some morphological characteristics have been highlighted and the mineralized phases on the surface have been mapped. The presence of the highly attenuating hydrogen in these phases makes them appear as dark or black in the neutron radiography, in contrast to the lighter tones of the metallic phase [11].

The analysis of the materials on the surface was of uttermost importance to come to understand the effects of both past restoration interventions and repairs and the long burial. To clarify these aspects, we analyzed micro-samples with optical microscope, SEM, bench FTIR, and X-Ray Diffraction. Beside the presence of the acrylic polymer, presumably dating back to recent conservation works, the results point to the presence of a thick crust of copper and calcium-copper silicates (from the interaction of silicates and calcium from the ground with copper) that lays on a thin layer of copper oxides. Moreover, the crust incorporates cupric carbonate hydroxide (malachite), copper phosphates, lead carbonate, and lead hydroxycarbonate, fragments of carbonized wood, pebbles, and other soil materials. A parallel examination of

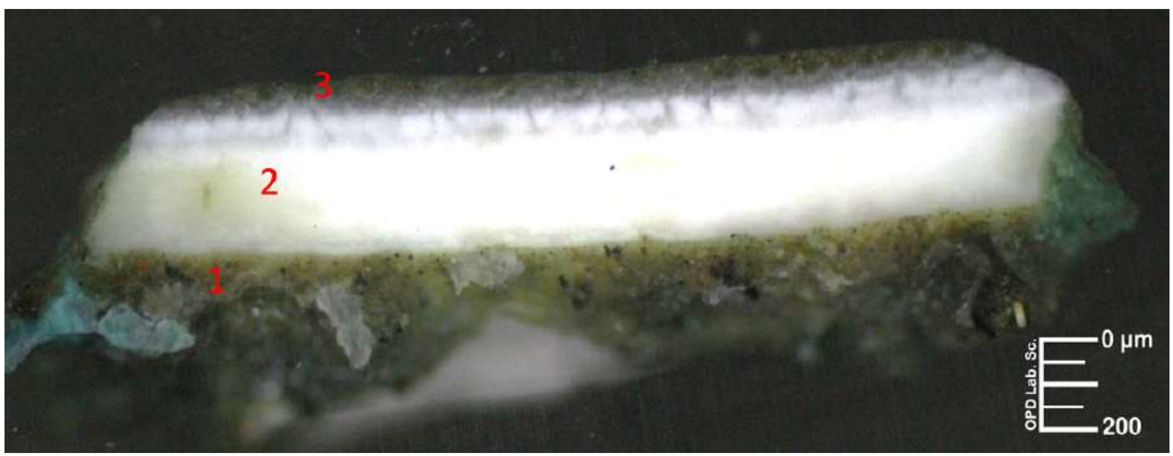

Fig. 4 Cross section of a sample including a painting layer on top of a plaster repair.

the patina of the surfaces of the cavity of the *Vittoria* and of some bronze frame fragments excavated at the same site (and never restored) revealed a pattern like that of the external surfaces of the statue, suggesting the natural origin of the patina, not induced by previous conservation treatments. Some gaps of the bronze, however, were filled with plaster in previous conservation works and painted green with a mix of barium sulphates, green earth, calcium and copper carbonates. Interestingly, on top of the painting a layer made of materials obtained grinding the natural encrustation was applied to better mask the repairs, as shown in Fig. 4, where the white plaster layer (2) is put above the thick natural encrustation (1). On top of the white plaster, an even, green layer of calcium and copper silicates and of phosphates (3) is observed, in an attempt to mimic the surrounding surface. In other cases, the surface layer observed seems to be the result of a treatment with chemicals, as reported in documentation of the 1948 restoration (for example using sulfuric acid) [12].

Conclusions

The work that we have illustrated in this contribution shows the importance of drawing a case-tailored diagnostic protocol prior to the execution of a complex conservation project, as in the case of the *Vittoria Alata*. While non-invasive methodologies, both imaging and punctual ones, were prioritized, a detailed study of the composition beneath the outer layer required a limited number of submillimeter samples to be taken. The data acquired underpinned the restoration intervention and added a piece to the knowledge of the bronze artistry in the Roman world.

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Nuclear Analysis of the Shroud of Turin

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Abstract

The Shroud of Turin contains full-size front and dorsal images of a man who was crucified exactly as Jesus was crucified according to the New Testament. Mysteries of the Shroud include how the images were formed and why the Shroud carbon dated to 1260-1390 AD. By following the scientific evidence where it leads, the Vertically Collimated Radiation Burst (VCRB) hypothesis was developed to explain these mysteries. According to this hypothesis, an extremely brief burst of charged particles emitted from the body produced the images, and neutrons in this radiation burst explain the carbon dating of the Shroud. According to MCNP nuclear analysis computer calculations, a small fraction of the neutrons in this radiation were absorbed in the trace amount of N-14 which produced new C-14 atoms in the fibers [$N^{14}(n,p)C^{14}$]. This shifted the measured carbon date forward from the true date. This explains all features of the carbon dating.

Keywords: shroud of Turin, Turin shroud, carbon dating of the shroud.

Introduction

The Shroud of Turin is one of the most mysterious and potentially significant items in human possession. It is a linen cloth that measures about 441 cm long by 112 cm wide (about 14 feet 6 inches by 3 feet 8 inches). It appears to have been well known and highly revered in the Byzantine Empire where it inspired paintings and images on coins starting in the sixth century. It was exhibited as Jesus' burial cloth in Lirey, France about 1355 and has been in Turin, Italy since 1578. The unique aspect about the cloth is that it contains full-size front and dorsal (back) images of a man who was scourged and crucified exactly as Jesus was according to the New Testament. Based on these images, ancient tradition has long claimed the Shroud to be the authentic burial cloth of Jesus. In 1978, five days of experiments on the Shroud by the Shroud of Turin Research Project (STURP) proved the images are not due to pigment, a scorch from a hot object, a liquid, or photography. The images also were not caused by contact with the body or by body decay products. The scientific evidence obtained by STURP appears to indicate the explanations for image formation and the carbon dating are related, because both appear to be the result of radiation emitted from the body.

Formation of the images

For an image formation hypothesis to be true, it must be consistent with all the evidence related to the front and dorsal images on the Shroud. For researchers to accept the hypothesis as true beyond a reasonable doubt, the hypothesis should make predictions that are testable and falsifiable, which means that if the prediction is tested and proven to be false, it will prove the hypothesis to be false, at least as stated. If the prediction is tested and proven to be true, it will increase the credibility of the hypothesis. Depending on the nature of the predictions and the testing, it may require testing of multiple predictions that are proven to be true before the hypothesis is generally accepted as true beyond a reasonable doubt.

The STURP experiments and subsequent analysis indicate the images have many different characteristics. 27 of these were analyzed [1] to determine a hypothesis for image formation. This image formation hypothesis proposes that an extremely brief intense burst of vertically collimated low energy radiation emitted in the body could have formed the images. When the charged particles, probably protons, deposited their charge on the cloth it caused corona discharges between the body and the cloth. This produced alternating currents in the fibers which produced extremely localized heating in the fibers. This produced the fiber discoloration on the Shroud which made the front and dorsal images of a crucified man on the cloth. If this burst of radiation also included neutrons, then it could also explain the carbon dating of the Shroud.

Carbon dating of the shroud

In 1988, a thin strip was cut from the corner of the Shroud near the feet of the front image. Samples were cut from this strip (Fig. 1) and sent to three carbon dating laboratories: Tucson in Arizona, Zurich in Switzerland, and Oxford in England. These laboratories cut their samples into smaller pieces so that ultimately 12 subsamples were carbon dated. Results were reported by Damon, et al. in the British journal *Nature* in 1989 [2]. This paper concluded that the Shroud dates to 1260 to 1390 AD, though most Shroud researchers believe this date should be rejected, i.e., given no credibility [3]. This is because: 1) they did not have the technology to pro-

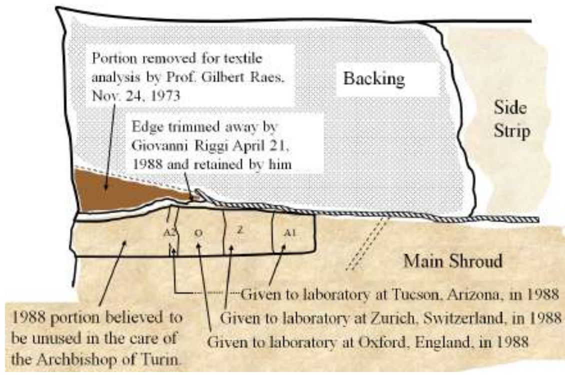

Fig. 1 Sample Locations.

Oxford	Zurich	Arizona
1155 ± 65	1217 ± 61	1249 ± 33
1205 ± 55	1228 ± 56	1260 ± 35
1220 ± 45	1271 ± 51	1344 ± 41
	1311 ± 45	1359 ± 41
	1315 ± 57	
1200.8±30.7	1273.9±23.7	1303.5±17.1

1277.8±12.6 (1260±31 →1260-1390)

Fig. 2 Carbon Dating Results (AD).

duce the images in 1260-1390, 2) there are many other date indicators that contradict the carbon dating to 1260-1390 AD, and 3) because of the statistical analysis of the measurement data discussed below.

Fig. 2 shows the dates and uncertainties for the 12 subsamples from Damon [2] in black. The values in red are the author's calculated values starting from Damon's reported values. The values in red display one additional digit to the right of the decimal point to prevent propagating a round-off error to the next step. The weighted average or mean value of these three laboratory weighted mean values is in red at 1277.8 ± 12.6 AD. Instead of this value, Damon chose to report an unweighted mean of 1260 ± 31. 12.6 rounds to 13 but 31 was reported instead! The 1260 ± 31 date was then corrected for the changing C-14 concentration in the atmosphere to produce a range of 1260 to 1390 AD, with 95% confidence. The average of this range is 1325 AD. However, the analysis below indicates the presence of a systematic measurement error so the values cannot be trusted.

Analysis of the data

The average dates from the three laboratories can be correlated to the locations of the samples on the cloth. From left to right on the strip cut from the Shroud (Fig. 2), the samples were sent to Oxford, Zurich, and Arizona (Arizona did not date sample A2), but in this same sequence the carbon dates are increasing. This spatial dependence of the measured carbon date is plotted in Fig. 3 with the three laboratories, Oxford, Zurich, and Arizona plotted from left to right. The vertical bars indicate the one standard deviation range. The y-axis is the carbon date AD and the x-axis is the distance of the center of the sample from short edge of the cloth. This plot shows that the uncorrected average value of 1260 AD claimed in Damon, represented by the horizontal black dashed line in Fig. 3 only goes through the date from Zurich but not the dates from Oxford or Arizona. The best fit to the three laboratory average values is the red dashed line, which has a slope of about 36 years per cm (91 years per inch). This is very significant because if the sample point were moved 25.4 cm (10 inches) further from the short edge of the cloth and thus closer to the center of the body, then at this rate (36 years per cm) the measured carbon date would increase by about 910 years from 1260 AD to 2170 AD, which is a date to the future. This data indicates that an unknown factor appears to be causing the measured carbon date to be a function of the distance from the short edge of the cloth.

A Chi-squared statistical analysis can also be used to determine whether the 12 subsample dates and their uncertainties for the Shroud are consistent with each other, as they should be. This statistical analysis calculated a significance level for the 12 Shroud subsamples of only 1.4% (Table 5 of [4]), which indicates there is only a 1.4% chance that random errors alone can explain the spread in the data listed in Damon. The 1.4% is below the usual acceptance criteria of 5%. This indicates a systematic error was also likely affecting the measurements. Since it is not possible to determine the magnitude of this systematic measurement error, the only option is to reject the data, i.e., give no credibility to the measured carbon dates of the 12 subsamples or the alleged carbon date range of 1260 to 1390. This result is confirmed by the statistical analysis in four recent papers in peer-reviewed journals [5 ,6, 7, 8]. Three standards were also carbon dated at the same time as the Shroud samples. Since the measured carbon dates for the three standards were determined with reasonable accuracy, it should be accepted that the C^{14}/C^{12} ratio measurements for the twelve Shroud subsamples were likely correct. As a result, the spatial dependence of the carbon dates for the Shroud must result, not from errors in the measurements of the C^{14}/C^{12} ratios, but from something that altered the C^{14}/C^{12} ratios in the twelve subsamples as a function of the distance from the short side of the cloth.

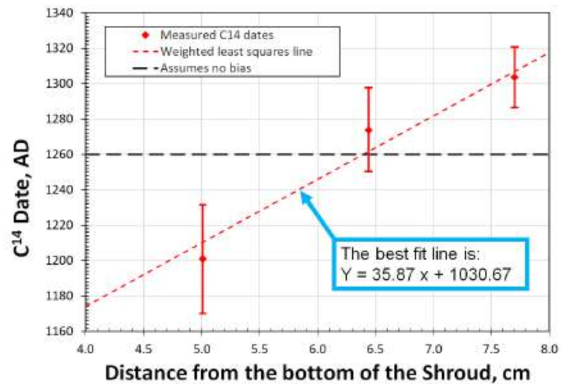

Fig. 3 Measured carbon dates are a function of the sample location.

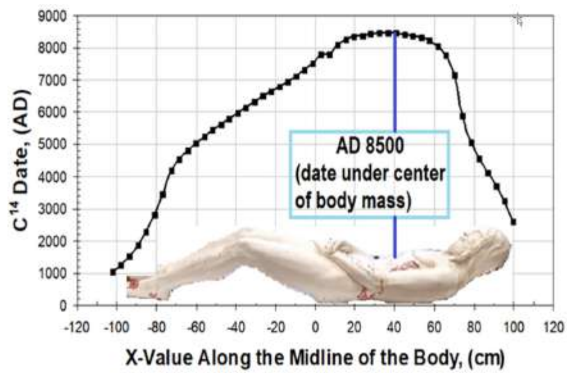

Fig. 4 MCNP calculated dates in cloth below the body.

Nuclear analysis computer calculations

Due to his extensive experience in calculating neutron distributions, the author recognized that the spatial dependence of the carbon date measurements for the Shroud (Fig. 3) is similar to the neutron distribution that would occur if neutrons were emitted from the body. To determine whether this could be the explanation for the carbon dates obtained in 1988, nuclear analysis computer calculations were performed using the MCNP computer code [9, 10]. MCNP is an acronym for Monte Carlo N-Particle where "N" stands for neutron. MCNP was developed at the Los Alamos National Laboratory over many decades by a team of people. It is considered by US government agencies to be fully verified and validated for general nuclear calculations based on comparison of MCNP calculations with thousands of experiments in nuclear facilities.

For simplicity, a human body was modeled in MCNP using simple geometrical volumes. The body was then surrounded by thin linen in the shape of a rectangular box to represent his burial cloth. Both were modeled on the back bench in a limestone tomb as it probably would have been designed in the first century. It was assumed that the neutrons were emitted homogeneously within the body. If there were such a neutron emission, a small fraction of these neutrons would have been absorbed in the trace amount of N-14 in the linen. When a N-14 nucleus absorbs a neutron, it ejects a proton, thus becoming a new C-14 atom [N^{14} + neutron $\rightarrow C^{14}$ + proton]. This production of new C-14 atoms in the samples will shift the measured carbon date to the future relative to the true date. For example, if the C-14 concentration were increased by 16.9%, it would shift the carbon date from 33 AD to 1325 AD.

Fig. 4 shows the distribution of carbon dates predicted by MCNP along the centerline of the body, i.e., along the backbone, on the section of the cloth that would have been under the body, where the dorsal image is now located. The carbon date distribution in Fig. 4 was normalized to a total neutron emission from the body of 2×10^{18} neutrons so that the second point from the left in Fig. 4 would have a carbon date of 1260 AD, which is the uncorrected average value from the three laboratories. 2×10^{18} neutrons is about one neutron for every ten billion neutrons in the body.

The slope of the line through the second point from the left in Fig. 4 is in good agreement with the slope of the line in Fig. 3, so that the MCNP calculated slope is in good agreement with the experimental slope of the carbon dates from the three laboratories. Thus, if 2×10^{18} neutrons were emitted homogeneously from the body, the results would probably be consistent with the four evidences regarding carbon dating: 1) the average date for the samples is 1325, 2) the change in the measured carbon date as a function of the distance from the short side of the cloth is about 36 years per cm, 3) the correct range and distribution of the twelve subsample dates, and 4) the carbon date for the Sudarium of Oviedo, Jesus' face cloth, which was measured to be about 700 AD. This neutron absorption hypothesis is the only hypothesis that is probably consistent with all four of these evidences. To assume that the Shroud was made in 1260-1390 is only consistent with the first of these four evidences, so this assumption should be rejected.

Conclusions

Consideration of the scientific evidence related to the images indicates they could possibly have been formed by an extremely brief intense burst of vertically collimated low energy charged particles such as protons emitted in the body [1].When these particles were absorbed on the cloth, they caused electrical currents in the fibers that produced extremely localized heating in the fibers. This produced extremely localized discoloration of the fibers that made the front and dorsal images of the crucified man. The best explanation for the carbon dating of the Shroud is that about 2×10^{18} neutrons were emitted from the body, with a small fraction of them being absorbed in the trace amount of N-14 in the fabric to produce new C-14 atoms [$N^{14}(n,p)C^{14}$] on the cloth that shifted the measured carbon date forward from the true date. This is the neutron absorption hypothesis. This explanation is the only hypothesis that could be consistent with the four things we know to be true about carbon dating related to the Shroud: 1) the average carbon date, 2) the slope of the carbon date, 3) the distribution and range of the 12 subsample dates, and 4) the carbon date for the Sudarium of Oviedo, which is believed to be Jesus' face cloth.

It is reasonable to conclude that the image formation and the carbon dating are related to each other since they are both the result of radiation emitted from the body. When these two explanations are combined, the result is the Vertically Collimated Radiation Burst (VCRB) hypothesis. The VCRB hypothesis proposes that an extremely brief intense burst of vertically collimated low energy particles were emitted in the body, probably by fission of about 0.0004% of the deuterium nuclei in the body, with protons causing the images and neutrons shifting the carbon date forward from the true date. What would cause deuterium nuclei to fission is not currently understood but might be investigated by future testing of the Shroud and by various considerations in modern physics. There is no known example of a human body producing an image of itself on a piece of cloth, except for the Shroud of Turin. In our current understanding of physics, there is no mechanism or process that can do this. Thus, to help humanity gain a more complete and accurate understanding of reality, further scientific testing should be performed on this unique cloth. This paper is an abridgment of [11].

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“Difficult” archives for “difficult” heritage conservation: applied value of 20th c. project documentation. On the materials of the Wolfsoniana-Genoa Collection

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Abstract

The 20th century modernist architectural and design heritage conservation is a difficult challenge from several aspects, deeply different between each other. Strictly technological needs are crossing with the questions of valorisation and even with ethics queries due to political engagement of such legacy, that is, in the same time, already protected by cultural heritage laws in the most part of European countries.

The heritage legislation and professional culture require the traditional, philological approach to the 20th century buildings, which, however, when built, represented a field for experiments. Innovative materials and techniques were largely involved in the construction and decoration of buildings. Some of them were created ad hoc, another were produced industrially, but are not in use anymore. The dictatorship economy (e.g. “autarchia” in fascist Italy) contributed richly in the creation of new “modern” and convenient materials. The conservation of the objects realized from various sorts of substances requires a deep awareness of their qualities and the creation of articulated strategies. The architectural, engineering and design-production archives can offer a rich and fruitful source for preliminary research and for elaboration of testing strategies and conservation approaches. They contain the information on the technologies of construction, productors and manufacturers, building and decorative materials etc. However, while fundamental for the conservation of pre-modernist heritage, the archives are often not sufficiently considered for restoration of the 20th century objects.

Wolfsoniana Genoa keeps several architectural and design production archives (among them the archives of architects Giuseppe Crosa di Vergagni, Pietro e Alfredo Fineschi, Beniamino Bellati, and MITA fabric factory), that present both works of art and technical documentation and have complessive nature. The paper focuses on the peculiarity of their contents, their value for history of building and design technology, their potential for conservation research purposes and involvement in the restoration projects.

Keywords: 20th century architecture and design, modernist heritage conservation, history of collections, archives, wolfsoniana.

Mitchell (Micky) Wolfson Jr. was among the first who started to collect architectural project designs and documentation, related to the buildings realized between 1870 and 1945, not only as works of art but "in function of ideas". Found in the mid-1980s in Genoa, the Wolfson collection now is divided between the Florida International University in Miami, USA, and Wolfsoniana – Palazzo Ducale Fondazione per la Cultura in Genoa, Italy[1]. The architecture documentation makes part of the Wolfson's heterogenous collection together with painting, sculpture, graphic works and prints, decorative arts, and ephemera. From the collection's optic, it is a part of the material culture of the civilization which produced it, a "tangible evidence concerning transformations in values and politics"[2].

The Wolfson's collection was born when the interest to the 20^{th} century built heritage, that now is often called with the generic name of "modernism", was still selective. While the attention to the Avant-Guard had been already strong, the "traditional" architecture was less taken in consideration, while the regime architecture was almost ignored. It was seen as contemporary and was not considered as a subject for restoration till 2000, except rear cases[3].

Unless several research and realized works, the modernist design and architectural heritage conservation is still a difficult challenge, where specific practical requirements of conservation techniques and approaches meet theorical questions of valorisation starting from the professional philosophical issues as "how to restore" and arriving sometimes to the ethic queries as "why to restore" due to political engagement of such legacy. At the same time, these buildings are already considered cultural heritage and protected by specific laws in the most part of European countries, in Italian case – by the Codice dei Beni Culturali e del Paesaggio (articles 10-20, 2004).

There are many examples of philologic restoration worldwide, as those of Bauhaus school in Dessau (1925-1926) by Walter Gropius, restored in 1996-2006, possible thanks to the great attention to the building authenticity and availability of archive sources, highly involved in the work. However, in most cases the interwar heritage, as usual, is adopted to another way of use or another function; the restoration is made with contemporary materials, the details are repristinated approximately or replaced by non-authentic ones. Sometimes it even needs to be put out of the political context in which it was created, as in case of the Palace of Italian Civilization in Roma (1937, completed in 1952), known as "the square Colosseum", built within an ambitious project of E 42 – World Fair 1942 to celebrate the 20^{th} anniversary of fascism, refurbished in 2015 to host the headquarters of Fendi fashion brand.

The conservation of the architecture and design archives is either complicated task for both reasons of conservation technology and contents. They are mostly composed of paper materials, often fragile (e.g. tracing paper) and of big format, which require special conditions of storage. At the same time, these materials are not attractive for the mass public and difficult to expose, if not in the special exhibitions on architecture. Unless the first museums of architecture were found since 1930s (The Schusev Museum of Architecture in Moscow and Musée du Monuments français are among the oldest; there are the architectural collections at the important museums as Centre George Pompidou or Museum of Modern Art New York) the interest to this kind of archives is rather recent. In 2000s the institutions as Le Cité de l'architecture e du patrimoine (2004) in Paris or Centro Studi e Archivio della Comunicazione dell'Università – CSAC (2007) in Parma, Museum of Modern Art of Trento and Rovereto (2002), Museum of Arts of XXI century – MAXXI (2009) in Rome with a huge 20^{th} c. architecture archives section were opened, now they have constant exhibition activity. The most part of

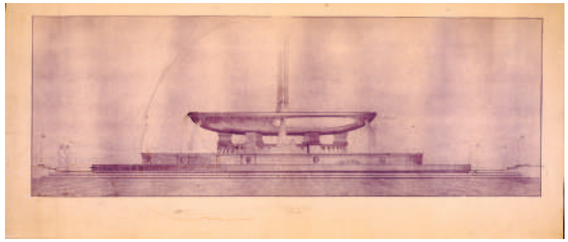

Fig. 1 Giuseppe Crosa di Vergagni, Monumental Fountain in piazza de Ferrari, 1932-1935, Genoa, Italy, GA1996.52*.

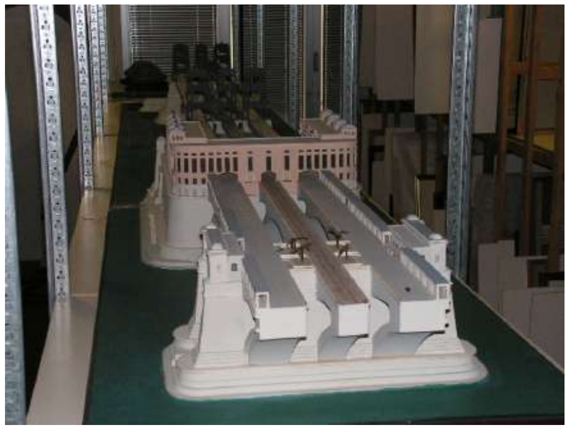

Fig. 2 Studio Armando Brasini, Maquette for the Messina Straight Bridge, 1956, GX1993.115 a, b.

this heritage, although, still belongs to private institutions and architect's heirs with very limited access.

Wolfsoniana keeps several archives by architects and designers which were donated by the heirs or acquired from them or from the antiquity sellers. Following the approach of its founder, the collection is not pointed only on "big" names, but on the authors who actually composed the architectural face of the period, the context. Among them there are those of Giuseppe Crosa di Vergagni and Pietro and Alfredo Fineschi, Beniamino Bellati, who worked in Genoa and the region and shaped the Ligurian architectural scene between two wars. These archives consist with project graphic and documentation, personal files: documents and correspondence, and in some cases personal libraries.

The architecture archives have an outstanding value not only in the meaning of the artistic heritage. They have concurrently high documental significance, that can be used for the conservation of built heritage itself. The applied relevance makes them a highly useful tool for the elaboration of restoration projects. They help to understand the original concept of the building, its construction history, the built and interior decoration materials. At the same time, they help to understand the author's design logic, his artistic personality, and his creative approach. Indeed, it is a good (unless unfortunately rare) practice to organise research groups before the restoration of a monument. Of this kind is the conference "Il Vittoriano e l'opera di Armando Brasini" planned in Rome in November 21-22, 2023, in occasion of the future restoration of the Vittoriano Monument, where the Wolfsoniana curators presented a proposal on the Project of the Messina Straight Bridge (1956, unbuilt) by Armando Brasini, which model is kept at the collection, together with other project documentation. In this case, the archival materials could be an indirect tool to the analysis of the "way of thinking" of the author, a contribution to the understanding of the construction concept of a building to restore.

Architectural models are another important kind of architecture archival materials. Wolfsoniana keeps some architectural models of noticeable Italian interwar buildings, among them there is the model of the Arengario in Piazza della Vittoria in Brescia by Antonio Maraini (sculptor) and Marcello Piacentini (architect), realized in 1928-1932. The wax maquette by Maraini represents a dynamic composition that is more expressive and less rigid than the final solution in rose stone – "pietra rosa di Tolmezzo", which gives us an idea of the author's original concept and its development.

In case of Piazza della Vittoria, as in many other Italian buildings realized between two wars, the traditional materials were used together with the new ones. As well-known, the early 20th century was a time of technological experiments, and the architecture was one of main fields for them. The research for standards, cheaper and easier to manage materials, bright and long-lasting colours, the possibility of mass production were actual for the just born building industry. Innovative materials and techniques were largely involved in the new construction and decoration, sometimes even imitated with traditional ones. Together with modernist design, they symbolized the modernity and progress, the intrinsic trends of the epoch[4]. Some of that materials were created ad hoc, another were produced industrially, but are not in use anymore. The dictatorship economy, as "autarchia" in fascist Italy, contributed richly in the creation of new "modern" and convenient materials, which were actively involved in design and construction. The heritage legislation and professional culture require the philological approach to the restoration 20th century architecture, the same which is used for the buildings of pre-industrial epoch. It requires the specific knowledge on the innovative materials, and the archives are the key source for them.

The Wolfsoniana from its beginning payed a great attention to the phenomenon of implementation of new technologies and experimental materials to the design, applied arts and architecture. The long-year research and collecting were summarized in the exhibition "L'Italia farà da sé"[5], curated by Matteo Fochessati and Gianni Franzone and shown at the Palazzo Ducale of Genoa in 2015. The exhibition showed the impact of "Autarchia" state policy on different levels of social and cultural life of the country. Among high number of propaganda advertisement, the collection presents several examples of items made with autarchic materials. Among them there are a chair from Palazzo Gualino by Giuseppe Pagano and Gino Levi Montalcini (1928) in Buxus; "Impero Moderno" coffee-set by Arrigo Finzi from autarchic silver; a table service for "Autarca" table

Fig. 3 Antonio Maraini (sculptor), Marcello Piacentini (architect). Maquette for the Arengario in Piazza della Vittoria, 1932, Brescia, Italy, GX1993.253.

Fig. 4 Arrigo Finzi; "Sant'Elia", Milano, Servizio Autarchia, 1940-1941, GG2018.11a-e.

with pieces produced in bachelite. The architectural and design project documentation in some cases gives the information on the materials used in the construction and their producers, that helps to make choices for the restoration and conservation projects.

Among the pieces of art and design, the design and architecture archives are apparently difficult to valorise and to disclose. The case of the MITA (Manifattura Italiana Tappeti – since 1940s – Tessuti, Artistici) archive disproves it. Thanks to the Wolfsoniana curatorial strategy the archive, consist of tissue panels samples, rugs, sketches, documents, photography, and advertise-

Fig. 5 Michael Rachlis, Sketch for the tapestry at the library of the 1st class area at the Andrea Doria Ocean Liner, 1952. Archivio MITA, Genova Nervi di M.A. Ponis, in comodato presso Wolfsoniana-Palazzo Ducale Fondazione per la Cultura, Genova.

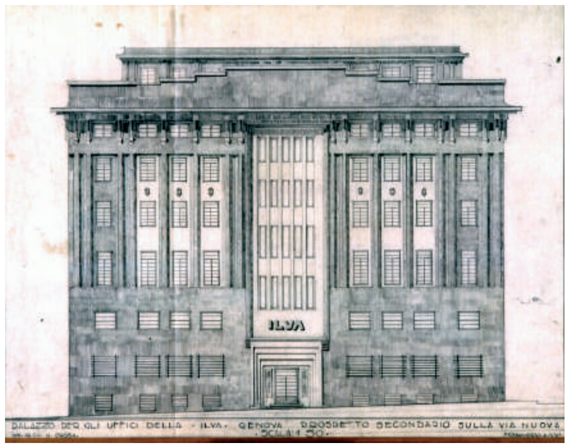

Fig. 6 Giuseppe Crosa di Vergagni, ILVA Office building in Via Corsica, Genoa, 1930-1931, GA1996.54.

ment production, found a great interest of researchers and public. After the exhibitions in Genoa and San Remo and Samugheo (2016)[6], the MITA exhibition was shown at the Wolfsonian in Miami Beach (2018) and at the Estorick Collection in London (2020-2021)[7]. Recently, the archive have attracted the attention of Brioni fashion brand, which reproduced the MITA tapestry "Andrea Doria", lost in the shipwreck in 1956, for its store in Milan. The contemporary reproduction, however, didn't apply the MITA technologies and materials, unless it would be possible thanks to the archive documentation.

The main area of the 20th century design and architecture archives is restoration of the interwar heritage. Wolfsoniana still in the early 2000 was among the institutions who recalled paying attention on the architectural heritage of 1920-1950s in Italy and in particularly in Liguria Region[8]. Since the exhibition "Architettura in Liguria: dagli anni venti agli anni Cinquanta" (2004) a lot of buildings, at that time in bad condition or even dismissed, where restored and found new life, although with questionable results. This is the case of the ILVA office building, realized in 1929-1930 by Giuseppe Crosa di Vergagni, refurbished in 1960s, restored in 1991 by De Ferrari Architetti studio and abandoned in 2000. It was recently converted in a luxury hotel "Meliá Genova", when the facades of the building were restored but the interiors completely modified according to the needs of new use and the hotel chain design criteria. Some elements of the interior decoration have been already lost in 1960s and there was no attempt to replace them in the further interventions. Sketches and drawings, belonged to the Wolfsoniana, conserve the memory of the original building, but could have been used for the elaboration of more authentic restoration project. Indeed, the norms and conditions for the restoration of the 20th century heritage are still a grey area as in Italy as worldwide. The law prescribes to respect the authentic aspect and materials and to repristinate missing details according to archival sources, visual or written, but on practice the approved and implemented projects are far from this condition.

Notes

* All reproduced objects belong to the Wolfsoniana – Palazzo Ducale Fondazione per la Cultura

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Notre-Dame de Paris et sa restauration au XIX^{e} siècle

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Abstract

La cathédrale Notre-Dame de Paris a été victime d'un incendie le 15 avril 2019, qui a entièrement détruit sa charpente et sa couverture, avec la célèbre flèche élevée par Eugène Viollet-le-Duc en 1859. En outre, l'incendie a causé de nombreux dommages, comme l'effondrement des voûtes de la croisée du transept. Au moment où la restauration est en cours, avec le choix de rebâtir la charpente et la couverture selon leur forme existante en 2019 et avec les mêmes matériaux, il apparaît intéressant et important de jeter un coup d'œil rétrospectif sur les travaux de restauration du XIX^{e} siècle, qui ont duré un quart de siècle et sont intervenus profondément dans la consistance matérielle de l'édifice. Il s'agit de présenter, sommairement mais le plus synthétiquement possible cette cathédrale désormais disparue – au moins en parti – et d'en comprendre les enjeux dans l'histoire des arts du XIX^{e} siècle.

On April 15th 2019, Notre-Dame Cathedral in Paris was victim of a fire that completely destroyed its framework and cover with the famous spire built by Eugène Viollet-le-Duc in 1859. In addition, the fire caused extensive damages, such as the collapse of the transept vault. At a time when the restoration is underway, with the choice in 2019 to rebuild the framework and the roof according to their existing form and with the same materials, it should be interesting and important to take a retrospective look at the restoration works of the nineteenth century, which lasted a quarter of a century and intervened deeply in the material consistency of the building. The presentation will focus, summarily but as synthetically as possible, on this cathedral that has almost disappeared – at least partially – and on the understanding of its stakes and issues in the history of the 19th century arts.

La restauration de Notre-Dame de Paris sous la direction de Jean-Baptiste Lassus et d'Eugène Viollet-le-Duc, puis d'Eugène Viollet-le-Duc seul à partir de 1857, est une entreprise colossale qui s'étend sur plus de vingt ans, les travaux commencés dès 1845 ne s'arrêtant pas à la fin « officielle » des travaux marquée par la consécration solennelle de l'édifice le 31 mai 1864, mais se poursuivant au-delà, au moins jusqu'aux notables finitions que sont la pose des pentures de la porte principale en 1867 ou la construction du presbytère en 1869.

Cette entreprise, est-il besoin de le dire, a transformé la cathédrale sous de multiples aspects et est intervenue puissamment dans sa substance, en dépassant évidemment les intentions affichées par les architectes dans leur projet, selon la notice imprimée et diffusée en 1843[1] qui ne fut pourtant pas pour rien dans leur succès au concours. Curieusement cependant, ce qui est un des grands chantiers artistiques du XIXe siècle n'a pas été étudié jusqu'ici de façon globale ou systématique et le bilan que l'on en a tiré, exprimé çà et là bien des fois depuis plus d'un siècle, reste assez superficiel. Pourtant, la restauration de Notre-Dame de Paris est documentée par un ensemble impressionnant d'archives, documents techniques ou comptables (les « attachements figurés » en particulier), dossiers administratifs, correspondance, sans oublier le « Journal des Travaux », tenu – avec quelques interruptions – entre le 30 avril 1844 et le 28 octobre 1865[2]. Une lecture attentive de ce dernier document, dans sa version numérisée accessible sur le site internet de la Médiathèque du Patrimoine[3] est à la base de l'article présenté ici.

Le 15 avril 2019 l'édifice a subi par le feu un dommage énorme, épouvantable, qui l'a privé de sa charpente et de sa couverture, avec la flèche. Au moment où se développe une campagne de restauration aux moyens inédits et ayant, sans aucun doute, au moins l'importance de celle du XIXe siècle, il me paraît essentiel de revenir sur l'intervention de Lassus et Viollet-le-Duc. Non seulement pour reconnaître ce qui, dans le monument, était leur œuvre et a disparu dans les flammes, mais encore pour bien se représenter l'état matériel de la cathédrale telle qu'elle était sortie de leurs travaux et telle qu'elle l'est toujours, aucun travail de même envergure n'ayant eu lieu depuis la fin du Second Empire. On connaît bien, ou l'on croit connaître, les principaux points de leur travail : l'intervention a en réalité été très profonde, intervenant systématiquement sur les surfaces murales, démolissant, incrustant, restituant tous les membres de l'architecture, bandeaux, ressauts, larmiers, contreforts, galeries, corniches, gargouilles, jugés nécessaires au fonctionnement comme à l'apparence de l'édifice. On peut sans doute dire qu'aucun lieu, qu'aucun espace de la cathédrale n'a été ignoré de la restauration, qui a eu la volonté de tout régénérer au plan technique et structurel, ne tolérant aucune faiblesse, aucun manque d'efficacité, comme de tout régénérer au plan esthétique, ne tolérant aucune absence, aucun vide, aucun masque de l'identité architecturale de la cathédrale telle qu'elle resplendissait à la fin du XIIIe siècle. On peut évidemment dire, bien que cela soit parfaitement vain, que cette intervention ne correspond pas à nos critères contemporains de l'intervention sur un édifice que l'on doit restaurer pour en assurer la conservation, qui sont aujourd'hui plus prudents, beaucoup moins systématiques et plus respectueux des différentes strates que l'Histoire accumule dans un édifice au cours du temps. Mais le propos des architectes restaurateurs du XIXe siècle n'était pas le même que le nôtre : s'ils voulaient, bien entendu, assurer la conservation de l'édifice – résultat évidemment atteint, même après la catastrophe du 15 avril –, ils voulaient également révéler avec éclat la présence de son témoignage dans l'espace commun et, pour eux, ce témoignage ne pouvait être que celui d'une forme complète, épanouie, démontrant les qualités d'une architecture décriée et méprisée aux temps de leur jeunesse et de leur formation, alors qu'elle représentait pour eux une des plus belles phases du développement historique de la Nation à laquelle ils appartenaient. Restaurer Notre-Dame de Paris était non seulement soigner et conserver un édifice qui en avait grand besoin, mais révéler son architecture et faire la démonstration de la validité de celle-ci dans le temps présent, comme de son identification au destin historique prêté à la France.

Dans le cadre de cette présentation, je n'ai l'ambition que de présenter brièvement les principaux points traités par ce grand chantier de restauration[4]. Les architectes ont sans doute adopté un plan, qui ne nous est pas connu, mais la lecture du *Journal des Travaux* permet de comprendre que, d'un point de vue chronologique, la question structurelle est traitée de façon prioritaire, en ayant soin, cependant, d'agir progressivement sans intervenir de façon lourde sur toutes les parties de l'édifice en même temps. Tous les arcs-boutants du chœur et de la nef ont, en effet, été démolis et reconstruits comme l'ensemble de leurs culées mais ce travail gigantesque est réalisé progressivement et prendra plus de dix ans : il débute dès la mise en chantier, en 1846, par les arcs situés au sud du chœur, se poursuit en tournant autour de celui-ci, puis au sud de la nef, s'achève enfin enfin au nord, en 1858. Lassus et Viollet-le-Duc sont bien conscients du rôle crucial que jouent les arcs-boutants pour l'équilibre de l'édifice, ainsi de celui qu'ils ont pour l'esthétique et le rythme des façades extérieures. C'est dans cette double perspective que les culées sont redessinées, avec les amortissements qui doivent contribuer à la stabilité, en même temps qu'au visage de la cathédrale. Ceux-ci, déjà explicitement dessinés dans le projet soumis en 1843, sont en forme de « tabernacle » abritant une statue, dominant la gargouille qui assure l'évacuation des eaux de pluie. Ces amortissements n'existaient pas sur les culées des arcs-boutants de la nef au moment du début de la restauration.

Une fois assurée la stabilité de l'édifice, le point sans doute le plus important, concernant aussi bien la cohérence structurelle de l'édifice que son identité architecturale, est celui des façades des transepts – celle du sud présente des désordres apparents, qu'une intervention du XVIII^e^ siècle n'avait pas réussi à corriger – et, dans une moindre mesure, celui de la façade occidentale, dont le point sensible est l'ornementation. On reste aujourd'hui surpris de l'ampleur et de la radicalité de l'intervention : Viollet-le-Duc n'hésite pas, à l'automne 1860, à démolir entièrement la façade du croisillon sud et sa rose et à la rebâtir aussitôt, par un chantier rapide qui a certainement été préparé dans ses moindres détails. Le démontage commence en septembre et, dès janvier 1861, la nouvelle rose et le gâble qui la surmonte sont reconstruits. Il n'existe pas de documentation photographique sur cette intervention spectaculaire, seul le détail d'une photographie de Baldus nous laisse peut-être entrevoir l'ampleur de l'installation qui permet de la réaliser. Viollet-le-Duc, voulant que la nouvelle rose soit, selon son propre raisonnement physique et architectural, plus résistante que la précédente dont les faiblesses avaient été mises en évidence, n'hésite pas à en épaissir les profils et, surtout, à faire tourner la rose de 15° de façon à ce qu'elle présente un élément de réseau et non un lobe dans son axe vertical. C'était, au nom d'un rationalisme constructif apprécié intuitivement de sa part, modifier une œuvre majeure de l'architecture gothique du XIII^e^ siècle, mais notre architecte était convaincu du résultat comme du mode de pensée qui l'autorisait. La reconstruction du pignon nord a suivi le même modèle, tout en intervenant seulement à la fin du chantier, en 1863. Il est à noter, que, dans ce cas, la rose et le pignon nord de la cathédrale ont été reconstruits en utilisant une part des éléments anciens, sans doute mieux conservés.

La façade occidentale se présentait au début des années 1840 en piteux état, avec deux « blessures » significatives, l'une révolutionnaire, l'autre non. C'est en 1771 en effet que le chapitre de la cathédrale avait demandé à son architecte, Jacques-Germain Soufflot, de modifier le portail central : suppression du trumeau, démolition d'une partie-des bas-reliefs du linteau pour ménager un arc en tiers-point permettant – paraît-il – la sortie du dais des processions. En 1793, alors que la cathédrale, où le culte catholique était interrompu, était le lieu de grandes cérémonies en l'honneur de la Liberté et de la Raison, il parut inconvenant de laisser sur la façade les statues des rois, que l'on croyait être ceux de France. Ils avaient donc été abattus et les figures des rois, abandonnées en tas sur le parvis constituèrent même, durant quelques années, une sorte de « monument » à l'abolition de la monarchie. Le projet de Lassus et Viollet-le-Duc projetait de rétablir intégralement la grande file de statues. Là encore, les architectes ont traité au long cours le rétablissement de cette façade, restaurant la galerie elle-même (colonnes) dès 1846, alors que le replacement des statues des rois ne s'achèvera qu'avec le chantier, en 1864[5]. Outre la galerie des rois, la rose occidentale est entièrement démontée et reconstruite, en partie avec ses matériaux d'origine, en 1847-1848, en même temps qu'est restaurée la Galerie de la Vierge entre les deux tours. Le portail central sera restauré, trumeau rétabli, bas-relief complété, statues restituées, les portails latéraux également (1848-1854), travail artistique de haute précision auquel Viollet-le-Duc attache une très grande importance. La sculpture de Notre-Dame avait été attribuée à plusieurs ateliers : Victor Pyanet (façade), Martrou (nef), Bies et Delafontaine (transepts), Caudron (chœur) et, pour la statuaire, Adolphe-Victor Geoffroy-Dechaume. Ce dernier réalisera les grandes figures des ébrasements et du trumeau. Pyanet s'occupe, lui, sous l'étroite direction de Viollet-le-Duc, de réaliser le bestiaire fantastique qui orne les balustrades (entre autres le célèbre Styrge), dont l'architecte assure avoir observé sur les pièces en place les traces des figures médiévales disparues.

Avec le chantier de restauration, il avait été commandé aux architectes l'édification d'une nouvelle sacristie. Sa construction commence avec le chantier et sera menée à bien dans la première étape de celui-ci, jusqu'en 1851. Il ne peut être de mon propos ici de commenter ce nouveau bâtiment, véritable manifeste néo-gothique, qui nécessiterait à lui seul une monographie. La construction de la sacristie entraîne cependant la reconstruction de la chapelle latérale qui servait d'accès à l'ancienne et la modification des deux chapelles qui desservent le nouvel édifice. Dans les chapelles du chœur et de la nef, de nombreuses voûtes ont été refaites, ainsi que dans les tribunes. A la fin du chantier, les chapelles recevront pour la plupart un décor peint exécuté sur les cartons de Viollet-le-Duc6, décor malheureusement supprimé, dans les années 1960, aux chapelles latérales de la nef et sur les parois du transept. Un autre point très important lié à la présentation de l'édifice est celui des fenêtres éclairant les chapelles latérales. La plupart de celle-ci avaient perdu leurs gâbles, remplacés par des corniches droites ou même des frontons d'esprit néoclassique, ainsi que les gargouilles évacuant l'eau de leurs toitures. Tout ces éléments sont corrigés avec soin, les baies recevant de nouveaux gâbles et fenestrages – conformément au projet de 1843 –, celles de la nef et des transepts de nouveaux appuis, les réseaux en grande partie remplacés. D'une façon plus générale, sur les façades, tous les ornements, tous les amortissements ont été repris, refaits, reconstruits.

A l'intérieur de Notre-Dame, malgré les déclarations respectueuses formulées dans le mémoire accompagnant le projet initial, Viollet-le-Duc avait bien entendu pour désir de rendre à l'édifice son identité gothique, identité à la fois stylistique et esthétique. Une intervention importante, même si elle ne concerne pas l'édifice proprement dit fut l'enlèvement des « Mays », c'est-à-dire ceux qui subsistaient des soixante-douze grands tableaux des XVIIe et XVIIIe siècles, offerts chaque année à la cathédrale par la corporation des Orfèvres et qui, placés devant les grands piliers de la nef, en masquaient délibérément l'architecture. Certes l'arrêt du culte et les différents usages de la cathédrale entre 1793 et 1802 avaient entraîné déjà le départ de beaucoup d'entre eux, mais un certain nombre avait été replacé après le Concordat. Le *Journal des travaux* mentionne, en 1862, le départ des huit derniers. L'autre question fondamentalement sensible était le décor du rond-point du chœur, réalisé par Robert de Cotte en 1718 pour accompagner les statues du Vœu de Louis XIII, qui masquait, après les avoir mutilés, l'ordonnance et le décor des piliers situés derrière l'autel. Les statues de Coysevox et Coustou avaient déjà fait, depuis 1790, comme les Mays, quelques aller-retour entre la cathédrale et le Louvre, au gré de la conjoncture politique, mais il était cette fois convenu de leur rendre leur emplacement d'origine. En dépit de ce qui était annoncé dans le projet, Viollet-le-Duc sacrifia l'architecture de Robert de Cotte, certes déjà dépouillée de son ornementation de bronze doré en 1793, afin de retrouver et rétablir l'ordonnance gothique du chœur de la cathédrale, où il replaça néanmoins les statues royales de part et d'autre de la Vierge de Pitié. Il est permis de penser que cette intervention lui paraissait essentielle, tant l'opposition de goût entre les valeurs du classicisme ou du néo-classicisme et du gothique était prégnante à ses yeux. C'était bien sûr une question de formes architecturales, mais aussi de décor, lumière et couleur. On a déjà mentionné les nouvelles peintures murales des chapelles, très colorées. Il faut y ajouter, bien entendu, tout le chantier de restitution de vitraux de pleine couleur aux chapelles et, surtout, aux fenêtres hautes du chœur de de la nef. L'architecte et les acteurs de la restauration avaient bien présent à l'esprit que l'édifice avait surtout perdu son caractère médiéval au XVIIIe siècle[7], c'est-à-dire très récemment, sous l'influence de ce goût moderne.

A l'intérieur, l'architecture gothique de Notre-Dame fut partiellement modifiée, d'une façon sensible et imprévue, sous l'influence de découvertes archéologiques et pour un résultat que l'on pourrait qualifier de « pédagogique ». Le *Journal des travaux* signale en effet, en 1849 puis en 1854 la découverte dans les maçonneries de fragments remployés, qui sont attribués aux réseaux des roses figurant dans l'élévation initiale de la nef, à quatre niveaux, avant la modification des fenêtres hautes. Viollet-le-Duc, tout en interprétant imparfaitement le dessin de ces roses, obtient l'autorisation de les rétablir sur l'élévation du transept, ainsi que sur les travées en retour du chœur et de la nef, modification substantielle de l'aspect de l'édifice.

Le dernier élément d'importance de la grande restauration de Notre-Dame est bien entendu celui de sa toiture et de la flèche. Celle-ci avait, sans doute, été abattue en 1793[8], son mauvais état étant signalé depuis 1744 et sa démolition prescrite depuis 1788. Le projet de Lassus et Viollet-le-Duc avait prévu de la rétablir, en s'inspirant d'un dessin, seul document connu la représentant un tant soit peu fidèlement. Lassus décédé, c'est seul qu'Eugène Viollet-le-Duc aura en charge ce projet, dressé en 1857, approuvé puis construit en trois mois, de février à mai 1859. Son dessin s'écarte nettement de la documentation connue et du projet initial et propose une flèche à deux étages ajourés au lieu d'un seul, dont l'élancement (elle culminait à 95 mètres de hauteur) poussait certainement l'exercice au maximum possible, par rapport aux conditions dans lesquelles un tel ouvrage pouvait être élevé. L'architecte connaissait bien le système porteur de l'ancienne flèche médiévale (tabouret et souche, conservés dans l'espace de la charpente du comble) qu'il avait minutieusement étudié et dont il parle longuement dans le *Dictionnaire raisonné*. Au moment d'agir, il élimina cependant toute l'ancienne structure, sans doute par souci d'assurance et, pour installer la nouvelle charpente porteuse, dut démolir la voûte de la croisée du transept : les conditions créées par l'incendie de 2019, avec l'effondrement de cette voûte[9] ont en quelque sorte reproduit, pour le chantier qui est actuellement en cours, le même processus. On ne doit pas douter que la hauteur de la flèche ne réponde, d'une certaine façon, à la vision de l'architecte en ce qui concerne l'insertion de la cathédrale dans le paysage parisien. Jusqu'en 1831, Notre-Dame était coupée du fleuve, notamment par le palais archiépiscopal ainsi que par l'Hôtel-Dieu. Après le pillage et l'incendie du palais, il avait été décidé de ne pas reconstruire l'édifice et d'en réserver le terrain à une promenade publique, permettant cette scénographie de la cathédrale au bord du fleuve si célèbre de nos jours et imposant l'édifice comme une articulation majeure du paysage urbain du centre de Paris, alors qu'auparavant il n'était qu'au cœur de la Cité. Innovation que l'on peut qualifier d'idée de génie, Viollet-le-Duc installa sur les arêtiers épaulant la flèche, placés à la rencontre des toitures du chœur, de la nef et des transepts, des statues monumentales, représentant les douze apôtres et les symboles des quatre évangélistes, confiées à Geoffroy-Dechaume. Echelonnées sur leurs socles le long des arêtiers, ces statues accompagnent le mouvement ascendant de la flèche et ne contribuent pas peu à son dynamisme ainsi qu'à la réussite architecturale de l'ensemble. La réfection de la couverture en plomb accompagne évidemment la restauration complète de la cathédrale, cette fois encore par sections échelonnées qui se complètent peu à peu dans le temps long de la restauration. Viollet-le-Duc a choisi de remplacer intégralement la charpente des transepts et place au faîte du comble une crête ornementale, qui n'existait pas auparavant, en plomb sur armature de fer, dont le dessin apparait déjà dans le projet de 1843. L'exécution de la crête, des plombs ornementaux de la flèche et des statues est confié à l'entreprise Durand (reprise en 1860 par Monduit). Les statues ont une technique de réalisation très particulière, qu'on peut penser avoir été imaginée par l'architecte : elles sont creuses, en tôle de cuivre battu fixée à une armature intérieure en fer. Monduit réalisera plus tard, selon le même procédé que les statues de la flèche de Notre-Dame, mais à une autre échelle, d'abord la statue monumentale de Vercingétorix voulue par Napoléon III sur le Mont Auxois (1865), puis la statue de la Liberté éclairant le monde, offerte aux Etats-Unis par la France en 1886. Comme c'est bien connu, l'un des apôtres de la flèche de Notre-Dame a les traits de l'architecte et l'attitude de la statue le montre en train de regarder son œuvre.

Il est difficile de présenter un tel chantier de restauration sans tomber dans le catalogue, tel que je viens de le faire sommairement, des principales interventions dirigées par Lassus et Viollet-le-Duc. Une vision d'ensemble manque encore qui, je l'espère pourra attirer d'autres chercheurs. A la lecture du *Journal des travaux*, on prend conscience à la fois de l'échelle d'une entreprise, qui mobilise, pour les années actives, entre 100 et 250 ouvriers (voire plus) œuvrant ensemble durant plus de trois cent journées annuelles de douze heures de travail et se donne ainsi les moyens d'investir effectivement l'énorme édifice dans toutes ses parties, comme de la réalité quasi-artisanale des interventions, strictement réalisées dans le cadre des savoir-faire de maçonnerie, de charpente et de plomberie hérités des siècles précédents. Tout juste peut-on constater que dans les prestations de serrurerie il y a un développement qui s'écarte un peu de l'héritage technique du passé. Il n'y a, dans toute la restauration de Notre-Dame, que de rares interventions « contemporaines », comme la consolidation des galeries à jour sous les grandes roses du transept par des colonnes de fonte, ou les charpentes métalliques des couvertures des tours. Si l'on se reporte aux interventions majeures qui encadrent cette restauration de Notre-Dame, c'est-à-dire la restauration des cathédrales de Chartres ou de Metz après leurs incendies respectifs en 1836 et 1877[10], ou la reconstruction de la toiture de l'abbatiale de Saint-Denis en 1841, qui toutes délaissent la charpente en bois pour la charpente métallique, on ne peut que prendre acte de cette fidélité affichée aux savoir-faire des bâtisseurs médiévaux. On est également frappé de la stratégie à long terme des architectes, qui traitent de différentes questions posées de façon étalée parfois sur des décennies (ainsi les toitures ou les terrasses des tribunes, mais encore les statues de la Galerie des Rois et les portails de la façade, complétés ou traités au fil des années) et qui reprennent d'abord l'extérieur, en tournant de l'ouest au sud, à l'est puis au nord. Ce n'est qu'en 1858, une fois la stabilité structurelle régénérée par la reconstruction des arcs-boutants, que le chantier investit significativement l'intérieur, se réservant tout le transept et le chevet durant quatre années, le temps d'ériger la flèche, de reconstruire la rose sud et de restaurer le chœur. En vingt-cinq ans de chantier, Notre-Dame ne sera fermée au culte que six mois, du 16 août au 23 décembre 1862. Le dernier aspect qui mériterait une étude d'ensemble, bien que beaucoup d'interventions et d'acteurs aient déjà été signalés ou étudiés et décrits, est l'aspect proprement créatif de toute la partie décorative de la restauration, sculpture ornementale (combien de gargouilles ?), statuaire, vitraux et peintures murales, second œuvre de toute sorte, mobilier. Il y a une évidente unité d'ensemble de toutes ces créations, aussi bien pour Notre-Dame proprement dite que pour la nouvelle sacristie, parce que durant ces vingt-cinq années, les maîtres d'œuvre ont été, d'une part, à la source même de beaucoup de ces créations (on ne peut attribuer la paternité de la sculpture d'ornement à personne d'autre qu'à Eugène Viollet-le-Duc), d'autre part parce qu'ils sont restés fidèles aux créateurs qu'ils avaient appelés, sculpteurs, maîtres-verriers et autres – comme, d'ailleurs, aux entrepreneurs de maçonnerie, de charpente et de couverture, dont on peut dire, pour certains (les maçons Milon et Sauvage, le charpentier Bellu), que la carrière professionnelle s'est identifiée à ce chantier.

Notes

[1] Disponible en ligne : https://fr.wikisource.org/wiki/Projet_de_restauration_de_Notre-Dame_de_Paris/Première_Partie (consulté le 19 mai 2020).

[2] Ce document foisonnant, multiple, parfois décevant par ses manques ou son imprécision, devra être publié un jour. Il a été transcrit par Stéphanie-Diane Daussy que je remercie des précisions qu'elle a bien voulu m'apporter. Daussy, S.-D., «Le*Journal des travaux* de Notre-Dame de Paris (1844-1865). Apport à la connaissance de l'intimité d'un chantier», dans *Matériaux, métiers et techniques. Vers une histoire matérielle du chantier de restauration (1830-1914)*, Actes du colloque international Paris-Liège-Namur, 14-16 décembre 2017, Cl. Houbart, M. Piavaux et A. Timbert (dir.), à paraître.

[3] https://mediatheque-patrimoine.culture.gouv.fr/rechercher/archives/travaux-de-notre-dame-de-paris-1844-1865 (consulté en mai 2020).

[4] J'ai présenté par ailleurs un essai de chronologie du chantier de restauration de Notre-Dame, toujours d'après le *Journal des Travaux : « Notre-Dame de Paris et sa restauration au XIX*e siècle : une chronologie », sur le site https://www.scientifiquesnotre-dame.org/articles

[5] Dès 1848 (sans doute) des maquettes grandeur nature avaient été mises en place, dont témoigne une photo de Charles Nègre.

[6] Une partie des cartons originaux sont aujourd'hui conservés à Médiathèque du Patrimoine, à Charenton. Les peintures avaient fait l'objet d'une publication en 1870 : *Peintures Murales des chapelles de Notre-Dame de Paris, exécutées sur les cartons de E. Viollet-le-Duc, relevées par Maurice Ouradou, Paris, Morel, 1870.*

[7] L'enlèvement des vitraux médiévaux, sur commande du chapitre, est documenté en 1752 et 1755.

[8] La date n'apparaît pas dans les sources. Les architectes citent 1793 dans leur mémoire.

[9] Cette voûte, qui menaçait ruine, avait déjà été reconstruite par Germain Boffrand en 1725.

[10] Voir mon article : « Les cathédrales incendiées. La restauration des toitures des cathédrales françaises détruites par le feu aux XIXe et XXe siècles », sur le site https://www.scientifiquesnotre-dame.org/articles .

Technical Sponsor Lecture

Recent developments in X-ray imaging applied to Cultural Heritage

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Abstract

In Cultural Heritage (CH) the new technologies based on x-rays offer many advantages and opportunities. Compared to the classic radiography, now widespread as a method of non-destructive investigation in the field of CH, in recent years new technologies and new tools have been developed to expand the capability of investigations. In this paper we will highlight some of the most innovative techniques. With Digital Radiography (DR) it is possible to simplify and speed up the investigation; it provides digital images permitting post processing and allowing to easily share the results within the scientific community. Computed Tomography (CT) offers the advantage of three-dimensional reconstruction of the objects and finds allowing to highlight details otherwise not visible.

We will see two cases studies that use CT as a method of analysis. The first one is related to the problem of virtual unrolling papyrus scroll to read inside avoiding dangerous physical unrolling. The second one is a case of an eighteenth-century violin, in which the goal was to detect repairs already made and the typical characteristics of the realization of the instrument.

The numerous X-ray techniques and the increasing use of it in CH have stimulated the need to regulate the training and qualification of staff working in this field. In March 2022 a working group was established at the IAEA in Vienna to develop a training programme for people that will carry out radiological examinations on CH; this program is based on international standards, such as ISO 9712 or SNT-TC-1A. The drafting of the program was started to provide operators with the necessary training to integrate their basic skills considering two training paths. Staff trained according to this program will be able to plan and perform radiological examinations on CH as already happens in the field of industrial NDT.

Keywords: cultural heritage, computed tomography, X-ray imaging, image reconstruction, radiography.

1. Introduction

X-ray based diagnostic imaging enables non-invasive analysis of the internal structures of manufactured products; therefore, it is a very attractive technique in the field of CH, and in fact is widely used. This technique is often complementary to other imaging diagnostic methods, such as infrared reflectography (IR) suitable for the study of preparatory drawing [1].

Digital Radiography (DR) and Computed Tomography (CT) are techniques considered fundamental for the non-invasive analysis of works of art, such as paintings, ceramic, metal or stone artifacts, both for conservation purposes and for historical-artistic studies.

With DR you can simplify and speed up your investigation by providing digital images that allow post-processing and easily share results within the scientific community.

The CT, compared to the DR, offers the advantage of three-dimensional reconstruction of objects and artifacts allowing you to highlight details otherwise not visible.

In this paper we will look at some cases studies analyzed by CT, emphasizing the advantages of this technique. These techniques are quite complex to use if you don't have a proper interdisciplinary training from CH to NDT.

The numerous X-ray techniques used in the CH field have led in March 2022 to establishment of a working group at the IAEA in Vienna to develop a staff training programme that will carry out radiological examinations on CH following the international standards, such us ISO 9712 or SNT-TC-1A. The drafting of the programme was started to provide operators with the necessary training to complement their basic skills.

2. Digital Radiography e Computer Tomography

In recent years DR has developed more and more, making it a fundamental tool in various fields, from medical diagnostics to the characterization of materials and industrial components, up to the investigation of CH. Thanks to it you have the possibility to carry out non-invasive investigations on works of art to know the state of conservation or for subsequent possible restoration.

The potential and non-invasiveness of DR and CT allow to obtain results previously unthinkable in terms of image quality and spatial resolution; with some dedicated laboratory setups it is possible to obtain resolutions close to few tens of µm [4].

With the DR you can reveal a lot of useful information related to the work of art, such as: below paintings, highlight existing fractures, grouting, wooden integrations, metal nails, connecting elements of the boards, such as dowels or pins, canvases of encapsulation or stubble in the connections, damages due to attacks of xylophagous insects, gaps of the pictorial layer and additions. In this way it is possible to obtain a characterization and mapping of the materials used by the artist and during previous restorations. The classic X-ray 2D imaging has evolved in the CT, which offers the considerable advantage of placing in space all the elements that make up the work. It provides a three-dimensional reading of the results, allowing the determination of the exact position of any fractures, the actual size of metal inserts or the length and diameter of the tunnels produced by the attack of xylophagous insects. From the three-dimensional reconstruction of the scan, we have the possibility to operate virtual cuts, 2D (slices), and visualizing the inside of the structure. From here it is possible to highlight porosity, inclusions, deformations, or, in the case of wooden works, the sections of the wood, the fibrature, the assembly of the transverse table and to carry out separation between the parts that constitute the object by applying density thresholds [1].

3. Cases studies

In this paragraph we propose two different case studies on completely different objects. They were selected to emphasize the current potential of the CT technique.

The first is taken from a study by the University of Catania, which has carried out work on the virtual restoration of ancient papyri, proposing a software manipulation technique of X-ray tomographic images to virtually unroll the sample. The second case study is about the analysis, performed by the MotivexLab laboratory, of an 18th century violin made by a Venetian luthier named Santo Serafino (currently guarded by the Accademia Liuteria Piemontese).

3.1. Case one: Virtual unrolling of a papyrus

Physical unrolling of a papyrus to read its contents could cause irreversible damage to the artifact because of its fragile support. The use of the techniques described below and based on the use of the CT allowed to study these artifacts that otherwise would have been inaccessible because of their fragile nature.

In [2] the authors propose a virtual restoration method based on the software manipulation of tomographic images acquired with the CT. To test the proposed approach, a realistic papyrus model was made using the ancient method and pigments compatible with Egyptian use (Fig. 1).

This papyrus model was CT scanned acquiring 259 slices. The images contained in the slices represent the section of the papyrus, then they look like spirals. For each section of papyrus, the initial and final point of the spiral should be identified to construct an array of ordered pixels.

It is not easy to sort the points that make up the slice because the low resolution and some overlapping papyrus sheets. For this reason, the authors decided to use a single section profile to estimate all the others, assuming there are few differences between adjacent sections.

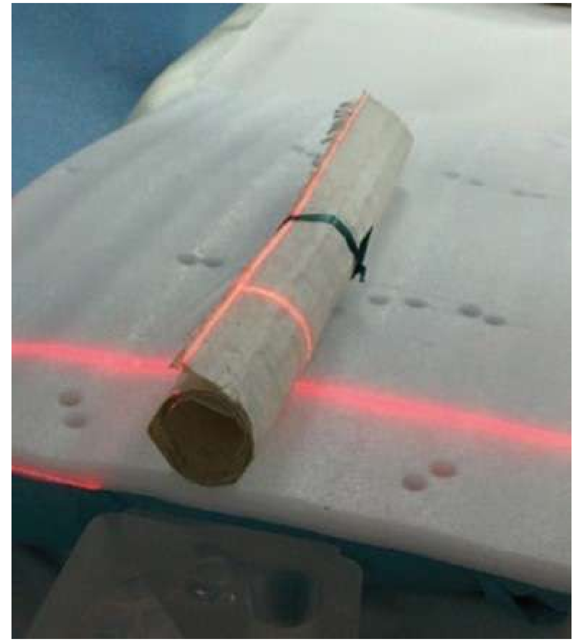

Fig. 1 Detail of the case study papyrus during the calibration phase before CT acquisition [2].

The method is basically based on the following steps:

- First you need to select a suitable slice so that you can almost fully identify the spiral through a segmentation; moreover, such slice must contain a low number of overlapping sheets.
- The spiral is then reconstructed using specific algorithms.
- The last step is the virtual unfolding of the papyrus, in which each slice containing the spiral is placed horizontally. By stacking the various lines of pixels obtained, we get the final image of the unrolled papyrus.

The below Figure 2 outlines this process schematically.

Figure 3 shows the results obtained by this method: in (a) the reference papyrus is shown, while in (b) the virtual papyrus is unrolled. We can therefore observe how, through the CT, it is possible to extract the information reported in the papyrus.

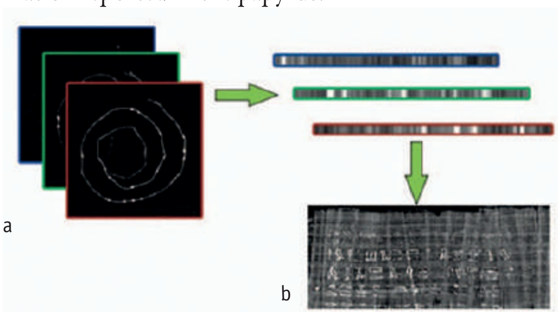

Fig. 2 Schematic proposed method to unroll papyrus [2].

Fig. 3 (a) The original study-case unrolled papyrus; (b) A virtually unrolled version of the papyrus through the proposed algorithm [2].

3.2. Case two: violin of the eighteenth century

Knowing repairs that have already taken place and their positioning allows those who work in the lutherie industry to quantify the real value of the instrument, as in this case of a violin, and know where and how restore it in case of further repair. Violin making is a sector of string and bow instruments that deals with the design, construction, and restoration. For restorers it is important to know the state of conservation of the instruments that they have in their hands, since most of these objects can have up to 400-year history. At the MotivexLab laboratory (Turin) was analyzed by CT a violin of the '700, probably made by a Venetian luthier named Santo Serafino (Fig. 4). This CT analysis was performed to detect all repairs already made in the past, and the typical characteristics of the realization of the instrument [6].

Thanks to the size of the CT cabin, it was possible to safely position the violin before proceeding with the CT scan. The artifact was first observed using 2D images (DR) to carry out an initial search for possible repairs (Fig. 5). Afterwards, the CT scan was carried out, followed by the reconstruction of the 3D volume by means of reconstruction software (VG studio) to prove the presence of the repairs made in past years (Fig. 6).

Fig. 4 Placement of the violin in the tomography booth [8]

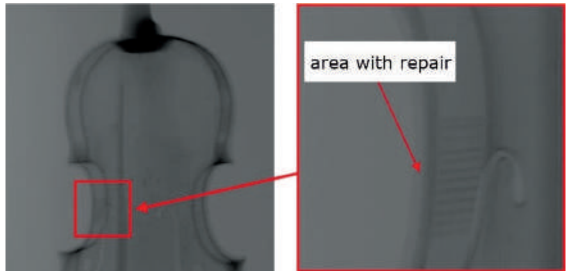

Fig. 5 Details of repair zones in the 2D images [6].

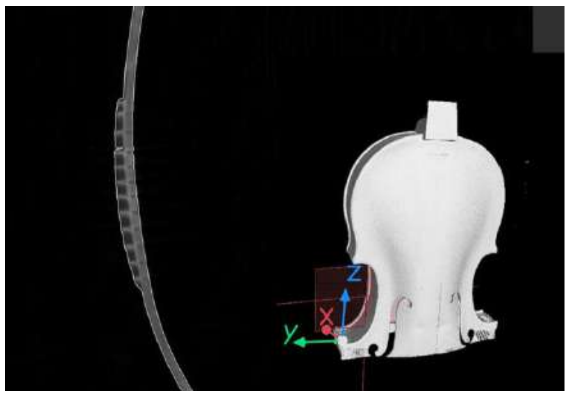

Fig. 6 Side view of instrument with repair detail in the 3D reconstruction image [6].

In Fig. 6 you can locate the repair area thanks to the possibility of selecting the sample on 3 plane (x,y,z). Indeed, it is possible to clearly see the presence of the two layers of wood; the innermost layer occupies only a small portion and is clear evidence of repair within the instrument [6].

In conclusion, we can say that the CT has become a formidable ally in obtaining the three-dimensional map of a work, determining its authenticity, its state of preservation and the possible need for conservative intervention [8].

4. Syllabus on Radiography for Cultural Heritage Applications (IAEA Vienna)

In this paper we have seen how the X-ray techniques applied to CH can be of great help for restorers who work in the preservation and restoration of the artifact, supported by preventive diagnostics. However, the use of techniques such as CT presupposes an interdisciplinary training based not only in CH but also in NDT

This need led, in March 2022, to establish a working group at the IAEA in Vienna (Consultant's Meeting (CM) on the Development of a Syllabus on Radiography for Cultural Heritage Applications) to develop a staff training program for operators that will carry out radiological examinations on cultural heritage in line with international standards, such as ISO 9712 or SNT-TC-1A.

The program may also be used to develop teaching material, e-learning material, or guidelines to provide theoretical and practical information to qualified radiologist. The drafting of the program was started to provide operators with the necessary training to integrate their basic skills considering two training paths:

- the first aimed at people with a qualification in preventive conservation/restoration/diagnostics of CH or scientific personnel working in a diagnostic laboratory or in a restoration laboratory willing to carry out radiological examinations.

- the second is aimed at people with existing industrial radiography qualifications/certifications who are willing to work in the CH sector.

The program is designed for 80 hours in the case of candidates with CH or RT2/RT3 background (second and third level respectively in RT according to ISO 9712) and 96 hours in the case of applicants with other scientific backgrounds. The personnel trained according to this program will be able to plan and perform radiological examinations on CH as already happens in the industrial NDT field.

During the meeting was identified the need to collect and organize training materials to support the program for the part of the CH radiological examinations, to which a consultation with the CH community is required. Several training materials are already available for the RT part which could be easily adapted to the programme.

Once all the teaching material has been collected, an e-learning platform will be set up where all the training material can be deposited. In addition, a meeting of CM members with representatives of the CH community was planned to ensure that the developed programme meets CH requirements [9].

5. Conclusions

In this paper we wanted to emphasize the advantages of the CT technique applied to CH by reporting two case studies. Choosing the CT over the classic X-ray techniques allows us to have more information from our artifact, with the considerable advantage of placing in space all the elements that make up the work. It is among the few non-invasive and non-destructive methods that allow the three-dimensional reconstruction of the internal structure and surface morphology, thanks to the powerful post-processing algorithms.

Finally, it has been briefly described how the institutions operating in these areas have created awareness in structuring and regulating the training and qualification activities of professionals.

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[10] ISO 9712:2021 Non-destructive testing — Qualification and certification of NDT personnel.

Part one – Non-destructive testing in Cultural Heritage

Infrared Imaging Analysis for in-situ inspection of a work of art: combined SWIR-MWIR methods for a painting on wood investigation

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Abstract

The conservation of works of art represents an important topic of great interest. In the case of painting on wood, various factors can affect its integrity. Deterioration processes can become irreversible with time and therefore it is important to detect and prevent their formation. Infrared imaging is a well-known contact-less and non-invasive technique. It is fast and of easy implementation and it represents a reliable means of providing a low-cost in situ analysis of an artwork. In this study a real artwork represented by a XVI century panel painting by the author Marco Cardisco entitled "*Adoration of the Magi*" was analyzed *in situ* combining the information obtained both at short (SWIR) and at medium (MWIR) wave infrared range. Through this approach and appropriate data processing, a wide variety of defects such as detachments, cracks, metallic inclusions but also *pentimenti* and others type of anomalies that has produced variations in the infrared signals analyzed associated with differences in the thermo-physical properties of the layers of the artwork were detected.

Keywords: active thermography, IR reflectography, Cardisco, panel painting, in-situ analysis, diagnostics.

1. Introduction

In order to preserve cultural heritage works, the use of non-invasive techniques to analyze their condition is nowadays a fundamental common practice [1-3]. Among the cases of interest, paintings on wood can be affected by different types of degradation due to the various factors that can affect their integrity such as the action of atmospheric pollutants, fluctuations in environmental parameters such as temperature and humidity, excessive exposure to inadequate light sources or the formation of patinas and bacterial biofilms. Their analysis represents a complex problem that must be tackled with adequate diagnostic methods to avoid the effects of degradation processes becoming irreversible over time. For this purpose, advanced diagnostic techniques based on the analysis of images acquired in different spectral ranges play a crucial role. Imaging techniques have found wide application in cultural heritage as they can provide structural but also technical and historical information of the artworks useful for conservators or to take a decision in planning a restoration work, choosing the most appropriate intervention strategy to apply [4, 5]. Among the various techniques, infrared imaging is a well-known contact-less and non-invasive method and it represents a reliable means of providing a low-cost *in situ* analysis of an artwork [6-9]. Infrared reflectography (IRR) is a well-known imaging methodology typically applied to paintings that exploits the transparency of pigments in the spectral region 0.9 - 1.7 micron (SWIR) allowing to view hidden details, including underdrawings or different versions of the subjects, the so-called *pentimenti*. Differently, active thermography (AT) technique applied in the thermal region 3-5 micron (MWIR) allow to detect a wide variety of both surface and subsurface defects such as nails, cracks, detachments and any type of anomaly that determines a change in the thermal response of the painting layers analyzed. In this work through the analysis of infrared images a real artwork represented by a XVI century panel painting by the author Marco Cardisco entitled "*Adoration of the Magi*" preserved in the S. Barbara chapel of Castel Nuovo in Naples was investigated *in situ*. In his investigation, complementary information was obtained from the analysis of the images acquired in both short (SWIR) and medium (MWIR) wave infrared range which allowed to highlight areas of the painting affected by actions of degradation, subsurface inclusions and also some *pentimenti*.

2. Materials and Methods

2.1 MWIR and SWIR analysis

Analyzes in the MWIR region were conducted by applying an active thermography (AT) operative protocol. A halogen lamp (1000 W) with tunable power was used to apply a thermal pulse of 10 s on each investigated area of the painting. Thermal frames achieved during and after heating were recorded for 120 s with a frame rate of 10 Hz using a MWIR camera FLIR X6580 sc with a cooled InSb detector mounting a 50 mm focal lens (spectral range 3.5–5 μm, FPA 640×512 pixels, IFOV 0.3 mrad and NETD ~ 20 mK at 25 °C). During the heating, the temperature increase was monitored to obtain a maximum $\Delta T = 3$ °C as uniform as possible on the investigated area of the painting. Analyzes in the SWIR region were conducted by infrared reflectography (IRR). A halogen lamp (1000 W) was used to illuminate the area of the painting investigated and infrared images were acquired using the SWIR camera XEVA 320 with InGaAs photodiode array detector mounting a 22 mm focal lens \(spectral range 0.9–1.7 μm, FPA 320×256 pixels). In both analyses, the camera was placed at 0° (frontally) with respect to the in-

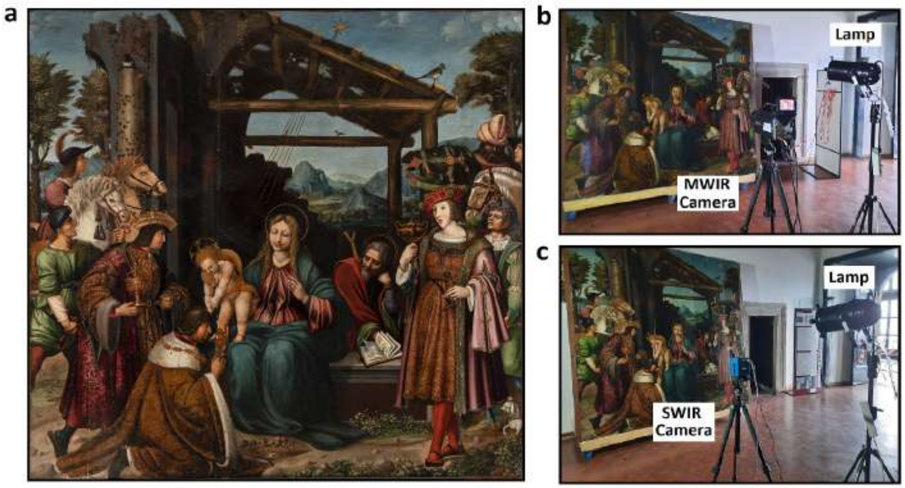

Fig. 1 Picture of the painting (a) and of the experimental set-up used for MWIR (b) and SWIR (c) analysis.

vestigated surface and the lamp at approximately 45° to avoid reflections in the camera. The measurements were performed *in situ* under environmental conditions with a temperature of about 21 °C and relative humidity of about 58%.

2.2 Artwork analyzed

The artwork analysed *in situ* was an oil painting realized on a supporting structure in wood obtained from the union of 5 vertical boards. The dimensions of the painting were 254 cm × 268 cm. It is a real work of art realized around 1519 by the author Marco Cardisco "il calabrese" entitled "*Adoration of the Magi*" (Fig. 1a). The painting was in the S. Barbara Chapel of Castel Nuovo in Naples. It depicts the Aragonese kings Alfonso I (standing to left in painting) and Ferdinand I (kneeling to left in painting) in the guise of the Magi, anachronistically depicted together with the young King of Spain Charles V of Habsburg (standing to right in painting). Fig.1 shows a picture of the painting (1a) and of the experimental setups used (1b and 1c).

3. Results and Discussion

Infrared analysis was carried out by dividing the artwork into 20 investigation areas of approximately 63 cm × 54 cm which were examined individually. For each of the areas, the AT and IRR analysis protocol described in section 2.1 was applied. In the case of AT measurements, the thermal images acquired were initially studied by spatial analysis to detect inhomogeneous areas with suspicious morphology and subsequently by temporal analysis to attempt their classification.

Due to their different thermophysical properties the defects show a characteristic time response, e.g. slow heating/cooling response for defects characterized by a low thermal conductivity as in the case of detachments or faster response as in the case of metallic inclusions [10]. Fig. 2 shows the images obtained through the AT measurements of some significant areas of the painting analyzed. The 1st column of the figure shows the visible images of the investigated area, while the 2nd and 3rd columns show two images obtained by respectively analyzing the thermal frames recorded in the first 10 s after heating ($t<10$ s) which mainly describe the thermal response of the more superficial pictorial layers (SL images) and the thermal frames recorded in the following instants ($t \geq 10$ s) which instead mainly describe the thermal response of the deeper pictorial layers (DL images). Fig. 2a-SL and Fig. 2b-SL show some (micro) ripples (1) in correspondence with which the adhesion with the wooden support is partially compromised as visible by the initial detachments (2) highlighted in both Fig. 2a-DL and Fig. 2b-DL that refer to the deeper layers. Fig. 2a-SL and Fig. 2b-SL show some slightly raised decorations of the clothes (3) probably made with a metallic pigment. In Fig. 2a-DL the area included in the red circle (4) is affected by the presence of various micro-cavities and holes probably due to the action of woodworms. In Fig. 2c-SL and Fig. 2d-SL, the metal joints (1, butterfly-shaped) of the wooden boards are visible. In Fig. 2c-SL and Fig. 2c-DL, near the joint, it is possible to observe areas of the painting (2 and red circle 3) probably affected by detachments involving deep pictorial layers. In the same images a deep engraving (4 and 5) on the wood panel is visible. In Fig. 2d-SL metallic inclusions are well visible (2), probably referring to nails or screws. In the same image, the natural texture of the wood (3) and some large brushstrokes of irregular shape (4) probably made in the initial stage of preparation of the painting also are visible. It is interesting to note how through the AT analysis some pentimenti were also detected. In Fig. 3, it can be well observed that while the faces of the two subjects (a and b) found in the SL images (2nd column) correspond to the visible ones (1st column), those detected in the DL images (3rd column) show different characteristics. In the case of IRR measurements, the infrared images acquired were compared with the visible ones and mainly made it possible to obtain information regarding the technique used by the artist for the preparatory stage of the painting and, also in this case, various pentimenti.

Fig. 4 shows both visible (colored) and infrared (gray scale) images of some investigated areas of the painting. The underdrawings were not clearly visible throughout the painting, probably due to the opaque nature in the SWIR region of some pigments used. However, by analyzing the images of the main subjects represented, some recurring characteristics in the artist's preparatory style can be highlighted. Infrared images of the Madonna (Fig. 4a), St. Joseph (Fig. 4b) and Alfonso I (Fig. 4c) seem to highlight a linear drawing with high contrast probably made with dark carbon ink applied with a brush. In both the Madonna and St. Joseph, the hair is only partially represented in the preparatory phase and then better defined in the final pictorial work. However, where visible, the underdrawing appears to have been done in detail and with care. Various *pentimenti* on secondary subjects and elements can be detected. In the infrared image of Fig. 4c it can be seen how the foot of the subject in the background is in a different position (higher) than that represented in the final painting. In this last, the original foot has been replaced with a brown stone. In the infrared image of Fig. 4d, the presence of a veil on

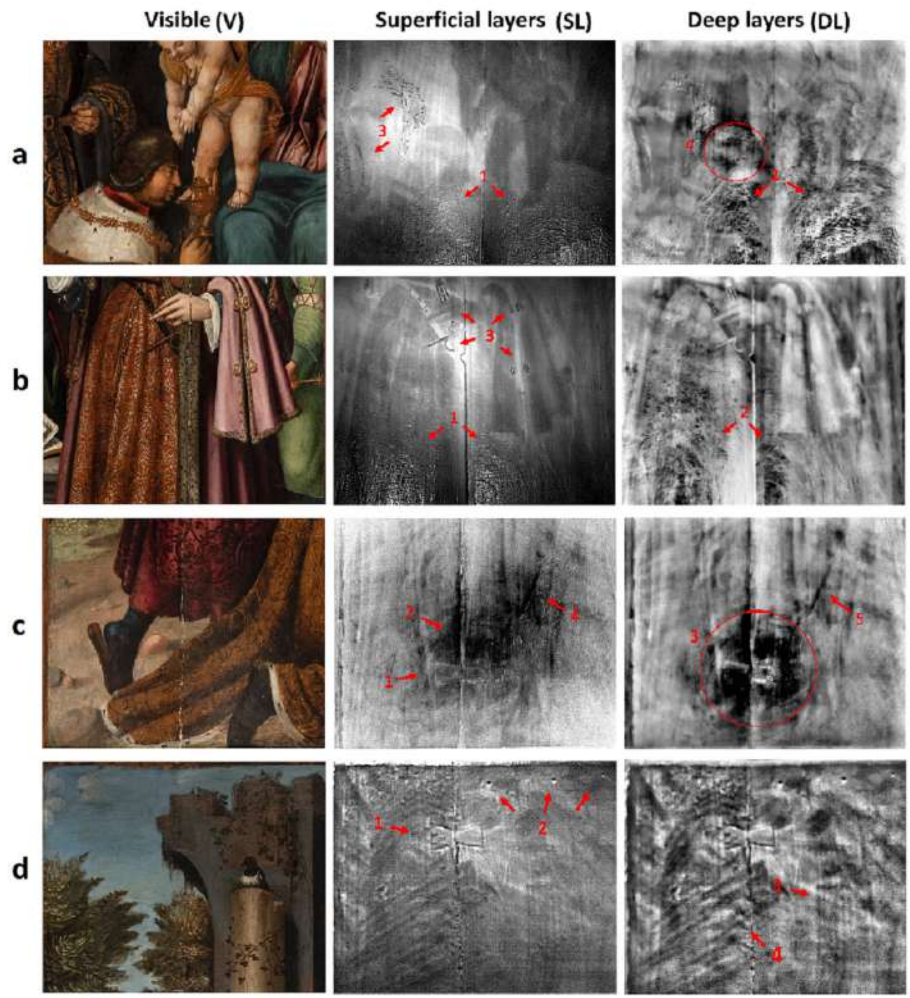

Fig. 2 Visible images of some inspected areas of the painting (1st column) and corresponding images (2nd and 3rd column) obtained from the analysis of AT measurements (MWIR range).

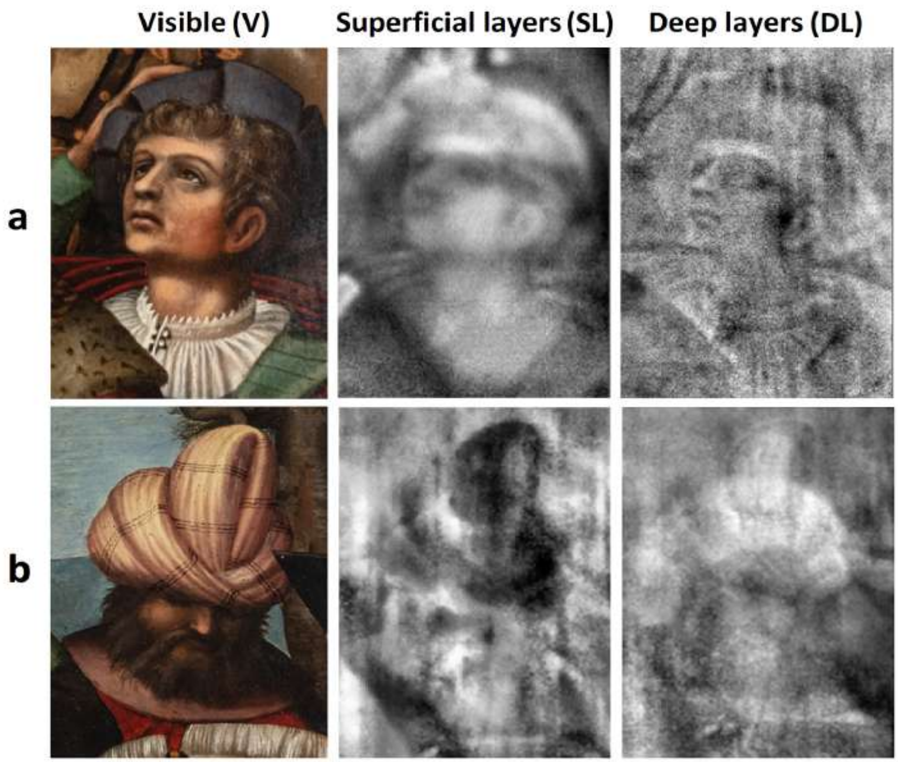

Fig. 3 Visible images of two subject of the painting (1st column) and corresponding AT images (2nd and 3rd column).

Ferdinand I's back can be observed, subsequently eliminated in the final painting. In the infrared image of Fig. 5d the preparatory background made with very marked dark brushstrokes on which the landscape represented in the final painting was made is visible.

4. Conclusions

The results obtained in this work have highlighted how the information concerns the state of health of the work as well as technical aspects related to its realization methods can be achieved from the analysis of the images acquired in the two infrared spectral band considered: SWIR and MWIR. These finding confirm that such combined infrared analyzes can provide support to other non-invasive techniques as an integral part of a multi-instrumental and multidisciplinary investigation, representing a useful and suitable analytical approach for in situ measurements.

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GPR investigation on the Saint John Baptistery at Florence, Italy

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Abstract

The Saint John Baptistery is one of the most outstanding historical monumental buildings in Florence. Built during the X-XII centuries and totally covered by white and dark-green marbles, it was object of conservation measurements through centuries under the supervision of the Opera del Duomo (OPA), with the most recent major conservation works performed around 1930. Due to the lack of detailed documents concerning its masonries structural and textural assemblages, the OPA planned an extensive NDT investigation campaign for reaching a full knowledge of the Baptistery masonries. The main NDT method used has been the GPR survey. In the frame of technical cooperation agreements of DST with OPA and IDS a complete campaign of GPR survey interested all the structural surfaces of the Baptistery: ground-floor, walls, women galleries, inner dome and roof. Investigations have been performed by means of several GPR antennas (400 MHz, 900 MHz, 1,500 Hz and 2,000 MHz) in order to achieve the best performance for all investigated structures. The results have allowed defining all the diverse masonry assemblages, marble cladding thickness and the underground soil setting. The development of a H-BIM content that includes all GPR radargram in the exact position, allowed a complete and clear lecture of the diverse masonry structures and assemblages. Underground features, highlighted by GPR survey, can also been used to plan and define well-addressed essays for direct investigation. This work tested and confirmed the utility of GPR as a fundamental NDT for the investigation of masonry apparatus of the historical cultural heritage monumental buildings. This work was partly developed thanks to the H-GPR project of the University of Firenze (PNR, DM737-2021), funded in the framework of the Next Generation EU program.

Keywords: Florence, baptistery, georadar, NDT, HBIM, stone building, masonry, conservation.

1. Introduction

Saint John Baptistery at Florence, Italy) (Fig. 1) was finished in its present form in the 11th century «Morolli 1994, Rocchi 1994, Cardini 1996 Degl'Innocenti 2017». Baptistery has octagonal shape, is 45 m wide and 45 m toll and is covered by an outer pyramidal roof and an inner dome constituted by eight segments of cylinder.

At the ground floor, the eight corner pillars are connected by an outer curtain wall and an inner colonnade «Giovannini 2006, Giorgi & Matracchi 2917». In the first and second floor there are continuous inner and outer walls with corridors in between, acting as *matronei* (women galleries), with 16 intermediate ribs acting as transversal connections and three windows for side opened towards the inner hall; the three doors (North, South, and East) have a plat-band as architrave (Fig. 2).

All the outer and inner surfaces are totally cladded by white and green marbles «Coli et al. 2021», in the *matronei* an external covering stone curtain, made by quartz-calcareous turbiditic sandstone, is present; the inner dome is plastered by a mosaic of the XIV century.

No historical documents or designs are available for defining the Baptistery structural assemblage and masonry setting.

Until now, for that knowledge, only a few pictures of the wall behind the marble cladding taken during same slabs substitution, observations inside the pole-plot holes and data from a few cores recovered by Garzonio et al. «2017» are available.

Therefore, further information can be only obtained by the use of NDT and namely by an extensive use of the GPR. For those purposes, the OPA, which since 1296 has in charge the Baptistery conservation, launched a series of GPR surveys for acquiring those data.

Fig. 1 The Saint John Baptistery at Florence, Italy.

2. 3D H-BIM model

On the base of a cloud points obtained by a laser scanner survey, furnished by the OPA, DST developed a 3D HBIM content (Fig. 2) «Coli et al. 2019», into which all the radargrams had been placed in their proper position in order to help in the interpretation and assigning the masonry properties and assemblage.

The 3D model with solid elements was reconstructed using Revit (© AUTODESK) for creating using parametric objects to which link different types of information or external files. Object-oriented modelling was developed by using system families for walls, floors, roofs and columns and customized families for those relating to the GPR radargrams.

Each object has its proper ID for identifying it and which can be used with the appropriate label and in an abacus that allows interrogating the model. The 3D visualization of the model can be done through customized views and in the 3D environment through dynamic and exploded sections that facilitate the query phase.

3. GPR surveys

The GPR method, as well known «Giannino & Leucci 2021», is based on the measurement of the time (two-way travel time) which elapses between the transmission of electromagnetic pulses in the radar frequencies (100 MHz-100 GHz) in the medium to be investigated by the transmitting antenna and their reception at the receiving antenna.

The radar pulse propagates in the medium with speed depending on the characteristics of the medium itself, above all the electrical conductivity and the relative electrical permittivity. When it encounters a surface of discontinuity, or materials with different electromagnetic characteristics, the radar waves are partly reflected and partly transmitted.

The radar pulses returning to the receiving antenna are converted into electrical signals and then transmitted to the control unit, amplified and recorded; the recorded and processed data are graphically returned by means of radargrams that highlight the various reflectors.

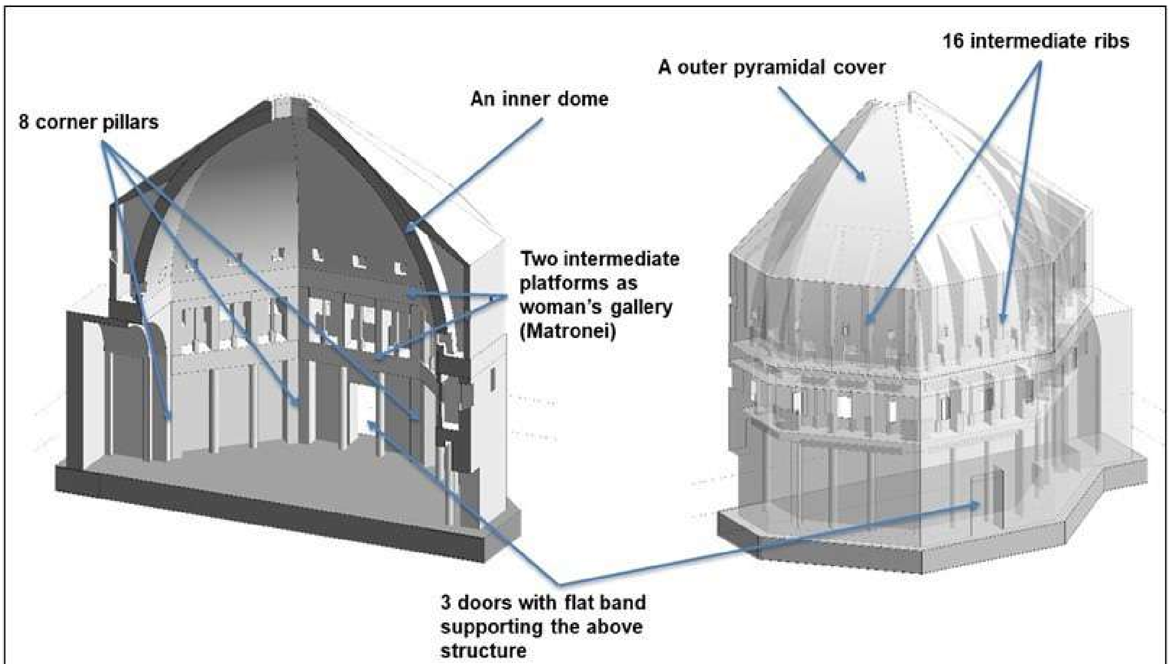

Fig. 2 3D H-BIM model resembling all the main structural elements of the Baptistery.


Fig. 3 GPR survey in progress on the inner dome.


Fig. 4 GPR survey from the inner side of the perimetral walls by Stream T mounted on an elevator.


Fig. 5 GPR survey in progress on the top floor by means of an elevator crane.

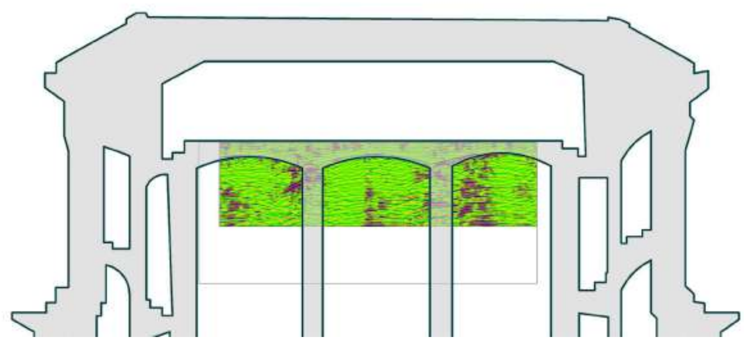
Fig. 6 Radargram of a GPR strip above the matronei arches in the 3D model.

Operatively, GPR surveys had been done by means of several antennas (all by IDS Georadar – part of Hexagon), each time chosen for having the best performance in regards to the goal:

- C-thrue: incorporates two dipole antennas at 1.5 GHz, which polarizations are orthogonal, separated by 10 cm; that allows a better surveying of the marble cladding, about up to 30 cm of thickness and had been also used for surveying the masonry on the inner dome about 90 cm thick (Fig. 3).

- Stream T: it is a third generation of GPR antenna consisting of 3 antenna modules at 900 MHz connected in a continuous chain (90 cm width), with horizontal polarization, and suitable to acquire data in a contactless mode, staying at about 15 cm from the surface, used for a full survey of the masonry of the wall and of the pyramidal cover, up to 1.3 m thick (Fig. 4, 5).

- RIS One: with a single 900 MHz antenna, for investigating the masonry below the *matronei* (Fig. 6).

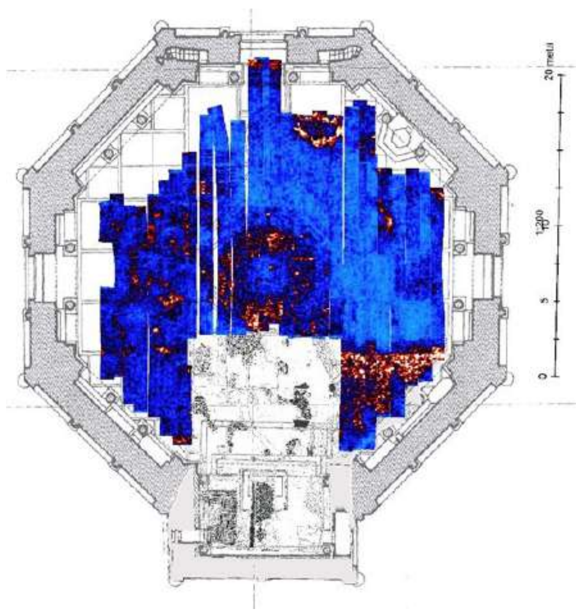

Fig. 7 Slice at 1.5 m of depth outlining the objects presents in the underground.

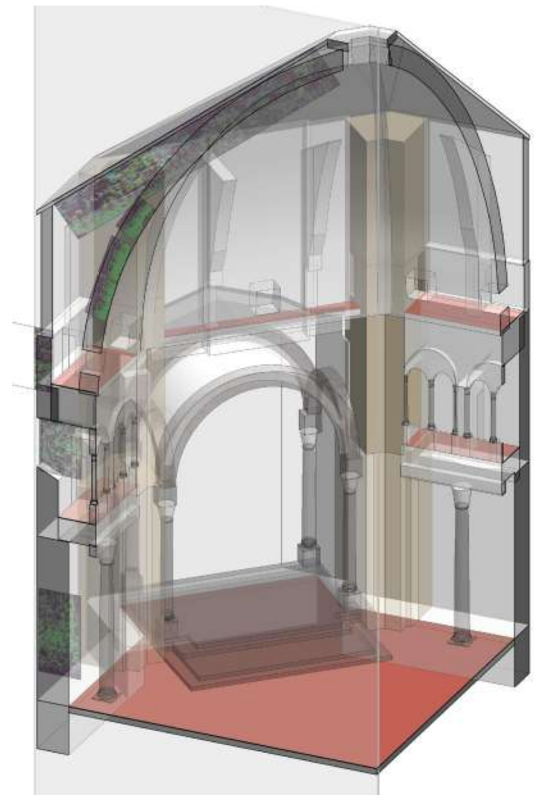

Fig. 8 Example of the radargrams mounted in their proper position in the 3D H-BIM content.

- Stream C: a special configuration consisting of an array, 1 m wide, of 32 dual polarization 600 MHz antennas, coupled with a Leica TS50 Total Station (by LeicaGeosystem part of Hexagon) for having a georeferenced GPR tomography of the underground of the ground floor (Fig. 7).

4. Results

This GPR survey campaign was very fruitful allowing to define assemblage and structure of the Baptistery masonry (Fig. 8), which resulted well done, not sack masonry but full masonry, as common for medieval Florentine buildings «Coli et al. 2022», these are solid masonry assembled, with non-homogeneous stone elements well meshed in the laying surface and bound by an excellent mortar.

In particular, radargrams of the external wall, that was investigated up to a maximum thickness of ~ 1.8 m with the Stream-T, show from the ground floor to the roof the external covering stone curtain above a regular blocky masonry. Radargrams of the inner dome, that was investigated with a C-thrue antenna up to a maximum thickness of ~ 1 m, show a regular stratification of briks over the whole thickness of the dome. The roof, that was investigated with a Stream-T antenna up to a maximum thickness of 2 m, appears as being characterized by a regular structure, with the 7 cm thick white marble slab overlaying the concrete structure that was realized during the 1930 major conservation works without using any iron elements. The radargrams highlight the boundary between the external roof and the lighter inner dome that in its upper part is realized with bricks.

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Infrared inspection of WW2 camouflage German helmets

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ABSTRACT
The German steel helmet is an icon of the last world war and it is highly appreciated by militaria collectors. From the period between the first and the second World War to August 1943, decals referring to the service branch were applied to the German helmets. In order to minimize their visibility the soldiers often covered the helmets with a camouflage paint, sometimes mixed to sawdust and sand.
Infrared pulsed thermography was used on different kinds of camouflage German steel helmets of the Second World War, to detect the presence of decals.
In most of the cases only the shape of the decal clearly appeared in the IR images. In some cases the paint surprisingly resulted to be transparent in the infrared radiation waveband from 3 to 5 μm used by the IR camera, thus allowing to see the drawing inside the decal.
Navy helmets were produced in fewer numbers and they are therefore more desirable for collectors. Navy and Army decals had the same external shape and the same internal drawing of an eagle on a swastika. They only differed for the color and the thickness of the eagle and the swastika due to a particular multilayer production process used for Navy decals. This work also describes a procedure capable of distinguishing Navy from Army decals, even when covered by the camo paint.

KEYWORDS: German helmet decal, camouflage, infrared thermography, Second World War, militaria.

Fig. 1 Second pattern LW eagle.

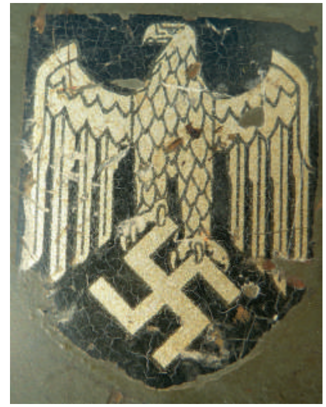

Fig. 2 Heer eagle.

Fig. 3 KM eagle with stepped rim.

Introduction

The German steel helmet was introduced in 1916 during the First World War, to limit wounds due to new weapons, in particular to grenade splinters. No decals were applied to the helmets during the First World War. Decals started to be applied to the helmets during the period between the two wars.

In 1935 a new steel helmet was introduced (Stahlhelm 35 or M35), reducing some of the disadvantages of the helmets used in the First World War. Before the beginning of the Second World War, Airforce (Luftwaffe - LW), Army (Heer) and Navy (Kriegsmarine - KM) helmets typically had one shield shaped decal on the right, with the three-color of the national flag, and one decal on the left, referring to the service branch. For the Luftwaffe, the service decal had the shape of an eagle grabbing a swastika. Two kinds of eagle existed: a first pattern eagle, which firstly appeared in 1936 and was used till 1939-1940, and a second pattern eagle (Fig. 1), which firstly appeared in 1937 and was used till 1943.

Army and Navy helmets had a similar shield shaped decal, with an eagle on a swastika (Fig. 2 and 3). The only difference was that, for the Navy, the eagle and the swastika had a golden color and, in the first years of production, also a layered structure, producing a step all around them, visible in Fig. 3.

In 1940, the construction of the helmet was simplified with the M40 model and the well visible national colour decal was eliminated from Army, Navy and Luftwaffe helmets. In August 1942, to save time in the production process, the helmet construction was further simplified, creating the M42 model. Starting from 28 August 1943 decals were eliminated from all helmets.

To limit helmets visibility, camo textiles covers started to be used, or more frequently they were painted with different kinds of paint, often mixed to sawdust and sand to make the surface more rough and less reflecting. Of course, colours could change according to the environment, from white for the snow to yellow for the desert.

The description of the German helmets and decals given above, is of course not exhaustive and more information on the different helmets, the five different manufacturers (ET, SE, Q, EF, NS) and the different decals

Fig. 4 M40 SE66 shipboard grey (Courtesy J. M. Meland).

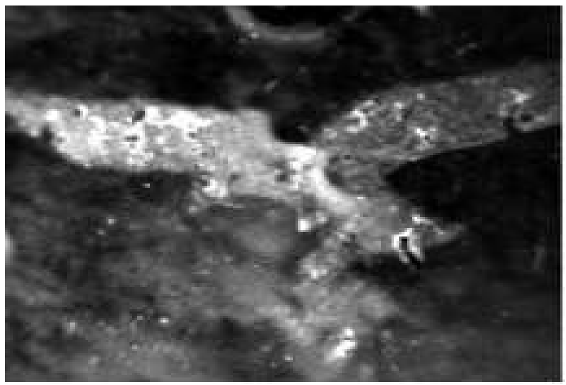

Fig. 5 Image of a second pattern LW eagle obtained by pulsed thermography.

used during the war, can be found in specialized books as «K. Niewiarowicz», « K. Niewiarowicz and A. Lehrman » or «J. M. Meland».

Collecting militaria

When at the beginning of 1900 industry and technology started to shape the world as we know it, weapons became more and more precise, and destructive. In the second world war entire towns were destroyed, countries were devastated, millions of people died, the entire world was shaken.

Today, a helmet, a witness and a symbol of all this, arrives somehow into our hands. A German helmet, with its distinctive shape designed to protect the soldier, is, probably more than anything else, an icon of the last world war and, for what it represents, it can arouse strong emotions in those understanding what the last world conflict has been and desiring to preserve its memory. Collectors of militaria are among those people and they are eager to know as much as possible about the items in their collection.

The value of an helmet depends very much on the grade of preservation and on the rarity of the object itself.

The number of Navy helmets was significantly less than for other branches and the layered structure often resulted in a more fragile decal. Navy helmets are, therefore, among the most valuable pieces.

Thermographic inspection

Infrared pulsed thermography («W.N. Reynolds») was used to inspect camo helmets and reveal possible decals hidden beneath the camo paint surface. The camera used for the experiments was a FLIR-Cedip Titanum with an IR Focal Pane Array sensor InSb 320x256 working between 3 to 5 µm and with a NETD of 20 mK at 30°C.

A flash lamp Elinchrom Style RX 1200 was used as a heat source. A filter was placed in front of the lamp, cutting its infrared emission, in order to avoid reflections from the lamp itself.

M40 SE66 shipboard grey

KM helmets were often camouflaged using the same paint used on the ships. Fig. 4 shows a M40 SE66 lot number 4938, painted on its surface with a typical shipboard grey colour. This helmet was found in Norway, and from the colour of the camouflage it was presumed to be KM. Fig. 5 shows, however, that behind the camo paint there is a second pattern LW eagle.

Fig. 6 DAK camo M35 ET64 helmet

Fig. 7 LW eagle with some damages extending to the original paint too.

M35 ET64 DAK

Deutsches Afrikakorps (DAK) helmets are rare because it is estimated that only one percent of the German forces were employed in Africa. Fig. 6 shows an helmet with a sprayed desert camouflage. The chinstrap is marked LBA (*Luftwaffe Beschaffung Amt*) and dated 1937. On the left side IR thermography showed a second pattern LW eagle (Fig. 7) and some damages on the original paint and on the decal, indicating that the helmet had long been in use before the camouflage process.

On the right side the national three-color shield was found, also severely damaged.

M35 ET64 with woodchip camo

The helmet of Fig. 8 is an M35 ET64. It was found in Sjoa (Norway). It was spray painted with added woodchips, in order to obtain a rougher and less reflecting surface. The internal original color is green, thus indicating a Heer or a KM. Woodchip can completely hide the decal in an IR pulsed thermography inspection. Fig. 9 shows the decal shape, but it is impossible to say if the decal is a Heer or a KM.

M40 ET64 with concrete camo

The helmet of Fig. 10 was found in Norway and it is covered by concrete painted in various tones of green and brown. Due to its vivid colors and the good condition of the surface, there were doubts about it authenticity. Similar helmets were found in Norway. The majority of collectors considered these helmets to be original, explaining that the good condition of the surface could be due to the fact that the helmets had been kept in a depository after the camouflage process.

IR thermography revealed a second pattern LW eagle appearing in between the concrete patches (Fig. 11), thus giving a further indication in favor of its authenticity.

M35 ET62 shipboard grey

The helmet of Fig. 12 was found in a coastal area of Norway and it has the typical shipboard grey camo used in many KM helmets. Surprisingly, its camo paint was transparent to the IR radiation in the 3 – 5 μm waveband used by the IR camera. This allowed to see the eagle and the swastika inside the decal (Fig. 13).

Fig. 8 M35 ET64 woodchip camo (courtesy J.M. Meland).

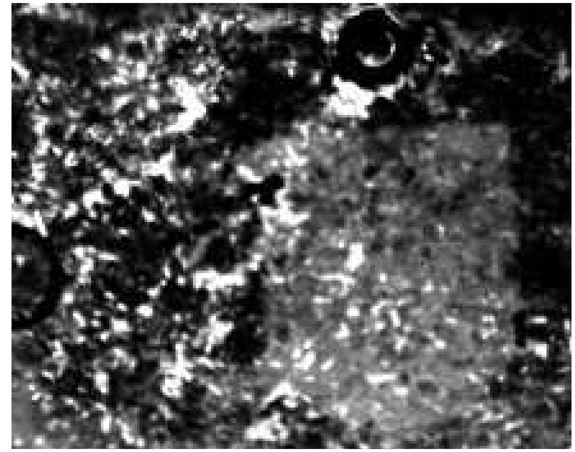

Fig. 9 Decal appearing on the left side.

Fig. 10 M40 ET64 covered by concrete patches and painted in green and brown (courtesy J.M. Meland).

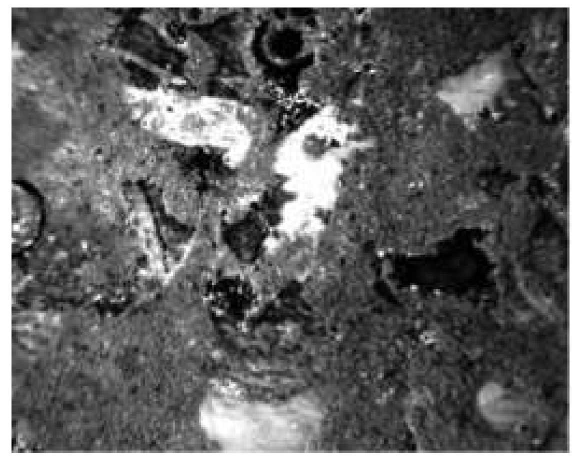

Fig. 11 Second pattern eagle appearing among the concrete patches.

Apart from the colour of the camo paint, there was no proof that the helmet was a real KM.

The golden colour of the decal did not appeared on the surface in any point and of course could not be seen in the infrared image. Several attempts were made acquiring a sequence of IR images after an heating pulse in order to obtain the equivalent of a phase image in pulsed phase thermography («X. Maldague, S. Marinetti »), in

Fig. 12 M35 ET62 shipboard grey.

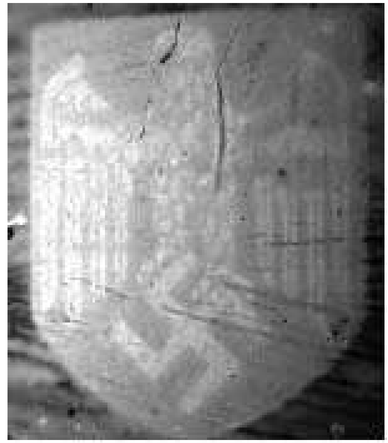

Fig. 13 Camo paint transparent in the 3-5 µm waveband.

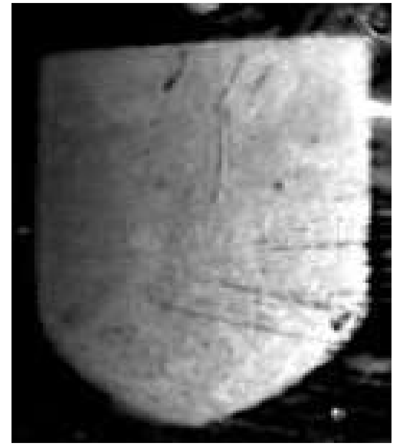

Fig. 14 Contour of the eagle and the swastika obtained in the 8-14 µm waveband.

the attempt to reveal the different local thickness of the eagle and the swastika. None of these attempts was successful, because in this case the visible light and the IR radiation were absorbed and emitted on different layers.

Pulsed thermography was then performed on this helmet using a FLIR Jade II IR camera, with a HgCdTe sensor, working in the 8-14 µm waveband, in which the camo paint was not transparent. Fig. 14 shows the result obtained. The shape of the eagle and the swastika inside the decal appear clearly as a darker area. This indicates not only that the area with the eagle and the swastika has a different thickness than the rest of the decal, as for a multilayer KM decal, but also that the multilayer structure of KM decals was obtained introducing a more conductive, probably metallic, thin layer as an intermediate layer.

Conclusions

Pulsed thermography proved to be an effective non-destructive procedure to see decals in most of the camo painted helmets. The addition of sand, sawdust and woodchip to the paint, could in principle hide completely a decal also for a thermographic inspection. The local thickness difference between KM and Heer decals could be used to differentiate them when the decal was covered by a sufficiently smooth layer of camo paint.

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Density estimation of historical wooden elements through means of thermographic correlation approach

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Abstract

Ancient wooden artifacts are vulnerable to deterioration from a variety of environmental and human factors. It is challenging to comprehend the assessment when the wooden part is placed inside a construction without performing a diagnostic procedure. While working with ancient wooden structures, tradition and preservation of the architectural, technological, and historical heritage are crucial. A series of non-destructive tests (NDT) must be carried out and developed in order to preserve and determine the nature of the structure and comprehend how to maintain it because wood is also a significantly heterogeneous material. Thermographic techniques are well recognized to be non-destructive, contactless, complete field techniques and are already common in the artistic sector. However, there is the possibility of estimating the physical properties (for example transmissivity, thermal conductivity, humidity level, etc.) and mechanical characteristics (density, compressive or bending strength, etc.), critical information, linked usually with wooden defects, when it comes to planning interventions of conservation. This work presents the preliminary results of a physical and mechanical characterization methodology of different chestnut elements in different states of conservation, with the aim of correlating thermal and density properties, for the purpose of conserving artistic assets.

Keywords: thermography, wood, density, mechanical properties, characterization.

Introduction

Wood is a very particular material being heterogeneous, anisotropic and often also defined as orthotropic [1]. In contrast to other materials, each sample may exhibit radically different physical and mechanical traits from others, even when compared to other samples of the same woody species or geographic origin. These characteristics raise the uncertainties and variability of the correlations discovered through experimental testing [2]. Architectural history includes also the study of connections, interventions, and connecting components [3].

The modern woods used in architecture for structural use, defined as engineering, try to overcome the intrinsic problems with particular processes, reducing them considerably [4]. It is necessary to develop non-destructive tests (NDT) methods of investigation that can validate the strength of the structures and the material, without damaging the existing historical elements.

The arboreal stem consists of essentially three tissues. The mechanical one is the most prevalent and consists of fibers parallel to each other and united in bundles and serves to support the structure. The conductive tissue is for the transport of the lymphatic system and finally, the parenchymal is reserved. The fibers respond differently to mechanical stress. In addition to this heterogeneity of the material, it is, by its nature, composed of some defects (knots, or knots clusters, mechanical cracks, splits, ring shakes and slope of the grain), which alter its physical and mechanical characteristics, adding a great variability of the results. For this reason, particular reference is made to these in assessments, in order to avoid possible structural collapse [5], [6].

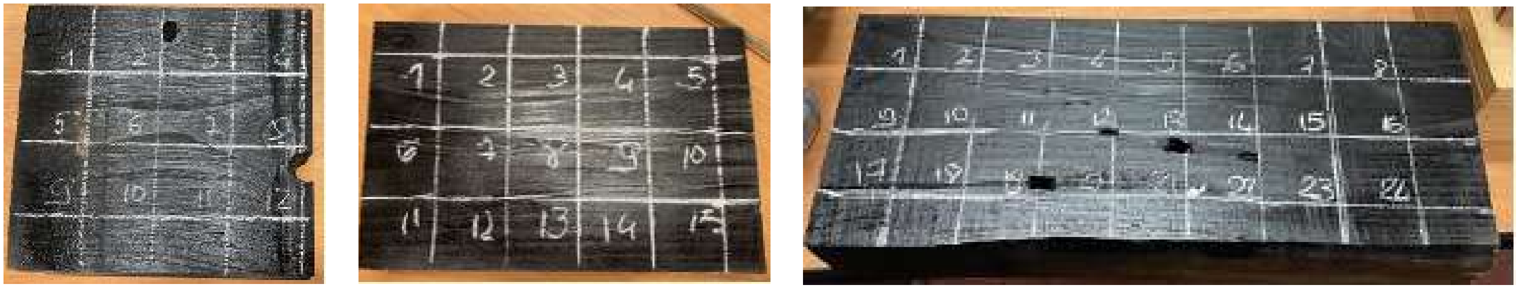
In this research, the authors aim to investigate and deepen the correlation between density and thermal properties of timber, through experimental NDT. In order to estimate density, an NDT method is proposed, to check and assess wooden constructions without causing damage: infrared thermography (IRT). Different chestnut samples provided by Brondello Erminio company of Cuneo were examined. The samples have the peculiarity of being both standard and reused with the aim of being able to also propose the possible reuse of wood elements and structures. This paper is presented as a first work of a wider and more complex research that will also evaluate the deepening of sustainability through a quantitative evaluation and an innovative approach to the material.

Tab. 1 Sample dimensions and strength-classes given by the visual grading.

Sample	Strength Class	Width [mm]	Hight [mm]	Lenght [mm]
1 - New	I	50	200	200
2 – Old salified	I	50	450	200
3 -Old dried	I	50	180	200

Materials and methods

The company's sawmill works only wood at km 0 with a supply radius of 20 km, for local wood essences. The company produces wooden products both for finishing and structural use starting from wood abandoned in the woods due to natural causes (storms, landslides, old age of wood) and also beams belonging to ancient farmhouses or abandoned roofs. The processing of recovered and reused wood consists of vaporization, drying or salification. The analyzed chestnut wood samples are 3, of which one of new production and two are from reuse, one salified and one dried, in order to compare



a b c

Fig. 1 Wood samples: new (a), old salified (b) and old dried (c).

the results. Regarding the chestnut samples (Table 1), all of them are considered as class I with a MoE of 10000 N/mm^2 according to UNI 11138:2004. In addition to the visual inspection two NDTs were conducted, hygrometric test and active thermography investigations. For the hygrometric tests, a hygrometer with superficial probes was used. The relative hygrometric test of the wood samples was performed in different positions by means of a Huepar M01 tester (scale G). A grid of points distant 50 mm was reported on the samples (Figure 1) and humidity was measured in the nodes of the grid. Measurements were performed with room temperature equal to 24°C and relative humidity equal to 26,5%

Thermographic approach for wood properties investigation is documented in literature and papers focus on hygrometric [7], density [8] [9] and mechanical [8] properties. All cited references refer to Active Pulsed Thermography. In the present paper Active Lock-In technique is applied and the phase plot of processed thermograms are analysed. Preliminarily, the sample surfaces exposed to heat stimulation were coated with a 0,1 mm thick black opaque spray paint to avoid problems related to emissivity calibration. Emissivity was then set to 0.96. By means of two halogen lamps, 500 Watt each, distant 400mm from the surface of the samples, a heat input was sent to the surface for 30 seconds and then the lamps were switched off for 60 seconds. 3 impulses were applied. An IR FLIR A6751sc thermal camera, sensitivity of less than 20 mK and 3-5 µm spectral range, positioned at 2000 mm from the target, acquired the heating and cooling profile of the surface during the test. The thermograms were then processed by means of dedicated algorithms to obtain phase maps.

Results and discussion

In Tables 2, 3 and 4 the relative humidity data are reported. The same data were plotted in Figures 2, 3, 4, with the corresponding phase contours.

The following observations can be reported: the phase plot mimics the wood fibre distribution; the humidity appears to be lower where fibers are denser and higher where fibers are less dense; the phase contrast between fibers is almost constant; humidity is more uniform in dried sample while it shows large differences in salified samples; the average value of salified sample humidity is higher than in dried sample.

The 3D phase map, processed from thermal data obtained during lock in stimulation of samples, is related to the local conductivity value [10]. In the present research a plane white heat source was used in place of a

Tab. 2 % relative humidity, salified sample.

Grid node	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
%humidity	19	20,1	14,1	12,6	13,7	12,6	12,4	12
Grid node	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
%humidity	18,5	18,3	14,3	14	12,8	14,7	12,5	12,2
Grid node	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
%humidity	17,7	15,2	13,3	13,7	13,9	14,6	13,8	13

Tab. 3 % relative humidity, dried sample.

Grid node	**1**	**2**	**3**	**4**	**5**
%humidity	11,4	11,4	11,3	11,6	12,5
Grid node	**6**	**7**	**8**	**9**	**10**
%humidity	12,2	11,8	11,8	11,7	11,6
Grid node	**11**	**12**	**13**	**14**	**15**
%humidity	11,7	11,7	11,6	11,9	12,5

Tab. 4 % relative humidity, new sample.

Grid node	**1**	**2**	**3**	**4**
%humidity	11	11	11,1	11
Grid node	**5**	**6**	**7**	**8**
%humidity	11,3	11,3	110,9	10,8
Grid node	**9**	**10**	**11**	**12**
%humidity	11,5	11,4	11,2	11,1

Fig. 2 New sample phase plot (left) and humidity plot (right).

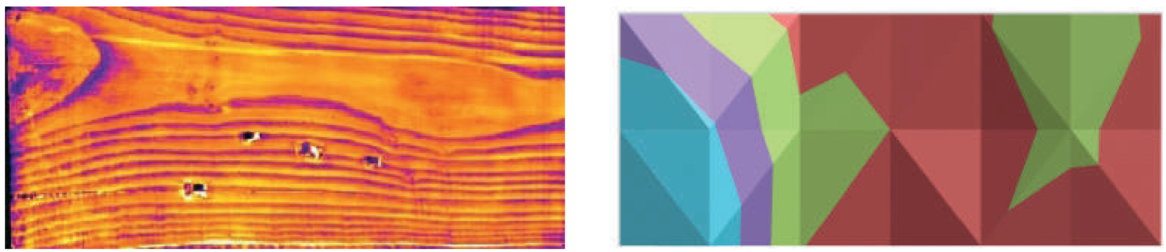


Fig. 3 Salified sample phase plot (left) and humidity plot (right).

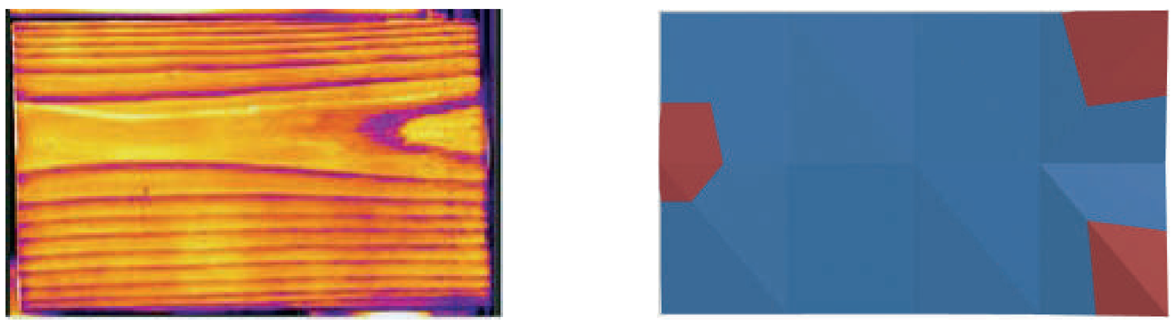


Fig. 4 Dried sample phase plot (left) and humidity plot (right).

monocromatic laser spot. The heat in this case propagates from the surface to the inner part if the material is homogeneous. If the surface is composed by is non homogeneous material, different material absorbance and transmittance generate thermal differences in different points of the surface. The heat capacity of the wood fibres can be affected by the influence of water presence [7]. These thermal differences can generate heat diffusion and heat fluxes between points on the surfaces; then the phase diagram provides then information on diffusivity both toward the internal volume and between different points of the surface. Water has a high absorbance and low transmittance in the IR spectrum and then, the different distribution of water between fibers can affect the surface temperature distribution and consequently the phase plot.

Conclusions

Aim of this research was to develop methods of investigation to quantify the strength of the structures and the material, without damaging the existing historical elements. Diagnostics and evaluation of degradation status with non-destructive tests (NDT) well applies to this aim. By means of non-destructive investigations, and in particular hygrometric and active thermograpy techniques, three samples of Castanea sativa in different physical conditions, were investigated, without altering the samples. A clear correlation was found between humidity ratio and thermal phase plot. It has been found a full correspondence between the actual density and the estimated surface density and this step allows to continue the research in the next step through the correlation of the mapping of phase, humidity and density.

Analyzing the investigated physical properties in a timely manner, three correlations are obtained between the big unknowns of wood. Humidity is one of the most important factors of wood and is less often investigated due to seasonal and punctual variability in the sample. Variable behavior and heterogeneity make this investigation complex. On the other hand, the density is strictly connected to the percentage of humidity and is one of the fundamental requirements and unknowns that concern the existing wooden structures.

The correlation between these physical properties also leads to the mechanical knowledge of the wooden element. The research, still in progress, foresees this evolution so it is possible to have reliable curves and correlation maps that can be used for in situ work.

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Study of the dynamic behaviour of a timber altarpiece using Laser Vibrometers

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Abstract

The preservation and maintenance of cultural heritage is of great importance for future generations. Non-destructive investigation methods play a crucial role in assessing the state of conservation of historical artifacts. In this work, a study on the dynamic behaviour of the replica of a timber altarpiece using a laser vibrometer is presented. The objective of this study is to analyse the dynamic response of an altarpiece when stimulated with volumes comparable to that of the human voice. Experimental tests were conducted on the replica and the results were analysed and discussed. The proposed method has shown to be effective in characterizing the dynamic behaviour of the artwork, providing valuable insights into its structural response and condition. This study demonstrates the potential of laser vibrometers as a non-destructive investigation method for the diagnostics and conservation of cultural heritage.

Keywords: non-destructive investigations, laser vibrometer, dynamic behavior, structural damages, diagnostics.

1. Introduction

In the measurement of vibrations it is common to use devices, called accelerometers, which are securely attached to the sample being examined (Sabato et al. 2017) (De Stefano et al. 2016). While this approach is applicable to most objects, it is generally not suitable for the surfaces of artworks, as they should be handled as minimally as possible. For this reason, the aim of the following analyses is to understand whether it is possible to achieve a dynamic identification of an artwork, in this case a wooden altarpiece, using laser vibrometry technology that operates without physical contact between the instrument and the art object. Although the non-invasive diagnostic technique of acoustically stimulated laser vibrometry has been conducted on frescoes (Calicchia et al. 2005), mosaics, ceramics, easel paintings (Castellini et al. 2000, 2003) and statues (Arciniegas et al. 2023), providing promising results in detect damaged portions of surfaces, literature lacks information on such tests conducted on altarpieces and, above all, there is a notable absence of details regarding the appropriate volume level to apply to obtain results. Therefore, experiments have been conducted on a laboratory replica of the original artwork, tested with different types of constraints, to determine the sound level at which results can be measured. The present article presents the conducted analyses, the obtained data and some relevant considerations.

2. Masterpiece under investigation

The artwork under investigation is the *San Giobbe altarpiece* (Fig. 1a), selected upon the request of the Gallerie dell'Accademia museum in Venice (Italy), with the ultimate goal of assessing the feasibility of its potential relocation.

San Giobbe altarpiece was painted by the renowned Italian artist Giovanni Bellini in 1477-1478. Originally, the artwork adorned the second altar in the church of San Giobbe and Bernardino and in 1815 it was transferred to the Gallerie dell'Accademia for conservation purposes.

Structurally, the *San Giobbe altarpiece* is currently 453x259 cm in size and it consists of 13 horizontally grained 2-cm-thick poplar panels with larch longitudinal beams and transverse supports on the back (Fig. 1b). The examination of the 13 panels reveals a distinction in quality between the first five panels, which are superior in grain and lack knots, and the subsequent panels. It is likely that the artist intentionally used higher quality wood for the figure portion of the painting (Savio, 1994). However, issues arise with the lower quality wood used from the sixth panel onwards, leading to infestations, warping and fragility. The support frame structure of the altar consists of four larch beams, each measuring 453x20x5 cm. The altar was outfitted with 212 trapezoidal wooden wedges applied with animal glue (Nepi Scirè, 1994). The exact composition of the protective layer on the panels is unknown, but it is assumed to be a mixture of plaster and rabbit skin glue, which was commonly used at the time. Analysis of the painted films revealed old layers of varnish and a thin layer of lead white underpainting with varying binders, suggesting a combination of oils and tempera (Volpin, 1994). Currently, the painting is resting on a wooden base supported by metal profiles screwed into the wall and by six lateral spring supports, three per side positioned about 1.20 m apart.

a

b

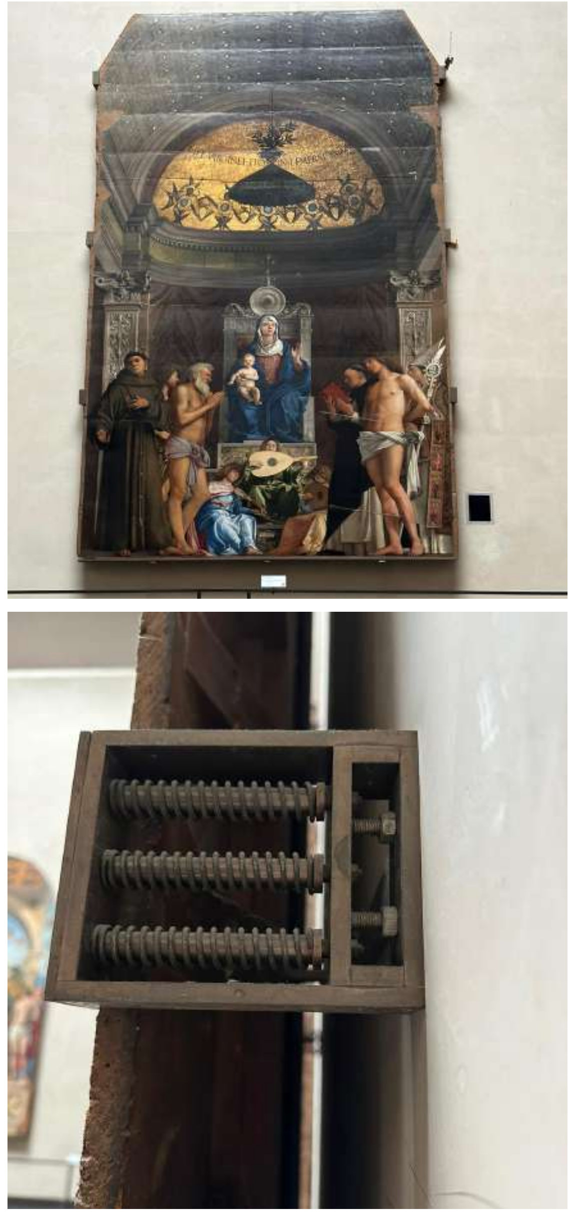


Fig. 1 a) *San Giobbe altarpiece,* 1477-1478 ; b) *San Giobbe altarpiece*'s support frame.

a b c

Fig. 2 a) altarpiece's base replica, b), animal glue, c) screws removal.

3. San Giobbe Altarpiece Laboratory Replica

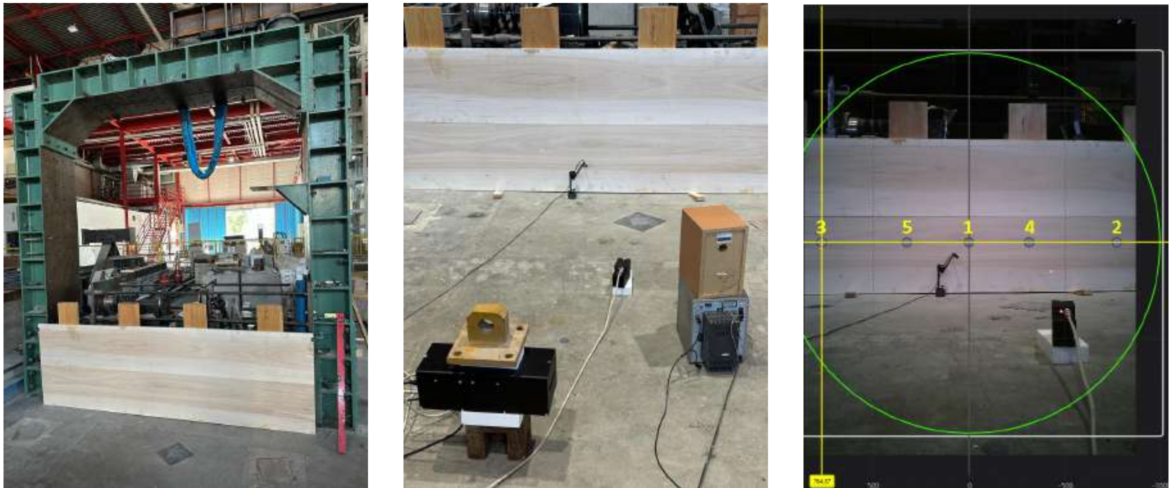
A non-invasive approach that can be useful for the objective and reliable assessment of the dynamic behavior of several kind of structural elements, in particular panels, plates and walls, is represented by the acousto-vibrometric technique: an acoustic wave, with a variable frequency between a few tens and a few hundred Hertz, is directed towards the investigation area; at the same time, a highly sensitive interferometric laser vibrometer measures the oscillations locally induced by the sound pressure on the structure. For the present application, a VSM-1000-SCAN "Self-Mixing" laser vibrometer (manufactured by Julight Srl) was used. However, before subjecting the actual artwork to this test, preliminary trials on a replica of the *San Giobbe altarpiece*'s base were conducted (Fig. 2a). The aim of the test was to determine the minimum sound levels for accurately interpreting the results.

The specimen included two poplar wood boards measuring 40x250x2 cm, four larch wood beams measuring 20x5x100 cm and 32 trapezoidal fir wood wedges measuring 21 (larger base) x7 (smaller base) x5x5 cm. In order to recreate the original method, animal glue was used (Fig. 2b). This gelatin is commercially available as amber-colored beads. It was applied with brushes to join panels, beams and wedges, recreating the original arrangement. Some screws were added during assembly and removed after the glue dried, following the original restoration process (Fig. 2c).

4. Tests and instrumentation

As for the setup, the base of the replica was simply supported at the edge. The two outer vertical beams were supported by metal struts, replicating the arrangement of the altarpiece at the Gallerie dell'Accademia museum.

Furthermore, unlike the original artwork which is elevated 90 cm from the ground on a shelf, the laboratory altarpiece is placed directly on the floor. In relation to this, vibrometric tests were performed under two distinct conditions: in the first scenario, the altarpiece's replica is simply supported at the edges by the metal struts on the back and by the metal profiles on top (Fig. 3a), while in the second case, it was continuously supported by adding two wedges to fix the base and fastened to the top supports (Fig. 3b).



a b c

Fig. 3 a) Altarpiece simply supported, b) Altarpiece's replica restrained c) Tested points on the surface.

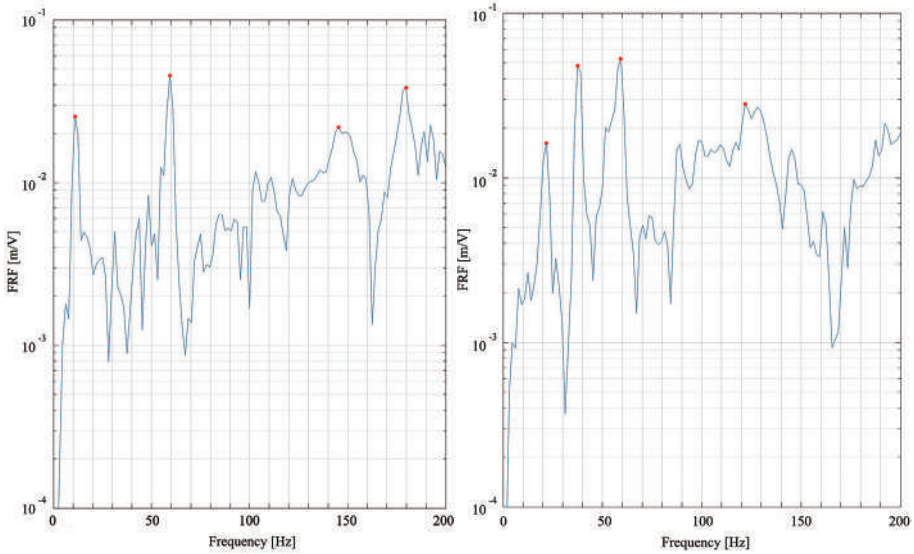
Once the setup was completed, the analyses were performed by identifying five significant points on the surface (Fig. 3c): two corresponding to the vertical beams and three in the area between the beams. The laser emitted by the vibrometer was directed at these points to record the natural frequencies of the altar's reproduction. This procedure was conducted both when the object was simply supported and when it was constrained, so ten tests were conducted.

In order to carry out the investigation, it is essential to induce vibrations in the sample and measure its response using the laser vibrometer. The "Self-mixing" scanning laser vibrometer VSM-1000-SCAN provided by Julight Srl was employed, characterized by a frequency response ranging from 0 to 20 kHz. For sound power measurements, the MPA416 microphone from BSWA Tech was used and it recorded the sound produced by a regular commercial speaker. The data acquisition was performed using the Apollo Box from Sinus GmbH. Lastly, the analysis was processed using the Samurai software from Sinus GmbH, which provides modules for FFT analysis and FRF (Frequency Response Function) calculation (see references for the websites).

The analysis of the signal was carried out using the FRF mode, enabling spectral analysis, for characterizing the altar's resonance and frequency response. In order to achieve this, frequency spectra were obtained from the output signal of the vibrometer. These spectra were then correlated with the excitation applied at a specific sound level. The FRF graphs of point 1, corresponding to the center of the panels, for both the simply supported and continuously supported cases are reported in Fig. 4a and Fig. 4b respectively.

The frequency response of point 1 is depicted Fig. 4a when the altar was simply supported on the edges. Analysis of the spectrum reveals that the main vibrations are concentrated at relatively low frequencies, while clear natural frequencies are not easily observed at medium-high frequencies. In this case, the peaks correspond to 10, 60, 145 and 180 Hz.

Fig. 4b illustrates the frequency response of point 1 when the altar's replica is continuously supported to both the base and the lateral supports. Consequently, the recorded values correspond to higher frequencies, exhibiting peaks at 20, 35, 60 and 120 Hz. Based on the graphs, it can be inferred that the object is susceptible to easy excitation at its resonant frequencies.



a b

Fig. 4 a) Pt. 1, FRF Simply supported altar's replica b) Pt. 1, FRF Constrained altar's replica.

Since there is a lack of available literature regarding the appropriate acoustic levels for this type of analysis, it was essential to perform preliminary laboratory tests. These tests involved associating a dBA value with the measured spectrum using a microphone and playing sound through a commercial speaker. In the phonometric measurement, an average was taken over a specific time interval, which in this case was 0.64 seconds. Within this time interval, a dBA value was analytically calculated, representing the average contributions of the spectrum of white noise between 0 and 250Hz. The resulting value was determined to be 63 dBA and was compared to typical noise levels (see references for the website). Consultation revealed that the sound emitted during the test corresponds to that of a "normal conversation", effectively recreating an everyday environment within a museum room. Consequently, the replica of the *San Giobbe's altar* was tested in a setting not higher than the original artwork's surroundings (Fig. 5).

Conclusions and future investigations

The investigations conducted on the *San Giobbe altarpiece*'s replica demonstrate the potential of laser vibrometers as a non-destructive investigation method for the diagnostics and conservation of cultural heritage. Through laboratory analyses, it has been discovered that for an altarpiece replica, both when it is constrained at the base and left free, its natural frequencies can be observed when stimulated with volumes comparable to that of the human voice. Given that the tests were conducted on the reproduction of the original artwork, future investigations in this field aim to assess the applicability of laser vibrometry within a museum setting and on original altarpieces of larger dimensions. Furthermore, additional analyses will be carried out, incorporating the protective and painting layers, to assess the effectiveness of the vibrometer on a dark-colored painted surface, which is predominantly present in the

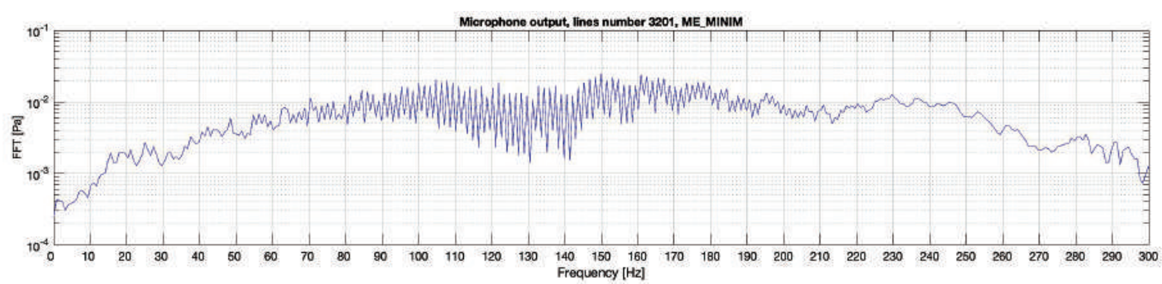


Fig. 5 Spectrum of the sound pressure waves recorded by the microphone.

San Giobbe panel. In relation to this, it is of interest to evaluate whether this technique can effectively identify localized issues such as detachments of color films, for instance through two-dimensional maps depicting vibration amplitudes measured at specific points along with a color scale for facilitating instant interpretation and detect potential structural damages that could compromise the integrity of the artwork.

Acknowledgements

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Observation of the internal structure of gilded and multilayered paintings by using THz Pulsed Time Domain Imaging and Pulsed Phase Thermography

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Abstract
Non-destructive observation of the internal structure of paintings provides useful information for conservation planning. The THz pulsed time domain technique using electromagnetic pulses and pulsed phase thermography using thermal pulses are compared as non-destructive inspection methods for paintings. Experimental results suggest that the THz pulsed time domain technique is effective for revealing precise layer structures from the support to the surface, while pulsed phase thermography is useful to observe the overall condition in a short time.

Keywords: gilded painting, internal structure, terahertz, time domain, pulsed phase thermography.

Introduction

For the past 20 years, THz pulsed time domain imaging (THz-TDI) has been used to study the internal structure of various paintings. The main advantage is that it can non-destructively provide cross-sectional images with sub-millimetre spatial resolution, which helps conservators to assess the condition of the preparation and support layers which is important for conservation planning. However, the commercial THz-TDI uses a scanning system to obtain three-dimensional data, resulting in a relatively long observation time, e.g., 30 minutes to measure the area of a 30 cm square. A further disadvantage is that THz-TDI is not able to observe the internal structure underneath metallic materials, such as gold leaf, due to the reflection at the surface. Active thermography, a common non-destructive testing method, has been advanced in numerical analysis to provide not only the temperature distribution but also the thermal conductivity distribution in the depth direction in a few minutes by using an infrared camera for data aquisition. It detects the propagation of thermal energy so that it can be applied to highly conductive materials such as metals and carbon fibre reinforced plastics (CFRP). We have recently used the pulsed phase thermography (PPT) to examine the internal separation of the wax-resin lining of canvas paintings and have compared the results with those obtained using THz-TDI. The experimental results confirmed that the delaminated areas were clearly observed by both techniques, and that the data were in good agreement with each other, as introduced in the following section. In this study we compared these two methods as a tool for observing the internal structure of two paintings, one is a tempera painting gilded with gold leaf and the other is a multi-layered oil painting, and discussed the advantages and disadvantages of these two methods from a practical point of view.

Observation methods

The THz time domain imaging (THz-TDI), which uses an electromagnetic pulse generated by a photoconductive antenna with a femtosecond laser pulse, has been progressed over the last two decades [1]. When a pulse is applied to a multi-layered sample as shown in Fig. 1 (a), a reflection pulse sequence generated at the surface and internal interfaces is obtained in the time domain (Fig. 1 (b). The delay of each pulse corresponds to the distance from the surface, resulting in a depth profile. Using a suitable scanning system, a cross-sectional image and 3D internal structure can be observed (Fig. 1 (c)). The authors introduced this technique to the field of cultural heritage research and analysed various masterpieces [2]. In this work, we used a turnkey, transportable THz-TDI system (T-Ray 5000, Luna innovation) of which photograph is shown in Fig. 1 (d) [3].

Fig. 2 (a) shows the schematic diagram of active thermography. The pulsed heat generated and emitted by flash lamps propagates into the object. Heat flow is affected by the presence of defects, such as an air gap in a solid material. The change in temperature is recorded by an infrared camera and analysed numerically to estimate the distribution of materials with different thermal conductivities [4, 5]. We used PPT system of which photograph is shown in Fig. 2 (b) (Ken Automation Inc.) composed of devices and software developed by edevis GmbH [6]. Unlike THz-TDI, which has been used in limited number of academic research institutions to now, a contract-based measurement service using PPT is available, so that conservators can use the technique without having to install the equipment. When active thermography is applied to paintings, some may be afraid of the effects of heating, but the instantaneous irradiation of a flash lamp has no effect at all on ordinary paintings, as the surface temperature changes by less than one degree Celsius.

The authors previously observed a wax-resin lined painting sample which contains artificial delamination defects [7]. Figs. 3 (b) and 3 (c) show the results obtained by the PPT and THz-TDI respectively, and Fig. 3 (d) shows the cross-sectional image along the yellow dotted line in Fig. 3 (c). The experimental results proved that the delaminated areas were clearly observed by both techniques. While THz-TDS is desirable when de-

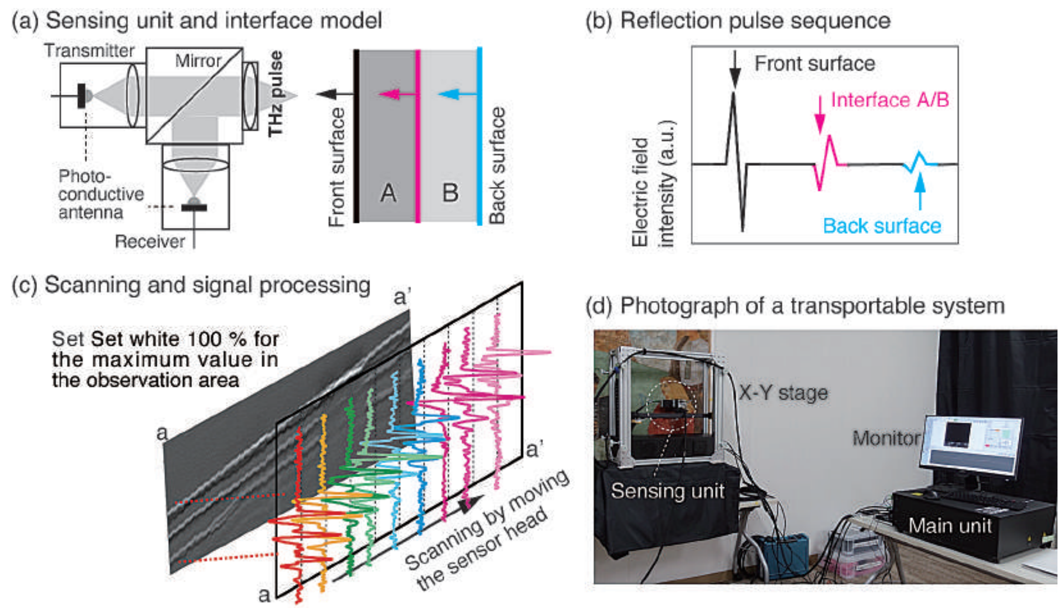

Fig. 1 Schematic diagram and photograph of THz-TDI.

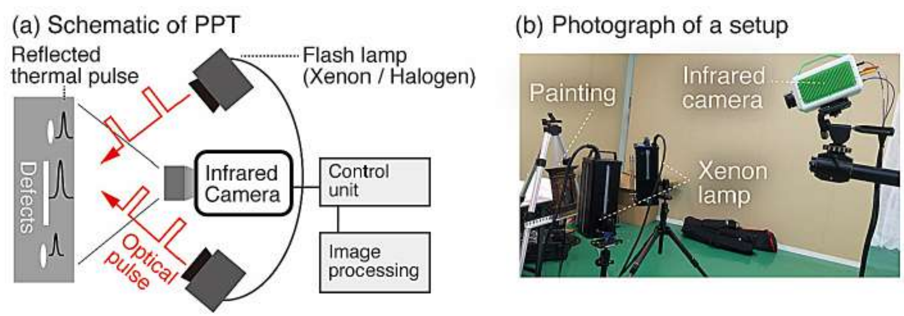

Fig. 2 Schematic diagram and photograph of PPT.

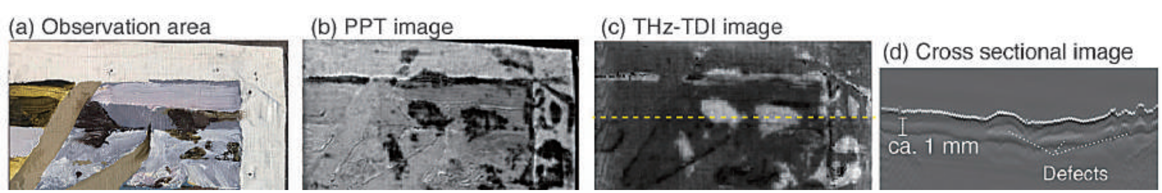

Fig. 3 Observation of the delaminated area of a canvas painting using PPT and THz-TDI. [7]

tailed cross sectional information is required, PPT provides the distribution of the delaminated areas at a quasi-instantaneous time. It is useful for conservators to examine the overall condition and particularly fragile areas before planning the conservation. In the following sections, we have compared these two methods on a gold gilded tempera painting on wood, and a multi-layered oil painting on canvas in which another layer of paint can be seen in the detached missing areas.

Tempera painting on wood panel gilded with gold leaf

Figure 4 (a) shows a tempera painting on wood panel gilded with gold leaf, of which provenance is unknown. The area of observation by THz-TDI is shown as a white rectangle. The THz reflection image and a typical cross-sectional image along the yellow dotted line are shown in the top and bottom images, respectively, in Fig. 4 (b). The spatial resolution, determined by the scanning conditions, is 0.5 mm for this measurement. There is no significant delamination in this painting, although the thickness of the gesso preparation layer was not uniform over the entire area. By overlaying the THz reflection image on top of the photograph (Fig. 4 (c)), the painted area on the gold leaf can be clearly seen, as indicated by the white dotted rectangle. As a THz pulse propagates through the painted layer, a strong reflection is generated at the gold surface and detected from the surface with a certain delay. Information about the area where the paint was applied over the gold leaf is very useful for conservators, as special attention must be paid to clean this area. However, the cross-sectional image can only be obtained in the area without gold leaf. For gilded areas, only surface features, such as *incisione* and surface scratches are recorded. In addition, a recently repainted area was not identified, probably because the materials used for the modern treatment were transparent in the THz band. Figs. 4 (d) to 4 (f) show the results obtained using PPT. Although the depth of each image is not quantitatively estimated, the image analysed by the lower frequency gives the condition of the deeper area, such as the preparation layer. As shown in the white dotted rectangle in Fig. 4 (a), the painted area on gold is clearly recognized without being overlaid on the photograph. Unlike THz-TDI, recently repainted areas are also detected as indicated in white dotted oval. The condition of the gold leaf can be estimated from Fig. 4 (b), and the details of the *incisione* for the preparation, such as the contours of the face and hands, appear in Fig. 4 (c). The data acquisition time for PPT is less than 1 minute. This is much faster than THz-TDI operating with a scanning system. Based on these results, PPT is considered to be suitable for the initial examination of a gilded tempera painting, as it provides useful information for conservation planning, including recently repainted areas.

Multi-layered oil painting on canvas

In conjunction with the results to be described later, the oil painting on canvas observed in this presentation has been represented by a rotation of 90 degrees, as shown in Figure 5 (a). This landscape painting of which provenance is unknown appears to have a multi-layered structure, judging from the view at the edge and the presence of paint in the areas where the top layer has peeled off. Synthetic resin has recently been applied to the entire area of the painting to adhere the surface cracks. An image obtained by THz-TDI and a typical cross-sectional image along the white line a-a' are shown in Fig. 5 (b). The multi-layered structure was observed throughout the painting, and each layer of almost constant thickness is clearly distinguishable, although small defects sometimes appear at the interface. The significantly clear structure of this painting allowed us to obtain more detailed information by extracting the reflection signals generated at the respective interface, simply by selecting the time window. Fig. 5 (c) shows the image of the layer approximately 0.3 mm below the surface. Different from the landscape painted on the surface, a female figure wearing a hat

Fig. 4 Comparison of imaging results of a tempera panel painting using THz-TDI and PPT.

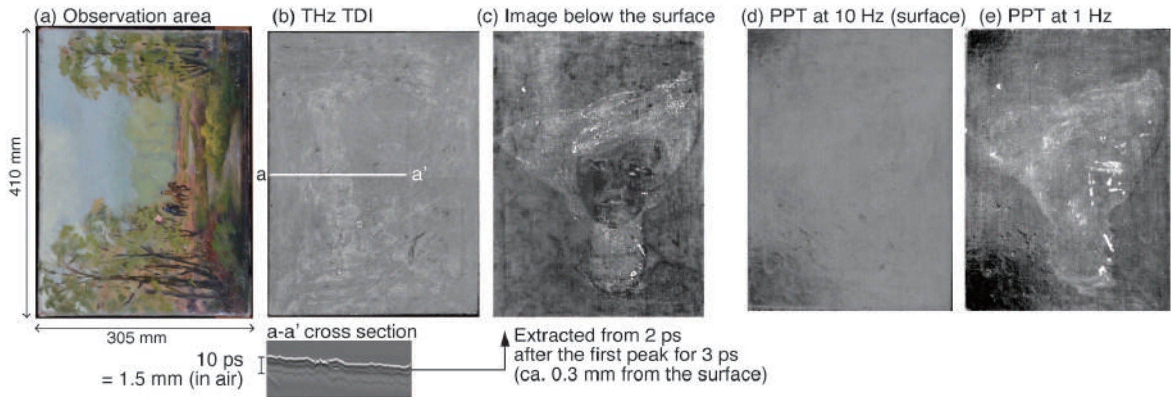

Fig. 5 Comparison of imaging results of a multi-layered oil painting using THz-TDI and PPT.

appeared. We will carry out XRF mapping to estimate the colours of the female images soon. Figs. 5 (d) and 5 (e) show the results obtained using PPT, extracted in the same way as in Fig. 4. The surface reflection was unexpectedly strong, and the landscape image did not appear, as shown in Fig. 5 (d). This may be due to the effect of surface treatment with synthetic resin. The female image obtained by THz-TDI before the measurement by PPT was also extracted by selection of optimal analysis conditions (Fig.5 (e)). If we had measured by PPT without knowing that a female figure exists underneath, it would have been too difficult to find it. Although the THz-TDI measurement time for this painting was approximately 3 hours, much longer than that with PPT, it provides interesting information not only for conservation planning but also for the history of the artwork.

Conclusions and future remarks

Two non-destructive testing techniques, THz-TDI using an electromagnetic pulse and PPT using a thermal pulse, are compared as practical measures for the study of the internal structure of paintings. Although the precise cross-sectional images can only be obtained by THz-TDI, PPT is more useful for examining the condition of the whole work in a limited time. Further fundamental research with different model specimens would make the use of PPT a common technique before conservation, in the near future.

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Engineering Archaeological Research: submillimetric X-Ray CT Scan of metal and hard stone objects in ancient Egyptian Mummies

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Abstract

The research work presented in this paper aims at demonstrating how technology can contribute in a novel and significant way to the archaeological research by searching for innovative solutions to answer questions springing from the realm of humanities. The specific target of this work is the production of submillimetric 3D virtual reconstructions of metal and hard-stone objects contained inside fully wrapped ancient Egyptian mummies. The main challenge is the need to create these reconstructions without removing the bandages and without causing any damage to the human remains. This paper describes the decision-making process leading to the choice of the methodology, which is computed tomography, and of the type of sample to be examined in order to perform a preliminary test and complete a feasibility study, before applying the process to an actual mummy. Tomographic scans were performed with an industrial experimental system, however designed according to the traditional medical configuration named "gantry", on three samples that had been mummified for this specific purpose. Their analysis was performed primarily to obtain information regarding the parameters necessary to produce virtual reconstructions. In parallel, considering the large amount of energy compared to the common medical CT, the opportunity was taken to verify the effects of irradiation on the scanned samples, used as reference. The chance was thus used to monitor the temperature trend and measure the level of absorbed dose inside and on the surface of the samples. The completion of this feasibility study will provide new and more detailed information on the material culture of Ancient Egypt within the ethical principle of respecting the dead and their funerary beliefs.

Keywords: mummies, egyptology, archaeometry, computed tomography, non destructive testing.

1. Introduction

The application of archaeometric techniques requires that scientists and humanists work together in order to create new forms of valorization and lead to new research questions (Greco, 2019). To demonstrate the importance of this relationship, it was decided to focus on a specific case study: verify the feasibility of producing, by means of a new form of X-ray computed tomography (CT), virtual 3D submillimetric reconstructions of metal and hard-stone artifacts contained inside fully wrapped ancient Egyptian mummies. This work will lead to the delineation of the guidelines necessary to apply such a study to the mummy of Kha (preserved at Museo Egizio in Turin, Italy), already analyzed by means of medical CT equipment (Museo Egizio di Torino, 2019), in order to obtain new and more detailed information. The main challenge of this process is to obtain such reconstructions without removing the bandages and damaging the biological tissues. The medical instrumentation already used on several mummies was limited by hospital requirements. This is why, in the case of very dense and high atomic number materials, the generated beam was not able to pass through the materials. On the contrary, industrial CT has no such limitations (du Plessis, Broeckhoven, Guelpa, & Roux, 2017), but it is often characterized by a small working chamber, not suitable for the analysis of large objects. Therefore, for such work, a hybrid instrument is needed, capable of developing powers characteristic of the industrial field and structured in a gantry architecture typical of medical equipment.

2. Methods and Materials

In order to avoid long set-up times directly on the mummy, irradiating it unnecessarily, the first step was to define an ad hoc test, which is the subject of this paper, capable of evaluating the instrument to be used, its parameters and the amount of possible damage to biological tissues. Regarding the parameters to be set on the machine, they should allow the creation of the reconstructions without artifacts and avoid any kind of damage to the specimen. The first type of damage is related to the amount of absorbed dose that could lead to the deterioration of DNA molecules, negatively affecting potential future analyses. In fact, it should be considered that the powers involved in this test are much higher than those used in the medical field. Nowadays, there are few studies on the effects of tomography on ancient and dry DNA and they do not detect significant damage except for absorbed dose values above 200 Gy, which is difficult to achieve by classical tomographic analyses (Immel, Cabec, Bonazzi, & Krause, 2016). In addition, it should be considered that, in the source, accelerated electrons dissipate 99% of their energy in the form of heat. Therefore, it is important to make sure that the instrument is not able to result in any temperature changes in the mummy, due to its preservation conditions.

2.1 The Samples

To perform the tomographic scans, three samples, defined as Artificial Sample 1 (AS1), 2 (AS2) and 3 (AS3), were produced in order to simulate the mummy of Kha in terms of density, atomic number and thermal behavior. In this way, the mummification of three porcine shanks, which offer a good approximation of human tissues, was carried out, performed following the steps of the ancient process:

First washing phase performed by means of water and gin to disinfect the samples.

Drying phase performed in 70 days, like in ancient Egypt (Ikram, 2017), by means of three artificial natron compositions. For the sample AS1, sodium carbonate decahydrate (Libowitzky & Giester, 2003), for AS2 a compound already used in some experimental archaeol-

Fig. 1 Coating with resins and wrapping in bandages.

ogy cases (Brier & Wade, 1997), as well as for AS3 (Abdel-Maksoud, 2001).

Second washing phase performed by water, in order to clean the samples from the salt.

Coating with oils and resins derived from coniferous plants due to their antibacterial properties.

Placement of some flint and limestones with the engraving "POLIME" and some gold rings on the samples, fixed by means of linen bandages (Fig. 1).

2.2 Absorbed Dose and Temperature Measurement

In order to measure the absorbed dose, it was decided to apply both on the surface and inside AS1, 60 lithium fluoride thermoluminescence crystals, kindly provided by the Department of Energy, Politecnico di Milano, which are passive dosimeters, known as TLD-100. The measured absorbed dose had to be lower than the value found in the literature of 200 Gy. In addition, results were compared with typical medical values and national exposure limits.

Regarding the temperature measurement, two measurement points were selected for each tested sample (AS3 and AS2), one on the bandages and one under them, in order to study its trend. In any case, both points were placed adjacent to the gold ring as it was the main study object. The measurement system used consisted of a two-channel thermometer to which T-type thermocouples were connected.

2.3 The Computed Tomograph

For economic and time reasons, it was decided to look for a pre-existing tool characterized by the features required by this test. The company Vetorix Engineering Srl recently made one suitable for the purpose, equipped with: a "gantry" structure; an X-ray tube, specifically designed for industrial nondestructive testing and capable of sustaining an acceleration of 225 kV; an a-Si detector characterized by a CsI:Tl scintillator and with a pixel pitch of 140 µm.

2.4 The Analysis

It was decided to place at the X-ray source a brass filter with a thickness of 0.8 mm to reduce from the beginning artifacts due to X-ray beam hardening phenomena given by gold. The first analyses were performed on AS2 to define the parameters (voltage = 210 kV; current = 1 mA; focal spot size = 0.4 mm; exposure time = 200 ms; rotation angle = 200° frames = 800, voxel size = 125 µm). Due to some artifacts in the scans of AS2 near the ring, it was decided to scan the next sample AS3 by adding an additional 0.8 mm thick brass filter. In this case, temperatures were also monitored.

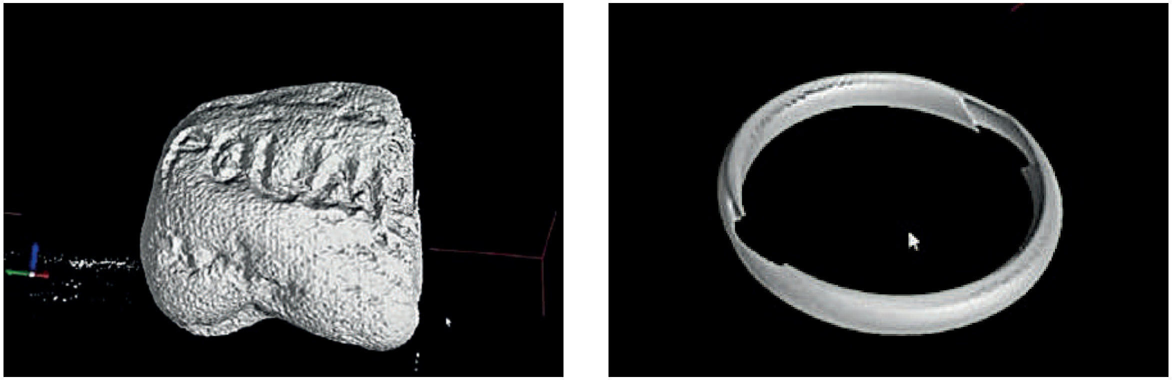


Fig. 2 Detail of the flint and wedding ring contained in AS2.

Fig. 3 Detail of the high-density parts and of the ring contained in AS3.

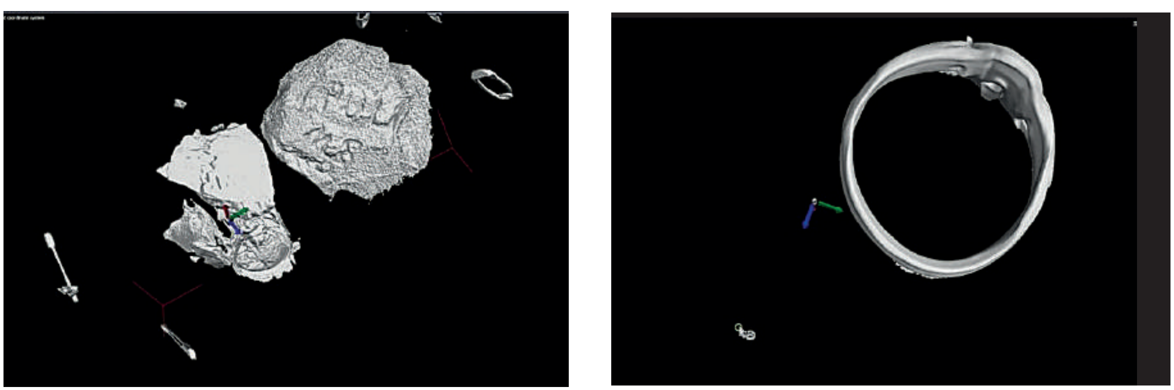


Fig. 4 Detail of the high-density parts and of the ring contained in AS1.

Results were verified by a second scan of AS2, but increasing the current to 1.6 mA, in order to increase the overall power of the system. To conclude, the last scan was performed on sample AS1 to measure the absorbed dose. The current was increased to 2 mA (close to the source limit) in order to verify the absorbed dose in a borderline scenario.

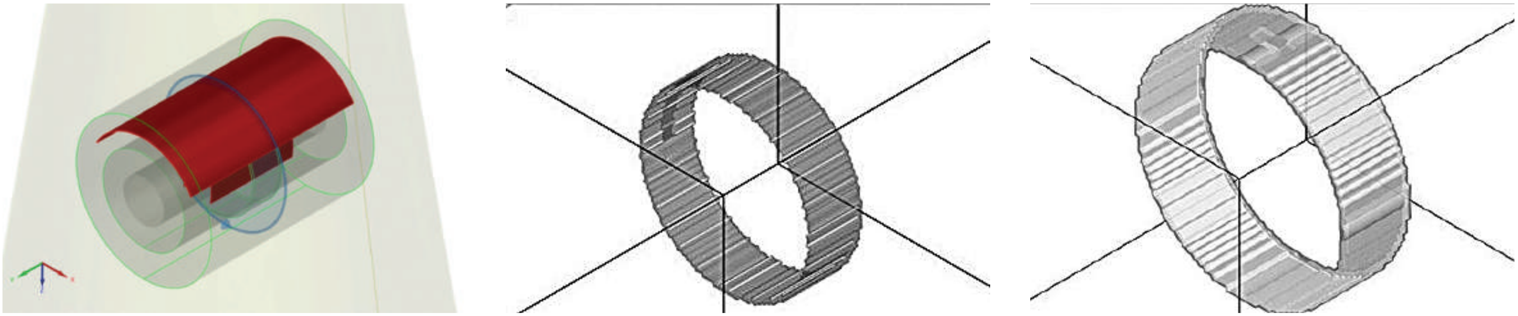
3. Results of the Scans

From the reconstruction of the first scan of AS2, it was possible to notice that the stone objects with their engravings were clearly visible without any artifact (Fig. 2). Interesting is the fact that by reducing the viewing grayscale window, it was possible to observe the flint disappear, leaving its internal iron veins. It means that, with this tomograph, it will be possible to obtain information not only about the shape, but also about the internal structure of the artifacts. Regarding the ring (Fig. 2), it was characterized by some metal artifacts that were reduced by iterative reconstruction techniques, resulting in a model of good quality, at least in terms of shape. That is why a second filter was applied to the scan of AS3 providing an immediate result. In fact, a significant reduction in artifacts was observed (Fig. 3). The stone is perfectly detailed without artifacts, like the thermocouples used for temperature monitoring and an Allen key used as position reference. Moreover, the complex shape of the ring is well distinguishable even without a metal artifact cleaning process. The last tomographic scan was performed on AS1 to measure the absorbed dose. In fact, the TLDs are clearly visible in the slices. In addition, the good rendering of the stone and steel pieces can be observed from the reconstruction. Regarding the ring, it was initially difficult to be identified (Fig. 4). However, this is not mainly due to metal artifacts, but rather to the large amount of limestone fragments surrounding the ring itself. In fact, during the creation of the holes for the TLDs placement, the limestone was shattered, and the fragments deposited on the ring itself. In fact, by further narrowing the grayscale window, the ring emerged from the debris showing its complex shape.

Regarding the safety of the archaeological artifact, from the scans of both AS3 and AS2, no significant temperature variations were detected. So, it can be said that these scans are not capable of generating X-ray induced heating phenomena and thus significant thermal damage to the mummy. Absorbed dose values measured from the scan of AS1 resulted to be in the order of magnitude of a hundred μGy and lower than the limit of 200 Gy. Moreover, values provided by the TLDs appear to be coherent with the ones of the medical field and lower than the national exposure limits, confirming the absence of significant damage to DNA molecules.

4. Digital Simulations by CIVAnde software package

The last part of the work involved the digital simulation of the tomographic scan of a portion of the arm of the mummy of Kha, including its gold bracelet. In particular, a 3D model reproducing bone, flesh, linen bandages and the jewelry was created including some air defects to act as a reference in the reconstruction (Fig. 5a). Starting with the experimental parameters (Fig. 5b), a series of simulations were then carried out using CIVAnde software. By keeping the same instrument of the test, improvements were achieved by increasing the exposure time and number of frames. In fact, a longer exposure time allows a reduction in artifacts in a manner similar to a major increase in current and a greater rotation of the source-detector group (i.e., a greater number of acquisitions) allows for an overall greater definition of the digital model. In this way, the gold bracelet was reconstructed with a good level of detail



a b c

Fig. 5 (a) 3D model of the arm; (b) Reconstruction of the bracelet with the test parameters; (c) Reconstruction of the bracelet with increased exposure time and number of acquisitions.

without showing artifacts and displaying the air defect located inside it with good definition (Fig. 5c).

5. Conclusions and Future Developments

The tests performed confirmed the effectiveness of the tomographic system used, making important steps forward compared to the classical axial tomographic scans performed so far on mummies with medical equipment. However, simulations performed by the CIVAnde software suggested that further improvements are possible and that more acquisitions (360° rotation of the source-detector group) and a longer exposure time (two times longer per acquisition than in the test) can lead to better overall quality. Moreover, the results obtained provided promising indications regarding the internal and external temperature variations and the absorbed dose profile, confirming the safety of the archaeological find during such analysis.

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Diagnostic campaign to assess the seismic vulnerability of the Castello Scaligero of Sirmione in Italy

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Abstract

Performing a reliable assessment of existing buildings is an unavoidable premise to design an effective intervention respecting the construction's historical and material values. Such an assessment is based on a deep knowledge of constructive phases, historical interventions, adopted techniques, the materials used at different stages, the structural behaviour, and the state of damage. The acquisition of this information requires a multidisciplinary approach including historical research, geometrical survey, visual inspection, crack pattern survey, static and dynamic monitoring, and on-site investigation techniques, i.e., Minor Destructive Tests (MDTs) and Non-Destructive Tests (NDTs), to define input parameters to numerical analyses. With a conservative approach aiming at the preservation of the manufact, it is preferable to use NDTs to collect information on the construction.

The Castello Scaligero of Sirmione was built in the second half of the 14th century on Lake Garda at the entrance of the medieval village of Sirmione. It is also directly connected with the entrance of the fortified city which has its own gateway and its own bridge. An extensive structural diagnostic investigation was performed with the use of NDT, with the aim to evaluate the state of conservation of the castle in order to define its seismic vulnerability. To this purpose, a wide diagnostic campaign was performed on the masonry walls of the castle including analysis of historical documentation, visual inspection, horizontal core drilling, video endoscopy, single and parallel flat jacks test, penetrometric measurements of the strength of mortar and sonic test. Moreover, a static structural monitoring system was installed, by using access techniques through positioning with ropes, on the most alarming cracks. The outputs of the diagnostic campaign have been used to implement a reliable structural model aimed toward the evaluation of seismic vulnerability of the castle and to identify structural elements requiring specific attention and eventual strengthening interventions.

Keywords: non-destructive tests, minor destructive tests, diagnosis, vulnerability assessment, historical building, castles, masonry.

Introduction

The *Castello Scaligero of Sirmione* (Fig. 1) in Italy is an extraordinary and very complex example of lakeside fortification built by the *Della Scala*, a family who ruled Verona and a large part of the Venetian area from 1259 to 1387. The entrance to the fortress is a fortified corridor characterized by a ravelin with drawbridge. Two levels of walls with battlements and ravelin define three inner courtyards. The central courtyard is protected by three open-gorged towers at the corners and a 37-meter-high keep; alongside the northern wall there is a barrack. The wall-walks run around the four sides of the main courtyard, crossing the three corner towers. On the east side of the castle, the dock encloses a small part of the lake (Cane et al. 2020, L'Occaso 2018, Perbellini 1982). Nowadays, the castle is owned by Italian Ministry of Culture. In 2021 the *Direzione regionale Musei Lombardia* - the administration responsible for the building management - began a wide investigation and monitoring campaign. The aim, on the one hand, was to verify the seismic vulnerability of the whole complex and, on the other, to define a consolidation intervention on the southern ravelin to guarantee the safety of museum staff and tourists crossing the internal bridge. Since the need to achieve quantitative values for the numerical model implementation, both Non-Destructive Techniques (NDTs) - sonic tests, penetrometric tests on mortars, durometric tests, drilling tests on wooden structures - and Minor Destructive Techniques (MDT) - single flat jack, two parallel flat jacks, continuous coring, and video-endoscopy-have been carried out for the analysis of the structure.

Approach And Methods

The evaluation of the structural safety of existing masonry buildings is a crucial issue due to the stratification of many constructive stages during the ages (so-called architectural palimpsest). The assessment of seismic vulnerability implies the reduction of the structure complexity to an interpretative model in order to perform proper structural analysis allowing both a qualitative interpretation and a quantitative evaluation of the structural behavior of the building. The reliability of the numerical model strongly depends on the level of knowledge of the construction under investigation. The current Italian code (Circ. 21/01/2019) highlights that a complete structural knowledge of a building cannot be achieved; so it traces a «path of knowledge» that can be developed at different levels of depth, depending on the information achieved during the diagnostic phase. The path of knowledge considers the following activities (D.P.C.M. 09/02/2011): i) geometric survey; ii) identification of the historical and constructive specificities of the building; iii) mechanical properties of materials; iv) foundation system and soil. According to the accuracy of the results obtained from the mentioned activities, different Levels of Knowledge (LKs) of the parameters involved in the model are identified corresponding to specific Confidence Factor (CF). The latter is a safety coefficient varying from 1.00 to 1.35, which is used to reduce the material mechanical characteristics considered in the structural analysis.

Fig. 1 Sirmione Castle.

Investigated aspects	Relevant information	Used Techniques	Level of knowledge		CFk
Geometric survey	Complete geometric survey, including cracks and deformations patterns	Laser scanner survey provided by client Visual inspection	Complete	☐	0.05
			Complete with cracks and deformations pattern survey	X	0
Identification of the historical and constructive specificities of the building	Identification of construction phases and interpretation of the structural behavior based on: materials and construction details survey associated with the transformation events.	Visual inspection MDT and NDT: Continous coring, videoendoscopy, sonic tests, drilling	Hypothetical	☐	0.12
			Partial	X	0.06
			Complete	☐	0
Mechanical properties of materials	Material mechanical parameters	MDT and NDT: single flat jack test; parallel flats jacks tests, penetrometric tests on mortar joints, drilling tests, durometric tests	Not available specific information	☐	0.12
			Limited	X	0.06
			Extended	☐	0
Foundation system and soil	Tests on soil and foundations	Geological report Photographic survey by underwater operators MDT and NDT: continous coring	Not available specific information	☐	0.06
			Limited	X	0.03
			Extended or exhaustive	☐	0

Fig. 2 Investigated knowledge aspects and partial safety factors.

With regards to the case history, an accurate diagnostic campaign has been performed. Such a campaign included analysis of historical documents, visual inspection of the overall architecture to detect cracks, a deformations patterns' survey and constructive discontinuities, survey of constructive details and state of conservation of materials and structures, mechanical characterization of materials. In Fig. 2 the achieved information is summarized, matching the level of knowledge accomplished for each investigated aspect to the corresponding partial CFk. A global CF of 1.15 resulted. The gathered information has been used to implement a structural model able to represent the real construction with a high level of precision and consequently it allowed to perform a reliable vulnerability assessment of the construction.

On site results

A 3D laser scanner geometric survey has allowed us to comprehend the geometry of the building with a high level of precision, that is essential to set an adequate knowledge path.

The subsequent analysis of the documentation available in the historical archives of the *Direzione regionale Musei Lombardia and Soprintendenza Archeologia, Belle Arti e Paesaggio* of *Brescia* has provided fundamental information on the construction and it has allowed the identification of specific aspects of the castle to better address in diagnostic activities.

A detailed visual inspection of the whole construction has been carried out with the purposes of identifying the different masonry typologies, the level of connection between adjacent walls, constructive discontinuities, material decay, and the crack and deformation pattern. Based on the achieved information, a static structural monitoring system has been installed on the most relevant cracks. A report has been consequently drafted according to a standardized layout devised by the authors within an European research project.

Five masonry types have been observed. The most recurring one is made of limestone ashlars regularly arranged, spaced out at intervals of every 1.5 m by two courses of bricks (the so called «*muratura listata*»). This masonry type characterizes defensive walls, keep, and open-gorged towers. The corners of the secondary towers are made of masonry bricks having a "sawtooth shape" that is joined to the previously mentioned brick' courses and provide a connection with the adjacent stone masonry due to its shape. This construction technique, the absence of connection between masonries of defensive walls and the adjacent towers and the open-gorged towers are typical features of the *Della Scala* architecture (Fig. 3). It adopts a logic based on defensive reasons and strongly influences the structural behavior of the construction.

With the purpose to identify material, geometry and constructive technique of the foundation system, underwater operators have performed a photographic survey. The obtained information has been integrated with those achieved from continuous coring on foundation masonries and hole prospecting by video-endoscopy.

Fig. 3 Comparison between keep and open-gorged towers of a) Sirmione castle and b) Ponti sul Mincio.

Foundations are set on clay soil. Two masonry bases have been recognized: i) regular arrangement of large, squared ashlars homogeneous along the whole wall depth characterizing most of the castle' structures; ii) irregular arrangement of smaller ashlars for the dock walls. Notwithstanding the construction practice of these structural elements in this area, wooden poles have not been observed, but their presence cannot be definitively excluded. Indeed, with the purpose of validating results, the above mentioned achievements were compared with those observed in a similar construction site. More specifically, the authors have recently handled a retrofitting intervention on the historical gateway bridge to the *Sirmione* town that it is coeval to castle and was formerly part of its defensive system. Here wooden poles can be clearly recognized under the plane of the foundation system. Since the analogies existing between the two buildings, it is reasonable to assume that a similar condition can be found in *Castello Scaligero* as well.

The mechanical characterization of masonry has been carried out by single flat jack (ASTM C 1196-09, 2009) and two parallel flat jacks (ASTM C 1197-09, 2009) which allow us to measure the state of local stress and to determine the characteristics of deformability of a representative structural sample of masonry respectively. In order to associate flat jacks results to specific masonry cross-section characteristics, continuous coring and video-endoscopy have been performed at the same location as well. The results have been further extended by non-destructive tests (e.g. sonic and penetrometric tests on mortar joints).

A specific visual inspection integrated by manual tools (awl and hammer) has been conducted on the wooden floors of the donjon according to UNI 11119:2004 to assess the state of conservation of the structural elements and to detect cracks, fissures, torsions, wood rot and holes of xylophgous insect attacks. The estimation of the decay extension and the investigation of parts of elements that cannot be directly observed through visual inspection (such as the heads of the walled-up beams) have been performed by drilling tests (Resistograph).

A detailed investigation has been conducted also on the wooden and metallic structures of the ravelin, where a retrofitting intervention based on the obtained results has been consequently designed and implemented. In this part of the building most of the activities have been carried out by access and positioning techniques through ropes to allow the close-up view of the structural elements particularly at critical points. After a preliminary visual inspection, to characterize materials properties and evaluate the state of conservation, drilling tests and durometric tests have been performed on wooden and metallic structures respectively.

Vulnerability assessment

The structural vulnerability assessment with respect to the seismic load combinations was carried out in compliance with the current Italian Building Codes (D.M. 17/1/2018, 2018). Based on geometric survey, a structural model of the construction has been implemented. The results of the diagnostic campaign have been integrated into the model by associating to each model unit specific mechanical properties, dimensions (which do not necessarily correspond to those of the actual elements, i.e. where constructive discontinuities or cracks occur), and reciprocal connections among structural elements (Fig. 4a). For example, the open-gorged towers have been modeled by defining two different materials for the corner and the central part of the walls and considering the interaction between them in the out-of-plane mechanisms.

The structural analysis has been carried out according to both static and the seismic conditions, also performing the analysis of the out of plane behavior of the macro-elements in compliance with D.P.C.M. 09/02/2011.The static and the seismic vulnerability have been analyzed on the global structure. Furthermore, a macro-elements local analysis has been performed by a 3D model taking into consideration the out of plan interaction between the different structural elements. The structural safety assessment in the static filed was satisfied; the seismic vulnerability assessment analyses allowed identifying the most critical conditions.

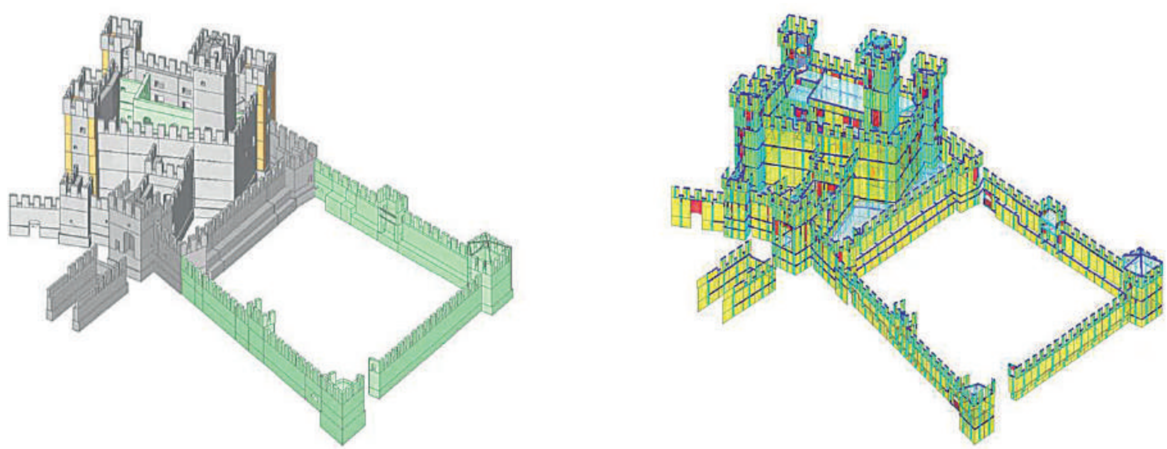

Fig. 4 a) 3D model with volumes and masses implemented by differentiating the masonry types (different colors), b) Equivalent Frame model.

Conclusion

The case history highlights that the Seismic Vulnerability Assessment of existing buildings does not require only tests on materials and structures, but an interdisciplinary and multidisciplinary approach. Such an approach should be pursued based on a wider path of knowledge that involves collecting in-depth historical and geometrical information. In this perspective NDTs have a fundamental importance because they allow to expand the information about constructive details and material properties and to reach, in a non-destructive and cost-effective way, a high level of knowledge. Moreover, the comparison with case studies showing significant analogies is a very important analytical tool because it allows us to deduce historical constructive practices that can help us better understand the structural behavior of the investigated construction.

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Notes

[1] CHANGES (Changes in cultural Heritage Activities: New Goals and Benefits for Economy and Society), project co-financed by European Union in partnership with *Politecnico* di *Milano* (IT), University of Leuven (BE), Deft (NL) e Uppsala (SE).

Non-invasive and micro-invasive investigations applied to large paintings. The case of the frescoed ceiling by Anton Raphael Mengs in Sant'Eusebio in Rome

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Abstract

Non-invasive and micro-invasive investigations have now reached a very pronounced maturity in the field of diagnostics on Cultural Heritage. Furthermore, the applications of non-invasive and micro-invasive investigations are now considered indispensable in studying and conservating works of art.

Over the last few years, a SOP (Standard Operating Procedure) has been developed, which links the various non-invasive investigations with micro-invasive investigations to optimize the analysis operations by maximizing the results and minimizing the economic costs.

The level of maturity and stability that the SOP has now acquired, explicitly developed for diagnostic investigations on Cultural Heritage, also allows this procedure to be applied in complex cases such as large painted surfaces.

Diagnostic investigations on large painted surfaces have the main problem of maintaining an acceptable quality of the results while not requiring excessive economic and time resources. An important case study to understand the pro and cons of non-invasive and micro-invasive diagnostic techniques on large paintings is the diagnostic campaign carried out on the occasion of the restoration of the 50 square meters frescoed ceiling by Anton Raphael Mengs in the church of San Eusebio in Rome on which multispectral imaging, X-ray spectroscopy, and instrumental stratigraphic investigations were applied on the entire surface of the fresco.

Keywords: mural paintings , Anton Raphael Mengs, NDT, cultural heritage.

Fig. 1 UV Fluorescence, detail of Saint Eusebio, sketch of Mengs defining shades.

Between the end of 2018 and the first months of 2019, the ceiling of the central nave of the church of Sant'Eusebio in Rome, painted in 1757 by Anton Raphael Mengs (Aussig, 1728 - Rome, 1779) for the Celestini fathers, underwent an essential diagnostic campaign and an accurate restoration intervention, financed and directed by the Soprintendenza Speciale di Roma. The intervention arose from a concrete need to protect and safeguard the valuable mural painting representing the Glory of Sant'Eusebio, which appeared very degraded and almost illegible due to the widespread saline efflorescences that covered the entire colored surface that was strongly impoverished due to previous unsupervised restorations.

The restoration has thus made it possible to focus on a little-known work by Mengs, not only deepening knowledge of it from a historical-artistic and technical-executive point of view but also reconstructing its history of conservation. The Glory of Saint Eusebius is the first mural painted by Mengs in his artistic career and the first significant "public" commission received in the papal capital, which marks his debut as a foreigner as he was on the Roman scene. Only three years later, thanks to the success achieved in Sant'Eusebio, the Bohemian painter cre-

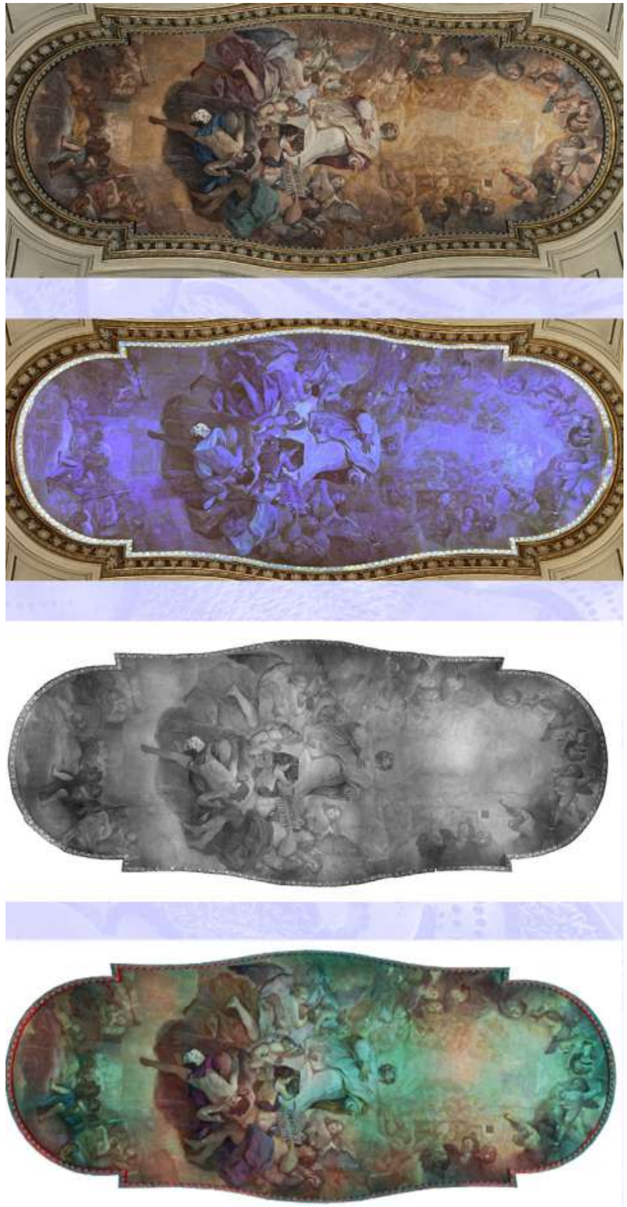

Fig. 2 Multispectral imaging, global view of the different analyses.

ated the famous Parnassus in the gallery of Villa Albani, considered the manifesto of neoclassical art.

The painted surface is 9,60 X 5 square meters and is painted on the ceiling 16 meters high. The painted ceiling is located in the church of Saint'Eusebio in Rome. The church is recalled being build before 471 C.A. and Anton Raphael Mengs painted the ceiling during major restoration works on the XVIII century.

The preliminary scientific investigations that were fulfilled on the painting aimed to support the imminent restoration work and obtain information on the mural painting's conservation history and executive technique.

The following analyzes were carried out:

Multispectral Imaging, among which:

- observation of Ultraviolet Fluorescence using Wood's Light (UV) to examine, as a first approximation, the nature of the more superficial materials and the localization of pictorial retouches;
- examination through Infrared Reflectography (IR) and False Color (IR-FC) to study the pictorial techniques, identify the possible presence of preparatory drawings, second thoughts, and retouches and make initial discrimination between the pigments used on the work of art.

Point Ppectroscopy among which:

- analysis by mobile XRF Spectrometer (EDX-RF) and Raman for defining the pigments in the pictorial palette and execution techniques.

At the end of the non-invasive campaign, three micro-samples were analyzed to chemically characterize some materials present in the work and detected by non-invasive investigations.

The multispectral imaging covered the entire surface of the mural painting. Almost 50 square meters.

As an example we report the extremely interesting results achieved with the UV Fluorescence technique. With this technique it was possible to determine the portions of the restoration and also to obtain information regarding the executive technique of the painter. In Figure 1 we show the characteristic response of UV Fluorescence to the sketch Mengs used to define shades and deepness in the mural painting.

Figure 2 shows the global images of the different imaging techniques.

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Glass-gems Exploration by Multidisciplinary Methods, Analyses and Experiments: the GEMMAE project

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Abstract

In Roman times, jewelry and glyptic objects could be manufactured starting from a variety of materials. In addition to gemstones, glass was also used, especially as imitation material.

To deepen the knowledge, conservation and valorization of museum collections of glass gems, we conceived the project GEMMAE: Glass-gems Exploration by Multidisciplinary Methods, Analyses and Experiments. Starting with an ongoing collaboration with the National Archaeological Museum in Aquileia, we designed a Particle Induced X-ray Emission/ Particle Induced Gamma-ray Emission (PIXE/PIGE) campaign, conducted for the first time on a significant set of samples (about one hundred), to determine their composition. Moreover, a campaign with the MOLAB (mobile laboratory, within the E-RIHS.it programme) has been carried out too, with the advantage of performing *in situ* spectroscopic investigations. Data analysis is still running, but first results testify the feasibility of a nondestructive approach for glass composition determination, and proves relevant to other glass-gems museum collections studies.

We emphasize that such a protocol could be considered an example of best practice and easy applicability to similar collections, since the large number of samples allows for statistically significant results to support provenance and dating studies.

Keywords: glass-gem, non-destructive techniques, particle induced X-ray emission (PIXE), particle induced gamma-ray emission (PIGE) .

Introduction

Artistic glassmaking has ancient origins: glassmakers of different historical periods and places used different raw materials and manufacturing techniques. From ancient times, glass was produced for a variety of uses and some peculiar examples are for example on exhibit at the British Museum [1]. Generally, glass classification follows elemental composition as for major (for example silica), minor (for example soda, ashes or potash) and trace components (for example B, F, Ti, Fe, but also Sb, Sn and Pb elements). Glasses were produced also for imitation purposes, for example in gemology [2]. In fact, ancient glass makers were also looking for new compositions to obtain glass of different colors and shades, which sometimes imitated natural gems and stones used in jewelry: opaque glasses could be obtained (and tuned) by means of the careful insertion of some elements, likely forming microcrystalline phases (as calcium or lead antimonate), while the coloration of glass is the result of complex interactions between structural and chemical effects. In particular, the presence and the relative concentration of transition metals play a fundamental role, acting as chromophores in the glass base matrix. The whole composition of the specimens thus reflects the progress reached by the manufacturers' workshop and it can be used as an archaeological marker of production times and geographical area of provenance. Roman glass makers skillfully achieved the control over colour, mixing colourizers and decolourizers [3]. Some examples come from the National Archaeological Museum of Aquileia (Italy) [4-5], the collection of which comprises more than 1300 glass-gems, dating from the 2nd century BCE to the 3rd century CE. Such a rich collection, however, has not yet been in-depth analysed from a scientific point of view: in fact, the finding site is known (Aquileia itself), but for many of its masterpieces there remain unresolved questions and issues yet to be investigated.

Aquileia is one of the most important Roman sites in Northern Italy, declared a World Heritage Site (UNESCO) in 1998. The city was founded in 181 BCE in a strategic area, connecting the West to the East, the Mediterranean to the northern and eastern regions of ancient Europe. In the Roman period Aquileia was a thriving trading centre, and a cosmopolitan place of different peoples, languages and cultures. In this context, manufacturing activities developed: excellences were, in addition to gems and cameos, extremely refined artefacts in amber and glass. In such productions, the workshops of Aquileia played a leading role [6].

To deepen the knowledge, the conservation and the valorization of the glass-gems collections, starting with the National Archaeological Museum of Aquileia, we conceived a research project entitled "Glass-gems Exploration by Multidisciplinary Methods, Analyses and Experiments" (GEMMAE). The first step of the project concerned a Particle Induced X-ray Emission/Particle Induced Gamma-ray Emission (PIXE/PIGE) campaign designed and carried out for the first time on a significant set of samples, deriving glass specimens composition. These techniques were chosen since they are non-destructive, and this is a mandatory requirement when cultural heritage samples are studied. Moreover, these analyses do not involve any contact or any pre-treatment of the specimens. The only requirement is the shipping of the samples to the laboratory, since the measurements cannot be performed in situ.

Major, minor and trace elements have been detected, being very useful indicators for dating, provenance, and manufacturing issues. However, further analyses are needed to derive mineralogical phases too. For this reason a multidisciplinary suite of techniques has been conceived, thanks also to a MOLAB access granted to GEMMAE.

First results of this project [7-8] testify the feasibility of a non-destructive approach for the glass composition determination, a relevant issue for museum glass-gems collections in consideration of the large number of artefacts from the site of Roman Aquileia.

We stress that a similar protocol could be considered a best practice example and easily applicable to similar collections, since the large number of samples allows for a statistically significant result, supporting provenance and dating studies.

Materials and methods

During a preliminary campaign, carried out *in situ* at the National Archaeological Museum of Aquileia, a set of 105 samples has been carefully selected mainly by typological and glyptic features. These specimens were studied during a PIXE/PIGE analysis campaign. Most of the analysed glass-gems are dated to the Roman period (2nd century BCE-3rd century CE) and the specimens had not been characterized before by any scientific analyses.

Glass-gems have different colours and transparencies, and they can be at first divided in two main macro-groups, represented by:

- Single-colour glass-gems;
- Multilayered glass-gems (with layers of different colours).

Many glass-gems sub-families can also be defined, since single-colour glass-gems could show images in negative or in relief, and multi-layered gems could present two or more layers, and inlays of different materials too. We will not discuss further in this paper the iconographical and gemological details, since our present goal is related to the project itself.

The website of the National Archaeological Museum of Aquileia reports many examples of glass-gems [5].

Under microscope observation (hand-held digital microscope, 50x-100x enlargements), glass-gems displayed many surface defects and alterations. A very simple and gentle cleaning has been performed before the PIXE/PIGE campaign, avoiding any mechanical procedure. However, the presence of calcium sulphate was detected, probably due to the common practice of plaster cast replicas for the purpose of glyptic studies.

Ion beam PIXE/PIGE analyses were carried out at the NewAGLAE facility (Centre de Recherche et Restauration des Musées de France - C2RMF, Equipex ANR-10-EQPX-22), based in the Palais du Louvre in Paris (France). The set-up and the experiment details are described elsewhere [9]. These techniques are non-destructive, have been conducted in air, have a beam spot of 50 μm and the combination of X and gamma rays collect information from a bigger volume upper than 30 μm. Complementary techniques were used too, thanks to the MOLAB suite, mainly spectroscopic techniques, for the mineralogical phases discrimination.

First results and discussion

A large number of spectra has been acquired, and the data analysis is still running. PIXE results for glass

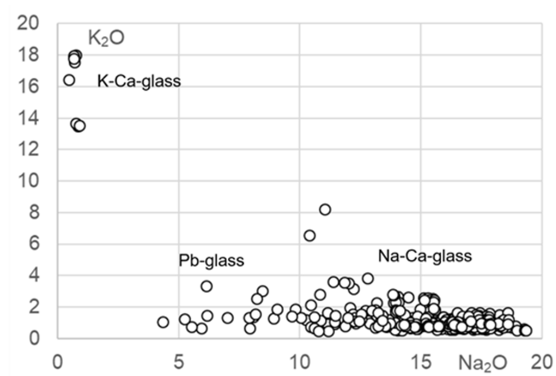

Fig. 1 Na_2O vs K_2O binary diagram, where main compositional groups are displayed composition were derived, after PIGE normalization (details on data treatment are available in [9]). Figure 1 displays a general overview of the results, correlating sodium and potassium oxide contents.

Main results and general issues are described in the following.

Most of the collection was made with natron (mineral flux). MgO and K_2O contents are less than 2 wt%. A good group of artifacts show slightly higher Mn and K contents than natron glass, and for these specimens the use of less controlled fluxes in purity and composition, such as mixed alkali fluxes, can be assumed.

CaO levels were detected between 3 and 16 wt%, thus indicating the use of the stabilizer within the glass formula. The lack of correlation between Ca and Sr and between Ca and Ma, suggests that no shells or dolomite were used as stabilizer: it is a pure limestone.

The contents of chromophore elements, as the elements referable to opacifiers, are strongly correlated with the color and with the opacity/transparency of the glass. However, PIXE/PIGE analyses return mainly the elemental composition. Thus, in order to have further insights (about mineralogical phases, or about the presence of different oxides) spectroscopic data are required, as the one collected by complementary spectroscopic techniques.

Conclusions

In Roman times, pieces of jewelry and glyptic items could be manufactured starting with different materials. Apart from gemstones, also glasses were used, mainly with the aim to imitate them. The glass composition has been derived by PIXE/PIGE analyses, though the presence of some alterations on a limited number of specimens, and first results were presented. The PIXE/PIGE technique was preferred for its high sensitivity down to trace elements, although XRF (especially on synchrotron radiation lines) can achieve similar values. The choice of AGLAE FIXLAB facility was twofold: (i) a detailed quantitative composition was required, for the goal of our project, and AGLAE facility allows the combined detection of major, minor and trace elements; (ii) non-destructive techniques were mandatory for the study of items from the collection preserved in the National Archaeological Museum of Aquileia. Both conditions were satisfied in this project, and this testifies its feasibility. The entire collection can be described as composed by soda-lime-silica glass (see Figure 1). Only three artifacts belong to the compositional group of K-Ca-Si glass: a rod of opaque white glass and two monochrome gems one dark blue, and one of colorless glass. Other spectroscopic data were collected by MOLAB and they will be part of further in-depth analyses, as well as comparison with the literature (see for example [10]).

Our study is an excellent example of best practice that can be exported to the study of other museum collections, to learn about, conserve and valorize cultural heritage, from a truly interdisciplinary Heritage Science perspective. We highlight that only a similar case study was found in the literature [11]. Finally, we outline that GEMMAE project embraces some of the goals of the UN 2030 agenda too.

Acknowledgments

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Non-invasive and micro-invasive investigations on Cultural Heritage to support the modern training of restorers. The case of the Scientific Laboratories of the Istituto Restauro Roma

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Abstract

Non-invasive and micro-invasive investigations on Cultural Heritage have become fundamental for optimizing the phases of restoration of works of art. For the diagnostic campaigns to be effective, a close collaboration is necessary between the diagnostic scientist who carries out the investigations and the restorers who need the scientific results. The ability to share a common lexicon and basic scientific knowledge between scientists and restorers is crucial in modern restorers. These skills allow for a fluid and effective dialogue between the different parties. For this to happen, the scientific curricular courses of the master's degree courses of modern restorers and the institutional didactic laboratories that allow the operational application of theoretical studies are of great importance.

Indeed, the scientific laboratories of the Istituto Restauro Roma carry out their educational and operational tasks in the didactic workshops where, directly in the cases of interest, the training of the future restorers takes place. Physicists, chemists, and biologists work together with students to scientifically represent the conservation issues that educational restoration yards have to face.

In this presentation, we show some cases in which non-invasive and micro-invasive physical, chemical, and biological investigations have been of help for the training of future restorers.

Keywords: NDT, restorer students, scientific analyses.

The restorer's job is highly delicate as he intervenes on very precious objects on which it is impossible to make mistakes.

Nowadays, the training path of a restorer is at the university level with a 5-year course with 300 training credits.

Of these, 54 are devoted to technical subjects such as chemistry, physics, materials science, and information technology.

The importance given to technical studies for restorers is very high as 30 training credits are provided in the first two years of the 5-year course.

It is also necessary to remember the curriculum of a typical student who begins to study restoration; most of the students come from art high schools, and only a few of them come from scientific high schools and, therefore, most of the students who begin their studies in restoration have a low preparation in the scientific fields.

It is then necessary that the scientific teachings are given in an intelligible form to the young students and this teaching must be directed to their future professional needs.

Restoration is a very practical professional application; it is, therefore, essential that the scientific teaching model that is given to these future restorers reflects this purpose.

The scientific laboratories of the University Institute of Restoration IRR (Istituto Restauro Roma) try to adapt precisely to this situation by providing the students with theoretical lessons but also with practical training experiences.

Regarding scientific work in laboratories, much emphasis is placed on making students try out the most straightforward and direct operations and learning with a try and fail method that seems the best one to increase and speed up the learning curve.

And more specifically when we talk about chemistry applied to Cultural Heritage and polychrome surfaces specifically developed laboratory activities allow a better understanding of the dissolution processes (whether physical, chemical-physical, or purely chemical) at the basis of cleaning, that is one of the most important operation a restorer must learn. By becoming familiar with the basic scientific instruments, the young restorers then learn to distinguish solvents into classes according to their mode of action: neutral ones, dipolar aprotic ones, acid or alkaline ones, and water. Solvents are also characterized in terms of density, volatility, and viscosity.

The experiments carried out are numerous and include, among others: the determination of the density of liquids and metallic specimens, creation of heating curves, extraction with solvents, methods of separation of mixtures, chromatography, chemical

Fig. 1 Students applying NDT techniques on paintings.

transformations, and physical transformations, energetic aspects of the reactions chemical reactions, conservation of mass in chemical reactions, solubility tests of substances as the temperature varies, evaluation of polarity and miscibility of liquids, solubility tests of solids in liquids, preparation of solutions of known strength, reactions between ions in solution, evaluation of reaction kinetics and influencing factors, properties of acids and bases, pH measurement with indicator papers, pH measurement with a pH meter, titrations, evaluation of the strength of acids and bases, redox reactions.

At the other side, if we speak more directly of NDT on Cultural Heritage and polychrome surfaces, the most useful investigations for students to learn are the multispectral imaging and the spot spectroscopies.

With this type of investigation, completely non-invasive, it is possible to support the work of restorers.

We show a specific case of didactic restoration carried out on the painting "La Pietà" from the church of San Gregorio dei Muratori in Rome.

All the portable non-invasive investigations applicable to paintings on canvas, such as UV Fluorescence, Infrared Reflectography, false colors, X-ray Fluores-

Fig. 2 The painting "La Pietà", before restoration.

Fig. 3 The painting "La Pietà", after restoration.

cence, and Raman spectroscopy, were carried out on this painting directly in the church with the presence of the students.

In the next images are shown the students during the experience, the painting before and after the restoration and the NDT diagnostic results so useful to the job.

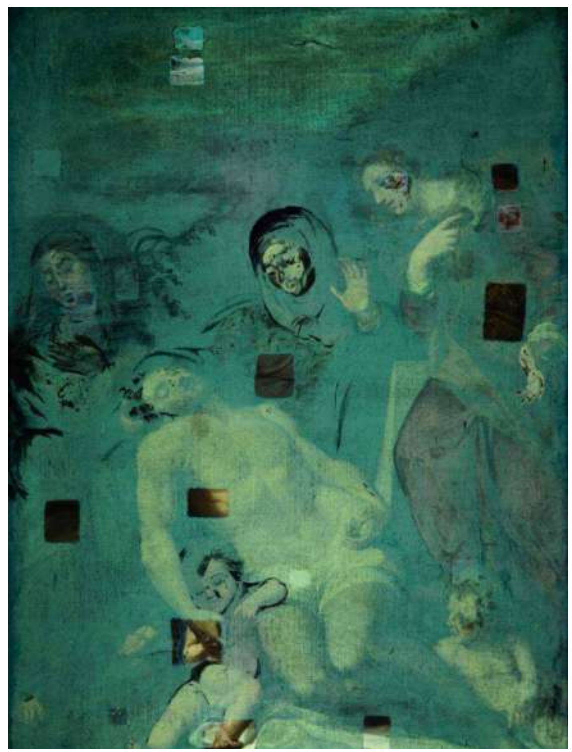

Fig. 4 The painting "La Pietà", detail of X Radiography on repainting.

Fig. 5 The painting "La Pietà", UV Fluorescence.

From historic wind instruments to modern copies to rediscover ancient sounds

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Abstract

All musical instruments, from ancient times till today, are firstly created with the aim of being played, emitting a beautiful sound, communicating, and entertaining with the music produced through them. Secondly, they are further appreciated for the elements that make them highly valuable artistic objects. To preserve and transmit the material characteristics of such objects, their sounds are often lost. In fact, the use of woodwind instruments is particularly problematic, as, during the execution, there are considerable changes in humidity and temperature inside the barrel of the instrument with consequent risks in terms of conservation.

X-ray CT is already a powerful imaging technique, widely used to study internal structures and characteristics of different types of objects in a lot of fields of application, from medicine to industry and material science. Over the years it has also acquired more and more importance in the field of Cultural Heritage, being a non-invasive analysis technique. Thanks to CT analysis, it is possible to obtain information regarding, for example, the construction techniques and the state of conservation of the artistic artefact.

The first steps of this work were carried out by analysing three wind instruments, two from the late Eighteenth Century and one from the late Twentieth Century. The first one is a piccolo flute whose manufacturer is unknown, though some features could suggest an English or American origin. The second musical instrument is a baroque transverse flute, probably produced by Lorenzo Cerino, an Italian instrument maker active in Turin (Italy) in the late Eighteenth Century [1]. The third instrument is a copy of a Renaissance recorder, made by the luthier Canevari, in the 1970s, probably inspired by originals found in the museums of Bologna.

Keywords: cultural heritage, state of conservation, woodwind instruments, flute, computed tomography.

Introduction

In museum collections, one can find a multitude of historic musical instruments that were crafted not only as mere artifacts, but as functional entities designed to fascinate, communicate, and entertain. Museums have the task of preserving and handing down the material and immaterial qualities of these instruments.

However, among the various types of musical instruments, woodwind instruments pose a particular challenge. This is primarily due to the moisture generated by the musician's breath during their performance, which subsequently permeates the instrument itself. Fluctuations in humidity and temperature within the instrument's barrel can give rise to conservation risks, as they significantly heighten the likelihood of cracks forming and the wood warping. As a result of these problems, most museums do not allow historical wind instruments to be played, which otherwise could undergo irreversible damage and permanent distortions, altering their sound irreparably. In this conservation policy there is an inherent contradiction: to preserve the original sound, these instruments are made silent, depriving them of their musical significance.

New opportunities to reproduce historical wind instruments and to restore their forgotten sound, giving voice to these instruments again, are offered using non-invasive analytical techniques and digital technologies for measurement and subsequent modeling.

X-ray Computed Tomography (CT) scanning has proven to be an effective analytical technique for examining the internal structure of various cultural heritage objects. However, when it comes to studying musical instruments, the intricate shapes, diverse materials, and larger sizes pose additional challenges in obtaining high-quality CT scans. Previous projects, primarily aimed for assessing the instruments' conservation status or exploring their internal structure, have addressed the acquisition of CT scans for musical instruments yet and have published detailed technical guidelines [2]. Nevertheless, when the goal of tomography is to extract precise digital geometric models for the creation of acoustically accurate replicas, it becomes necessary to establish additional metrological and practical specifications.

Computed tomography, jointly to modern Selective Laser Sintering (SLS) 3D printers, can help to preserve even the sound of the most fragile musical instruments, guaranteeing the physical integrity of the originals. Through this project, it could be also possible to plan a

Fig. 1 Soprano flute in C, copy of a Renaissance recorder by Fulvio Canevari (~1970). (b) Detail of the cedar block.

virtual restoration, consisting in the creation of digitally restored copies with a 3D printer, allowing to recover the sound of damaged instruments, no longer able to emit a beautiful sound.

Materials and Methods

The instrument on which the subsequent observations will focus is a copy of a Renaissance recorder, made by the craftsman Fulvio Canevari in the 1970s, probably inspired by originals found in the museums of Bologna. It is a soprano flute in C, with a frequency for A equal to 440 Hz. This flute consists of several components: headjoint, body, a block inserted in the headjoint. The first two sections are made of boxwood with an ivory ring to reinforce the back hole of the body. They are joined by a brass ring, on which two waxed thread tenons are inserted. Since the wire is modern and not original, it was removed before the tomography was done. The block, in the other hand, is made of cedar wood.

The tomographic analysis took place within a specially equipped X-ray measurement laboratory at the Physics Department of the University of Turin. To conduct the analysis, a specifically created instrumental setup was utilized, employing components that had previously been employed for other applications [1].

The X-ray source employed was the Hamamatsu Microfocus L8121-03. The rotating platform, with a diameter of approximately 20 cm, provided a stable base for positioning the object being analyzed. This setup enabled the acquisition of multi-angle images, enhancing the tomographic reconstruction process. For detection purposes, the Flat Panel (FP) Shad-o-Box 6K HS detector, manufactured by Teledyne Dalsa, was utilized. This detector featured a single pixel size of 49.5 µm and a 14-bit analog-to-digital converter (A/D), already used for high-resolution CT of other wooden materials [3]. To ensure precise alignment with the X-ray source, the detector was installed on a mechanical XY scanning system. This scanning system allowed for optimal positioning of the detector in relation to the X-ray source, enhancing the accuracy and quality of the acquired tomographic data. The main characteristic of both the X-ray source and the flat panel detector are summarized in Table 1.

To scan larger areas beyond the sensitive area of the detector ($11.4 \times 14.6\ cm^2$), a tile-scan approach was employed, which involved acquiring images in different positions by either moving the object or the detector

Shad-O-Box 6K HS Flat Panel Detector		**Hamamatsu Microfocus L8121-03 X-ray Source**	
Pixel number	2304 × 2940	Target	Tungsten
Active area	$11.4 \times 14.6\ cm^2$	Voltage	40-150 kV
Pixel size	49.5 µm	Max Current	500 µA
A/D converter	14 bit	Max Power	75 W
Energy range	15-225 keV	Focal Spot	Small ≈ 7 µm Medium ≈ 20 µm Large ≈ 50 µm
Scintillator	CsI	Beam angle	43°
Data transfer	Gigabit Ethernet	Exit window	Be, 200 µm

Tab. 1 Technical specifications of the equipment used.

itself. During this work, in cases where the vertical extent of the object exceeded the range of a single scan, the data acquisition was divided into multiple scans, with the object being moved vertically between scans. To ensure the seamless merging of the reconstructed volumes and to prevent any loss of information, the scans were carefully executed with overlapping regions. It was crucial for these overlapping regions to contain identifiable reference points that would facilitate the subsequent alignment of the individual parts. If the object under analysis did not possess suitable reference points, appropriate markers were introduced to enable the alignment of the different scans [4]. Unlike previous works, the instruments analyzed in this study were disassembled for CT analysis. This disassembly included the removal of brass elements to avoid metal artifacts during the reconstruction. Disassembling the instruments is useful for segmentation processes, facilitating the extraction of finer details from all parts of the instruments. An overview of the main experimental parameters involved in the CT analysis are provided in Table 2.

Renaissance recorder	
Dimension of the object	Length ≈ 327 mm
	Diameter ≈ 30 mm
Material	Boxwood, ivory
X-ray tube voltage	90 kV
X-ray tube current	500 µA
X-ray filter	Al (2 mm)
Focal spot size	L (50 µm)
Source-Detector distance (SDD)	1400 mm ± 2 mm
Source-Object distance (SOD)	1300 mm ± 2 mm
Object-Detector distance (ODD)	100 mm ± 2 mm
Angular step	0.25°
Integration time	4 s
Scan phases (portions)	2

Tab. 2 Experimental CT conditions.

Results and Discussion

Through the conducted analyses, valuable qualitative insights into the condition of the examined samples were obtained. The use of computed tomography revealed the presence of several characteristics, including:

- fractures within the structure of the samples, indicating potential weaknesses;
- cracks, associated with wood knots, which could affect the integrity and functionality of the analyzed objects;
- areas with higher radiopacity, linked to high density material inclusions;
- addition of wax shims along the edges of the flute's holes. These additions were interpreted as intentional modifications made by the flute maker to fine-tune the instrument's intonation. Consequently, they are considered integral to the flute's original design.

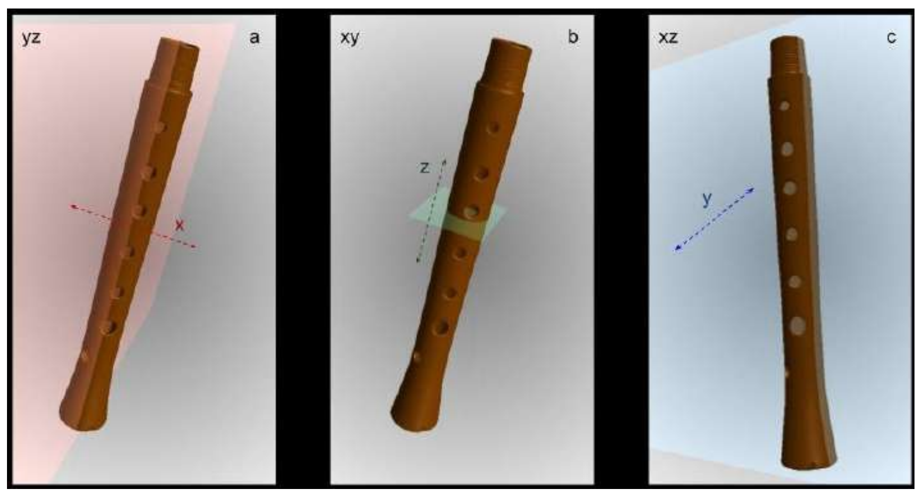

Fig. 2 Schematic representation of the three CT reconstructed slices direction: (a) sagittal section corresponds to yz plane along x direction; (b) transversal section corresponds to xy plane along z axis; (c) longitudinal section corresponds to xz plane along y direction.

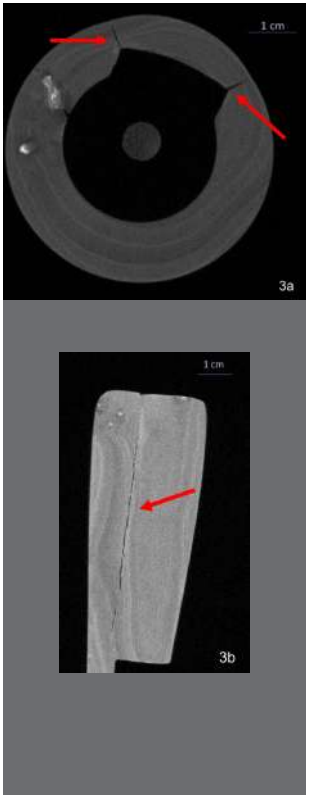

Fig. 3 CT transversal (a) and longitudinal (b) slices of the headjoint, in which is visible the fractures (red arrows).

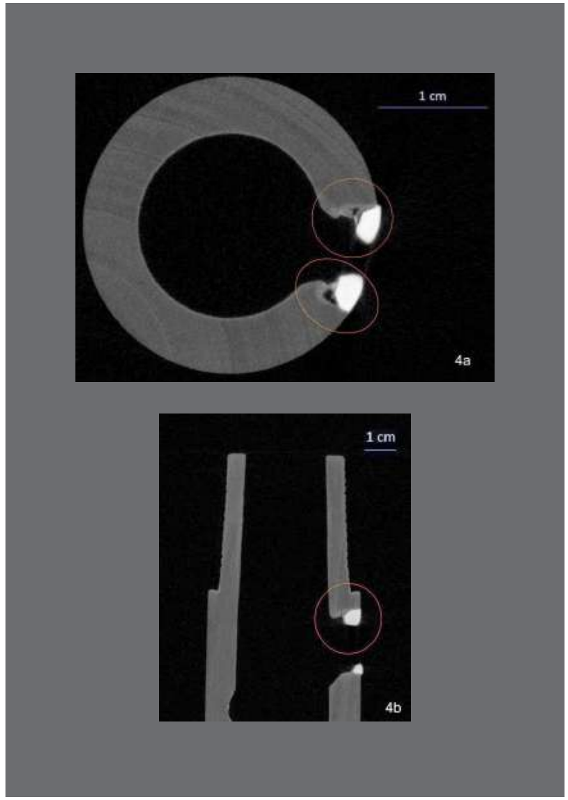

Fig. 4 CT transversal (a) and sagittal (b) slices of the upper zone of the body, in which it is possible to see the lack of material in the fixing ivory ring.

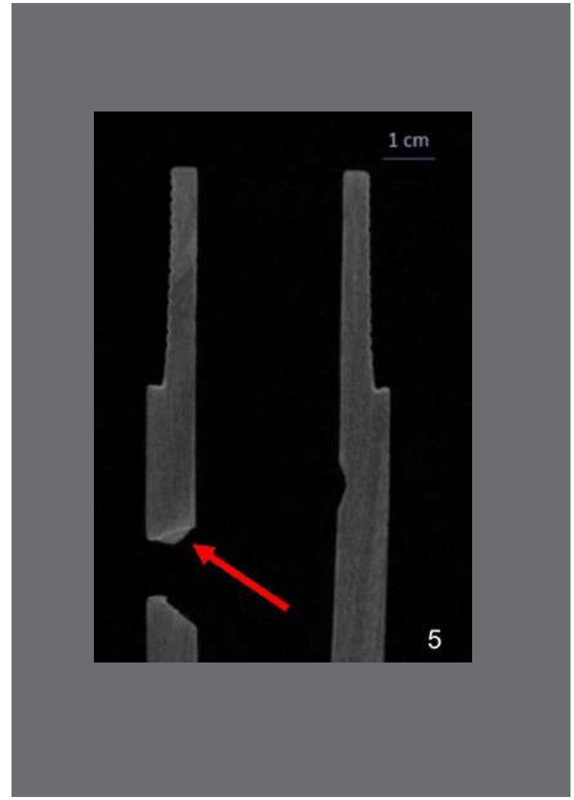

Fig. 5 CT sagittal slice of the body, in which it is possible to see wax layer (red arrow).

Figures 3 - 5 show the reconstructed CT sections of the examined instrument, relating to the observations made during the analysis. To improve visual clarity, Figure 2 illustrates the three spatial directions of the reconstructed tomographic slices, which will be referred to in subsequent figures.

The Recorder analyzed presents, in principle, a relatively good state of conservation, however some issues were observed.

Particular attention must be paid to the extensive fractures present in the head, which begin from the upper part of the head, where the block is inserted. They can be clearly seen from the reconstructed CT slices (Figure 3). Thanks to the longitudinal section, it is possible to see the extension of these fractures.

In addition, the lacks of material in the fixing the ivory ring of the back hole of the body, was observed in both the horizontal and sagittal sections (Figure 4a e 4b).

Finally, in correspondence to the edge of the holes, added wax shims, probably to adjust intonation, are clearly visible in the sagittal sections (Figure 5).

Conclusions

X-ray computed tomography (CT) has proven to be a valuable tool for non-destructive analysis of historical artifacts found in museums or private collections. In this study, our focus was on a specific category of artifacts: historical woodwind musical instruments, which were carefully examined using CT scanning. Musical instruments, in general, present fascinating opportunities for research as they provide insights into ancient manufacturing techniques and reveal the secrets of skilled craftsmen. Additionally, studying their conservation status is essential.

Woodwind instruments, due to conservation issues, can no longer be played, thereby depriving us of experiencing their original sounds. This project serves as a preliminary step towards a broader initiative aiming to analyse and create 3D digital models of these original instruments. This paper specifically focuses on the observations made regarding the conservation state of the analysed flutes. The evaluations allowed us to assess the presence of fractures, internal damage, and previous restoration interventions. This gathered information can also aid in determining the feasibility of future interventions on the original instruments.

Furthermore, the creation of a digital 3D model using CT scans opens possibilities for "virtual" restoration by digitally reproducing copies of the flutes using a 3D printer. As this study progresses, the next phase will involve the creation of "sounding" replicas of the original instruments, designed to be acoustically compatible and rigorously tested using appropriate analytical methods. Additionally, dimensional evaluations will be conducted on both the digital models and physical replicas to ensure compatibility and gain a more precise understanding of the entire protocol involved in this process.

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Advanced system for Frequency Resolved Acoustic Imaging for on-site investigations of Cultural Heritage: an example of public-private partnership (PPP) of centers of excellence

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Abstract

In the last two decades a new device, based on the acoustic energy absorption evaluation, was developed by the Laboratory of Acoustics Research applications for Cultural Heritage (LARCH) of the National Research Council. During the years, the original prototype was implemented with further technological innovations while a robust measuring procedure was elaborated. Laboratory tests and on-site investigations demonstrated the usefulness and suitability of the Frequency Resolved Acoustic Imaging diagnostics to reveal structural damage in art objects such as mural paintings, wall structures, glazed ceramic panels, and panel paintings.

Today, a stimulating public-private partnership between three relevant centers of excellence realized an advanced prototype presenting innovative technical solutions, higher performance and a compact configuration. ENEA, CNR and METAPROJECTS joined the partnership within the framework of the regional project ReMEDIA aiming at enhancing the TRL of the specific device in the context of Cultural Heritage applications.

In the present paper, the advanced system is described in its basic concept and the undergone realization phases, regarding the hardware and the firmware. The ENEA Diagnostics and Metrology Laboratory upgraded the device core unit with an I2S combiner to manage the output and the input channels, for the sound generation and the sound recording respectively. Furthermore, the concept of the new advanced system includes the integration of evaluation boards for the main functions. Upon specific initial requirements, METAPROJECTS defined the device architecture, its firmware, and realized the advanced prototype having a compact configuration in an integrated Play/Record Console that controls the measurements from a Human Machine Interface (HMI) as in an industrial process. The Play/Record Console interacts with the sound source and the microphone, as well as with the automatic motion controller.

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Keywords: acoustic imaging, diagnostics, cultural heritage, I2S, human machine interface.

Introduction

Commonly used Sonic and Ultrasonic techniques in Cultural Heritage diagnostics encompass a well-assessed class of methods mostly requiring the contact with the analyzed surface. Despite the usefulness of acoustics in non-destructive testing, the above drawback induced the Laboratory of Acoustics Research applications for Cultural Heritage (LARCH) of the National Research Council to develop a new and contactless device for Acoustic Imaging in the Audio Frequency range, based on the acoustic energy absorption evaluation. During the last two decades, the original prototype was implemented in its basic configuration and successively equipped with further technological innovations, such as a high directive acoustic source, a miniature microphone, the automatic scanning frame, a robust measuring procedure and data processing. The system, named Acoustic Energy Absorption Diagnostic Device (ACEADD), detects structural damage in multilayer structures: while the method was initially assessed for mapping detachments in frescoes [Calicchia, Cannelli, 2005], successive researches allowed to demonstrate its validity in glazed ceramic panels [Calicchia, Mimoso, Costa, 2011], panel paintings [Calicchia et al., 2018], and more recent-

a b

Fig. 1 The traditional ACEADD system (a) and its components (b).

ly in historical masonry structures for the presence of water-related deterioration [Proietti et al., 2021].

Within the framework of the recent ReMEDIA Project (Research and diagnostics of MEthods to contrast the DeterIoration caused by wAter in the Cultural Heritage), a public-private partnership among three relevant centers of excellence, ENEA, CNR and METAPROJECTS, has created a new implementation for the ACEADD system, adopting innovative technical solutions for improving the performances and pave the way to a marketable device.

The acoustic imaging method

In multilayer structures, the wave-material interaction contributes to the overall acoustic response of the analyzed object, where different absorption mechanisms, related to the structural properties of the materials and to their integrity, concur to produce acoustic energy absorption. Any parts presenting a non-perfect adherence between adjacent elements, vibrate when exposed to an external acoustic excitation field, partially absorbing the incoming acoustic energy. In addition, the porosity of the materials and their elastic properties affect acoustic absorption, thus another class of structural damage that can be investigated is the moisture effect on masonry, knowing the acoustic response of wet and dry walls.

In Fig. 1 The ACEADD traditional prototype (a) and its components (b) are shown during on-site investigation in the Catacombs of Priscilla in Rome. It includes: a 2-axes scanning frame (1 motorized axis); a sound signal transmitter-receiver unit; the source control; the microphone pre-amplifier; a National Instrument acquisition board with DA/AD converters; a PC for acquisition and data processing by custom software utilities in the NI LabView environment.

The device scans an area while an acoustic source radiates towards the surface an acoustic signal, and a microphone, aligned along the source central axis, records a composite acoustic pressure signal p(t), i.e. the superposition of the incident wave $p_i(t)$ and the reflected wave $p_r(t)$. The most effective excitation consists in a wide frequency band audio signal. The signal p(t) is proportional to the so called impulse response, h(t-τ), of the analyzed area centered in the point of measurement (the time τ is the delay at the receiver between the incident and the reflected waves). Its Fourier Transform, H(f), determines the amount of energy that is reflected back or absorbed inside the object, i.e. the acoustic energy reflection and absorption coefficients.

For each measuring point (i), the total amount of reflected energy Σ over the entire frequency interval Δf is acquired, and the percentage of the acoustic energy absorption ABS% is calculated with respect to the most reflecting point R, as in Eq. 1 and Eq. 2 respectively

$$\Sigma_i = \int_{\Delta f} df\, |H_i(f)|^2 \quad (1)$$

$$ABS\% = (\Sigma_R - \Sigma_i)/\Sigma_R \quad (2)$$

False color images display the quantity ABS% commonly using a (0-100) % scale. Further details about the experimental method, data analysis and other case studies can be found in previous works [Calicchia et al., 2018].

The advanced prototype

At the heart of the new hardware implementation is the use of a microcontroller process unit that exploits the I2S protocol, for respectively managing the generation and reception of the audio signal. Latest generation commercial devices have been selected in the design of the device, configuring the control unit within a compact and integrated Play/Record Console (PRC). The

PRC manages the different functionalities, also incorporating a user-friendly Human Machine Interface (HMI). Previous researches helped to define the initial requirements:

– the high performance and minimum size were the main criteria for the selection of the acoustic transducers; the models adopted in the original prototype were positively evaluated and reused (highly directive source Audio Spotlight AS8 by Holosonics, compact traditional ceiling loudspeaker CCM632 by Bowers&Wilkins, Class2 microphone i436 by MicW);

– a tradeoff between low cost and top performance for the DA/AD converters functions oriented the selection towards two Cirrus Logic components, with at least 192 kb/s, 24 bit;

– a compact processing module including the CPU, the digital interface based on a I2S protocol, the RAM and a memory buffer for short term storage that allows for data transfer to other devices (PC, Tablet etc.).

The expected advancements are the improvement of the signal-to-noise ratio, a simplified usage of the instrument, a reduction of the acquisition duration, a more compact and flexible configuration able to easily adapt the system to the investigated contexts. Further details on the adopted solutions will be presented in the following paragraphs.

The new concept based on I2S protocol

The main novelty has been introduced on the side of communication between audio devices through the use of the I2S protocol to manage the output and input channels. State-of-the-art components already integrated in ready-to-use evaluation boards was privileged, the use of which allowed to contain costs and leave more economic resources available for integration with the processing module.

In the field of digital audio applications, the need to communicate the signal between different devices has been well known for some time, which has led to the development of standard protocols for the digital interfaces. The I2S or Inter-IC Sound protocol, plays this role communicating with DA/AD converters, through a serial bus with 3-wire connection: i) CLK for the serial clock; ii) WS for the word selection that indicates which of the two separate channels is used (Left or Right channel); iii) DAT for the transmitted serial data.

Standard coding requires the L and R channels to be used simultaneously and synchronously for stereo audio transmission. A different coding is proposed, considering the L channel for the audio transmission line Tx, and the R channel for the receiving line Rx (L = Tx; R =Rx).

This unconventional coding requires an additional hardware component, an I2S combiner that separates

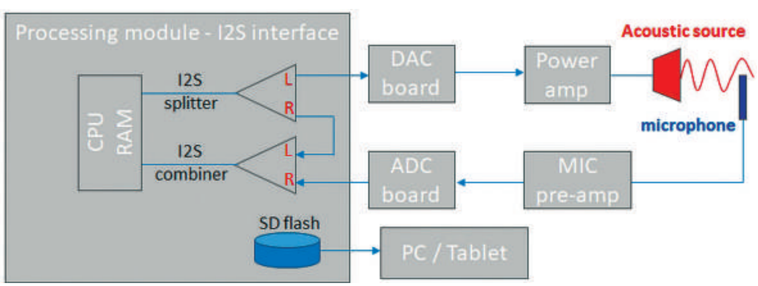

Fig. 2 The concept for advanced prototype of the ACEADD system.

the channels: in Fig. 2 the concept for advanced prototype of the ACEADD system.

Fig. 2 shows the operation of the splitter/combiner hardware device: it takes the signal portion in channel L of the transmission of the excitation sound pulse, uses it for monophonic coding towards the output transducer preceded by the DAC. Simultaneously it copies this signal into reception on the L channel of the I2S line, whose right channel is filled with the digitization of the monophonic signal coming from the microphone and converted by the ADC.

The result is to have the simultaneous coding of both signals at the input, with excellent use of the communication bandwidth and simplification in the signal processing phase.

For the DA conversion the Cirrus Logic evaluation board, equipped with the low power DAC board CS43189 was proposed, housing 2 output channels, 130 dB dynamic range, 32 bit resolution and up to 384 kHz sampling frequency. Similarly, for the AD conversion the Cirrus Logic evaluation board, equipped with the low noise and negligible distortion ADC board CS5341 was proposed, housing 2 single-ended input channels, 105 dB dynamic range, 24 bit resolution and up to 192 kHz sampling frequency.

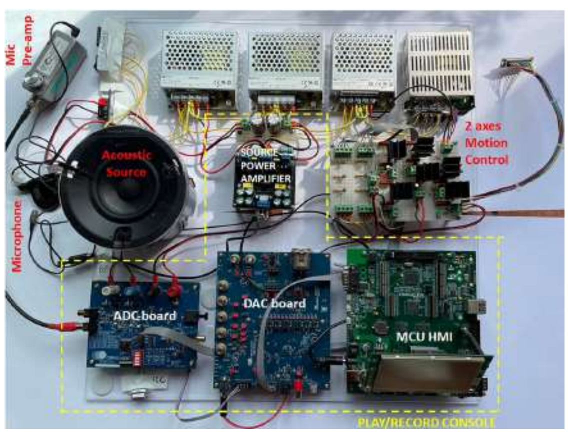

Fig. 3 The PRC not yet integrated in the chassis box during the testing phase.

Innovation in the new AI system

The concept of the new sensor involves the creation of a high-speed embedded system with ARM Micro-Controller Unit architecture (ARM MCU). The ADC and DAC converters have 24 bit high resolution and the low noise cards have excellent signal/noise ratio (S/N). The architecture of the device and its firmware have been defined and the construction of a demonstration prototype with a compact design has begun. An integrated Play/Record console has been created that controls measurements from a human machine interface (HMI) as in an industrial process. The PRC interacts with sound transducers as well as the automatic motion controller to generate raster-like acoustic images.

The stand-alone PRC houses an embedded Micro-Controller unit with HMI 480x272 LCD 4.3 resistive touch-screen (MCU HMI), able to manage all peripherals (audio transducers and axis movement) and to execute the actions of the configuration menu, the Start/Stop of data acquisition and the storage in the local memory bus. An ETHERNET port guarantees the LAN connection with a PC for data streaming. Real-time commands via PRC will be faster and more stable, as they do not require, for example, any remote control by external software. Local storage takes place on a MicroSD card internal to the HMI MCU.

Fig. 3 shows the PRC not yet integrated in the chassis box during the testing phase: the system highlighted with a yellow dashed line is connected to the peripherals, i.e. an acoustic source and a microphone, on the left side, and to the motor controller in top right.

The C language firmware uses high-speed DMA (memory to peripheral & peripheral to memory) system functions to enable audio sampling capture simultaneously with 24-bit output signal generation. The embedded real-time compact C language offers high performance without relying on a basic operating system. The compiled executive firmware is small and runs fast on ARM with pipelane fetch.

The high performances of the advanced system will guarantee an improved accuracy of the diagnostics based on acoustic imaging. This technique is presently employed to tackle important conservation problems, such as the analysis of water-related effects in antique masonry structures. This analysis is undergone in different projects through a holistic approach, by data integration with results derived from other well-assessed methodologies (such as IR Thermography, Unilateral Nuclear Magnetic Resonance U-NMR). The REMEDIA Project involves different methodologies to solve technical aspects of the acoustic diagnostics, and to validate it in both laboratory tests and onsite investigations. Furthermore, the CIACCO Project (Development and on-site application of innovative technologies to Contrast water InfiltrAtions in the roman ChurChes of the histOrical center) is intended to develop a suitable protocol by gathering the above techniques, to study the humidity distribution and its structural effects, with the geotechnical information, the monitoring of environmental parameters, the Laser Induced Fluorescence LIF maps to reveal the presence of surface deterioration due to salts efflorescence as well as biological attacks.

Conclusion

CNR, ENEA and METAPROJECTS created a partnership for the technological innovation of the ACEADD device. The outcomes of this activity are an advanced prototype with status of the art performance and a compact configuration, in order to increase the TRL of the specific device in the context of Cultural Heritage applications.

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NDT of fine Renaissance manufactures via on site X-Ray Diffraction

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Abstract
The paper reports on analyses carried out on brittle and very precious manufactures produced in the Renascence time and part of the Granduca Treasure in Florence. The analyses were intended to identify their original matter. Uncontrolled information was orally handed down on the manufacturing process, thus supporting uncertainties and even high wonder on the artists skinless of those time. Because of their brittleness and historical value, the collection of data had to be carried out directly on site at the formerly named Museo degli Argenti (Palazzo Pitti, Florence) and even without any either mechanical contact or invasive approach of the analysis.
In this respect, although the mobile x-ray diffractometer (DifRob®) was designed to achieve the best performances for in service inspection of industrial components, it revealed unexpected large usability for said manufactures and even several materials of interest for Cultural Heritages. Such an instrument doesn't require any mechanical contact with the object under investigation; it collects data by approaching the object surface from the distance of 5 mm. It uses appropriate controllers to pointing and positioning the instruments from distance. A part from these technological features, the paper is focused on the results obtained and the way to reaching them.
In fact, the results obtained from said precious manufactures (brochette) reported unexpected intensity distribution of the XRD lines; so we were induced to analyse several control specimens separately in laboratory, in order to compare the finger prints of the diffraction line distribution from different rock crystal specimen. The XRD pattern obtained from said Renaissance manufactures revealed several ambiguities in the interpretation. Said ambiguities could have been removed by invoking the apparent violation of XRD systematic extinctions. Said violations occur sometimes under special conditions in massive crystals. So, if we would remove the hypothesis of manufacturing from massive rock crystal, any violation either apparent or not would vanish. We cannot exclude that the production process has been carried out differently from the orally handed down one. In this respect it has been thus possible to propose answers to the questions related to the original matter and the production process as well. The consequence might have an interesting historical impact on the knowledge since then on the production processes.

Keywords: on site XRD, X-ray diffraction, Renaissance manufactures, rock crystal, Renaissance "arte vetraria".

To invoke the apparent violation of x-ray diffraction (XRD) systematic extinction could have provided evidences on the origin of the material used to manufacture precious and fine renaissance objects.

Systematic extinctions of X-ray diffraction lines occur in rock crystals due to the atomic geometrical arrangement as ordered lattices. Unexpectedly the graphics of Fig. 1 show several violations from thin and transparent renaissance manufactures object of the present work. Fact is that said violation are usually occurring in thick rock crystal and generated by multiple internal reflections from well planar atomic ordering (i.e. Renninger effect) «Azarof et al., 1974». The investigated manufactures are a part of the Granduca Treasure collection, conserved in Palazzo Pitti in Florence, known in the past as the Museo degli Argenti. It includes small jugs, cruets, jars, generally "brochette" as they are named later on in the text. They were used in the past Florentine Renaissance as very pretty gifts to the most eminent families.

Two opposite hypotheses were at the base of the current study; the question to answer was whether the manufactures were originated from either a block of natural rock crystal, through the moulding by very skill sculptors, or from other materials through processes as described in the book "Arte Vetraria" by Father Antonio Neri. «Neri, 1659»

Both the hypotheses were well supported by the visual analyses. In particular, the former one was supported mainly by the transparent and brilliant quality of the matter with the addition of highly artistic manufacture designs and morphologies, along with a certain transmitted tradition; the occasional occurrence of few damages and inclusions were also considered among proves to propose the natural rock crystal origin of the block material.

The latter was tending to consider the thinness of the brochette, the fine incisions, the workability of blocks of the crystalline quartz matter, along with the impact of those incisions and morphologies could have done on the structural framework of lattice plane and on the conservation of their regular arrangement as well. The brochette brittleness and even their preciousness are visible from the pictures of Fig. 1, where the related x-ray diffraction patterns are also reported.

X-ray diffraction is very frequently used to investigate specimens, in either powders or block forms «G. Berti et al, 2008». XRD patterns from powders of rock crystals are well known since a long and sometimes used as "reference" for the identification of the fine structure of diffraction line profile. In particular, the angular range 67-69 (in 2q) contains five diffraction lines, whose relative intensities are taken as the finger prints to qualify the quartz specimens. Glasses are instead among the most difficult materials to be analysed by such a method. This different effectiveness of XRD rises from the significant differences between the atomic arrangement, when dealing with the long range order of crystalline lattice of rock crystals and the short range order of glasses.

Evidences of said differences are shown in Fig. 2. Fig. 2a reports the diffraction pattern from modern commercial manufacture of glass (Fig. 2b). These evidences are synthesised as follows:

- Presence of background modulation with the tendency to decrease with increasing the angular incidence of the irradiation beam.

- Presence of modulations at short medium and long periods of angular values (in θ).

- The count per second of the intensity is limited to the range between 20 and 80 c/s with an average value at 60 c/s.

Absence of significant peaks of intensity.

Fig. 2c reports two different patterns in the range of 30-110 degrees in 2θ; the patterns have been collected from the same powdered specimen of quartz by two

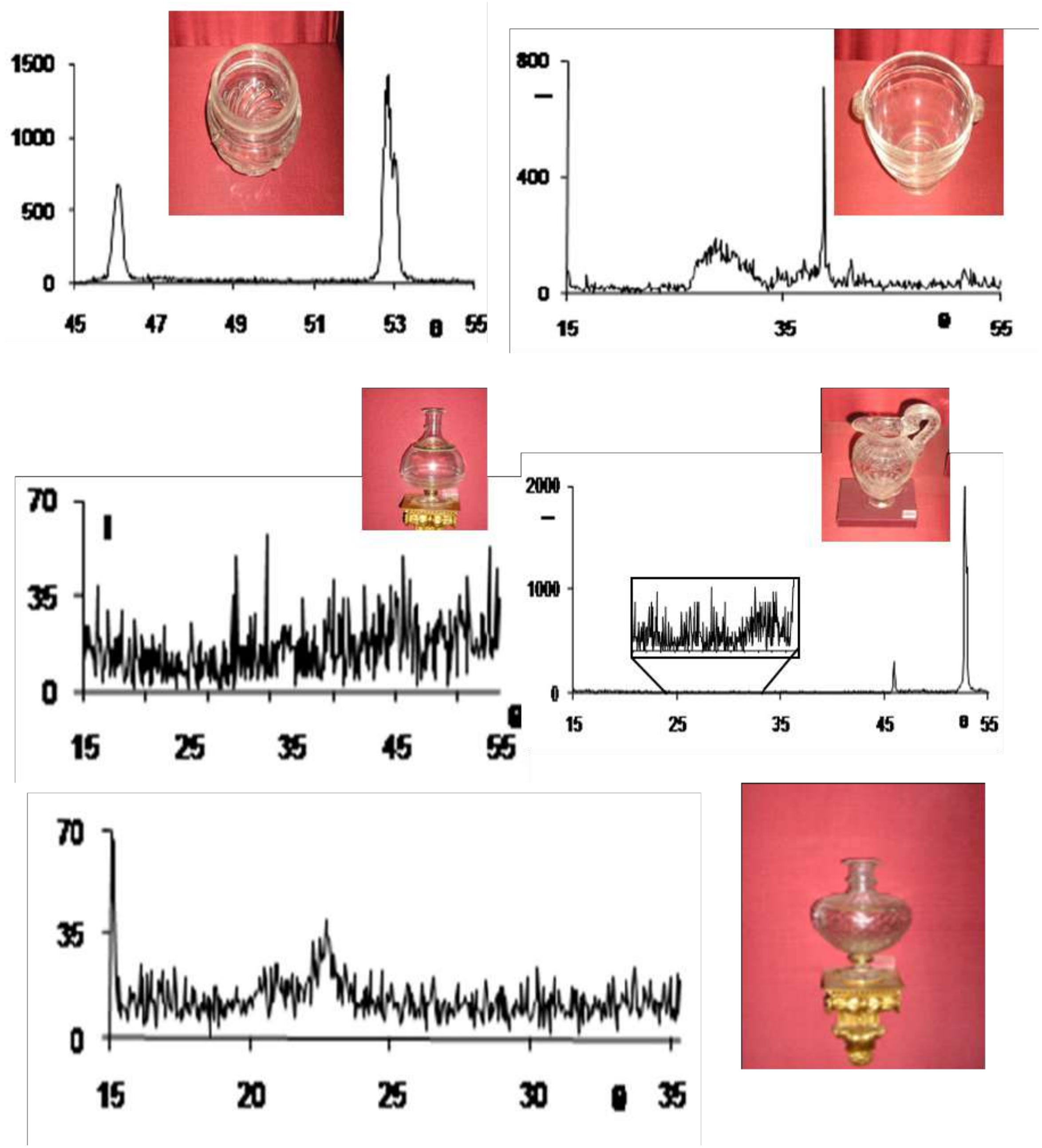

Fig. 1 Some of the investigated brittle and precious brocchette and related diffraction patterns. From top left Vasetto 01, Vasetto 02, Ampolla 01, Brocca 01, Ampolla 02.

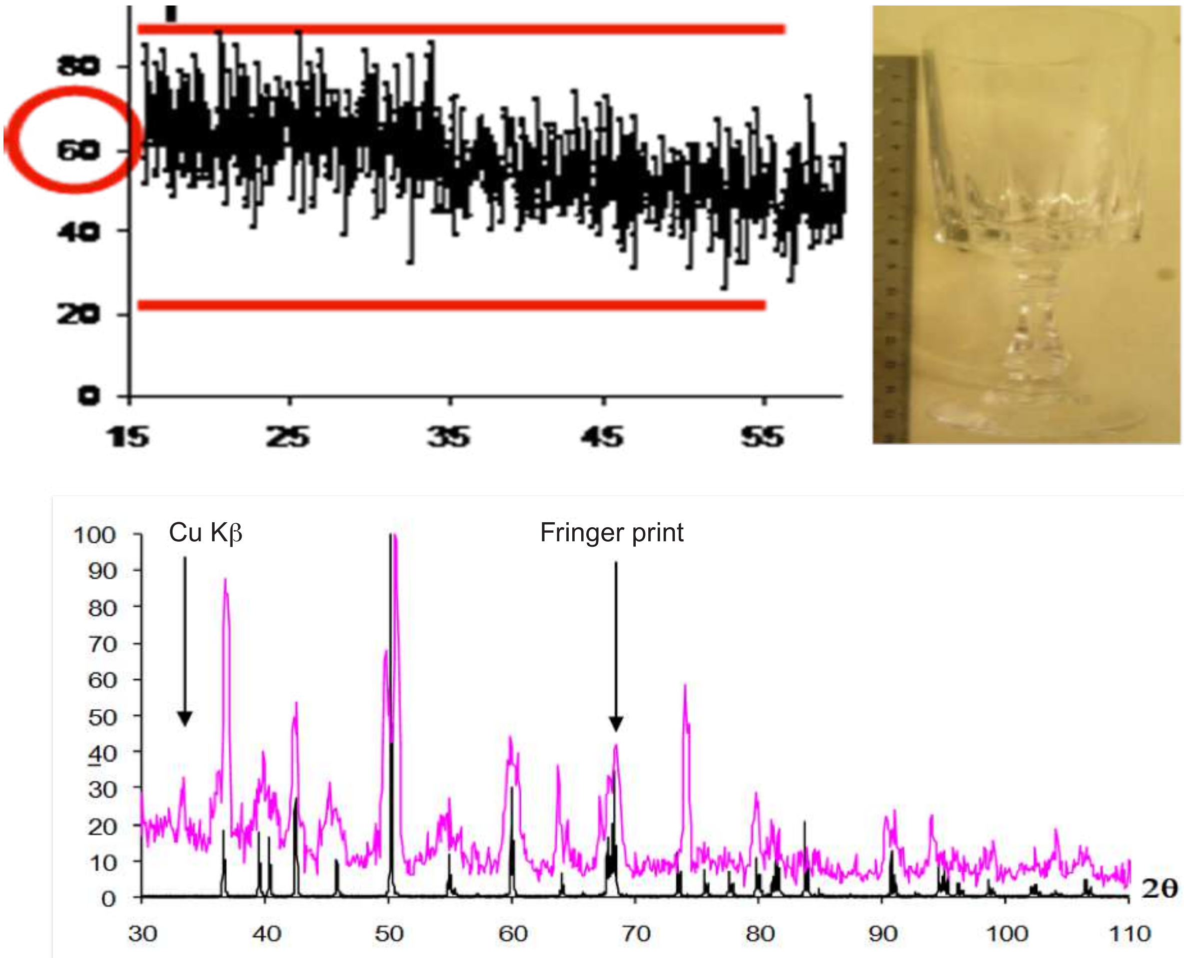

Fig. 2 The investigation on a commercial modern glass provided the expected glass diffraction pattern (top right, Fig. 2a); the modern commercial glass (top left, Fig. 2b); two diffraction patterns from powders of quartz collected by DifRob® (pink line) and a traditional diffractometer equipped with monochromator and other beam confining devices (blue line). The two patterns represent the finger print of the lattice asset of quartz in the investigated angular region. In particular, the region around 68-70 degrees (2θ) contains five overlapped peak representing the finger print of the specific specimen of quartz. The arrow on the left indicates one isolated peak from the CuKβ radiation; other peaks from the same radiation are confused and overlapped to the tails of other highest peak of the pattern collected with DifRob®. This radiation and other effects contributing to the background are eliminated by the presence of the monochromator in the pattern of the blue line. These same devices shell be adopted by DifRob® in the future.

distinct diffractometers. The former is the new diffractometer. DifRob® (pink signal) equipped with a very simple x-ray optics. The latter is a traditional lab. X-ray diffractometer in vertical Bragg Brentano geometry; it is equipped with divergence and receiving slits, monochromator, a couple of Soller slits, scintillator detector and other relevant devices to improve the resolution and keep low the background level of the pattern. These devices results in a sharper profiles of the diffraction lines than obtainable from DifRob®. More details are reported elsewhere «G. Berti 2005», «G.Berti, F.De Marco, 2009»

It emerges the peculiarity of the x-ray diffraction patterns when collected from either powders or blocks of rock crystal.

Roughness of surface, incision and edges can modify the background modulation, the diffraction line position and the related intensity distribution, thus resulting an excellent tool to investigate peculiarity of trade mark and authors skill, corrosion and conservation state of the manufacture.

When dealing with brochette, the following statement can be used to identify the pattern characteristics:

1. Low intensity of the background with modulation at short, medium and long period in (θ).
2. Evidence of line diffraction signal, in general of low intensity and uncorrelated with the families of planes; that is more typical of polycrystalline material than block of rock crystals

The impact of the incisions, surface edges and material moulding on the X-ray diffraction traces introduce ambiguities. This artistic manipulation can in fact introduce overlapping reflection effects on the X-ray diffraction pattern, thus misleading the interpretation even to any skill X-ray diffractionist. Glasses can reveal unexpected peaks over the signal modulation when inclusions/imperfections are investigated because of trapped residual minerals; or simply because of the porphyry used to smooth the residual surface imperfection. Even the crystal rocks can reveal low intensity or weakly modulated signals over unexpected regions of the pattern of quartz. In addition to these effects, the presence of inclusions over some brochette, introduces the suspect that impurities can have been trapped where the transparency decreases; these inclusions can have been originated either in the original material and not completely purified from the empirical thermal and purification process describe by Father Antonio Neri.

Padre Antonio Neri describes the procedure to eliminate salt from a substance that is mentioned as the "Polverino di Levante", «Neri 1659». This material is probably something like a quartz rich sandstone, the quartz is mixed to other salts minerals and impurities; the quartz extraction is requiring purification. This purification process is described as an empirical method which is rather questionable for its reproducibility in the modern sense.

Padre Antonio Neri «Neri 1659» describes also a method to obtain very transparent and brilliant glasses by powdering the mountain crystals, the "Cristallo di montagna" which is probably constituted by small crystal rocks with a large amount of lattice flaws and impurities, thus making them unsuitable for any artistic use. These small and imperfect or even large and highly imperfect rock crystals are much more common than large blocks (e.g. 10x10x20 cubic centimetres) of perfect rock crystals. The purification process were requiring several cycles of heating and sedimentation of impurities. Moreover, the result of the purification process would probably have required a refinement action by polishing the surface with using porphyry stones. In this operation small amount of thin powders might have been ingrained in special orientations and not visible at eye.

The adduced reasoning, to discuss the results, seems self-consistent even not definitive though. Whether these justifications were confirmed by further insights of this special history of the art and by the experimental reproduction of the Antonio Neri process, the concept of "Arte Vetraria" should be converted in the more modern concept of sinterisation; i.e. the art or, now a day, the technology to aggregate powders (silicates in this case) without melting and by forming a coherent mass by a cyclic process of heating and cooling.

A more detailed discussion of results is in "Not invasive XRD investigation on fine Renaissance manufactures of Museo degli Argenti of Palazzo Pitti in Florence"«G. Berti and F. De Marco (2023)».

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Contact angle as a non-destructive method to determine wettability changes induced by sub-aerial biofilms on built heritage porous substrates

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Abstract
Wettability and water transport mechanisms play a relevant role in the weathering of built heritage since liquid water is directly involved in many deterioration mechanisms. Moreover, water availability can promote the colonization of microorganisms on surfaces of built heritage. While microbial colonization of stone monuments was previously considered as a significant biodeteriorative threat in heritage studies and conservation practices, recent investigations have approached it from a different perspective, shedding new light on its actual impact. Recent studies have highlighted that microbial communities, known as sub-aerial biofilms (SABs), can have a neutral or even protective role in certain situations. In the present work, a benchtop contact angle instrument was used for studying the surface wettability induced by sub-aerial biofilms (SABs) on laboratory limestone samples. Complementary information on the water interaction with the substrate in the presence of a SAB was acquired via capillary absorption tests. Field measurements of wettability and water absorption properties of biocolonized plastered wall of a historic case study, Casa a Ponente, of Palazzo Rocca in Chiavari (Genova, Italy) were also performed.
Results confirmed the potential of contact angle measurements as a non-destructive monitoring tool for the wettability of biocolonized stone substrates. The presence of SABs is associated with measurable changes in the surface wettability, resulting in near-hydrophobic conditions observed in both the lab-scale colonized samples and the case study.

Keywords: bioprotection, contact angle, hydrophobicity, non-destructive methods, sustainability, water absorption.

1. Introduction

The interactions between microorganisms and masonry surfaces are the result of the activity of complex microbial communities present on the surface as sub-aerial biofilms (SABs). Traditionally, these interactions have been considered detrimental to the substrates, leading to biodeterioration [1,2]. However, recent studies, primarily based on case studies and empirical evidence, have highlighted that SABs can have a neutral or even protective role in certain situations [3–10].

Furthermore, liquid water is a key driver for deterioration of built heritage surfaces exposed outdoor, being involved in numerous weathering and alteration mechanisms, including biocolonization. Water availability is indeed crucial in promoting SABs formation and development. Therefore, recent studies have focused their attention on the SABs/substrate interaction, particularly looking at changes in water transport proprieties and suggesting that the presence of a biofilm can induce near hydrophobic characteristics to the surfaces [11,12].

Contact angle measurement provides key information on surface wettability and water absorption. Its non-destructive and non-invasive nature, along with recent instrumentational development allowing for in-situ measurements, make it highly advantageous.

The aim of this study was to investigate wettability changes induced by SABs on built heritage porous substrates, both through lab-scale experiments and on a real case study. For the laboratory testing, limestone samples were used and colonized with a SAB model system, representative of naturally formed biofilm under outdoor conditions [13]. Such samples were analysed with a benchtop contact angle instrument to investigate their wettability in comparison to the non-colonized ones. Complementary information on the water absorption behaviour with the SAB/substrate system was acquired by capillary absorption tests.

For the onsite measurements, the biocolonized plastered wall of *Casa a Ponente,* of Palazzo Rocca in Chiavari (Genova, Italy) was selected. The *Casa a Ponente* dates back to the first half of the 17th century [14] with a building and conservation history poorly documented. The plastered wall under study, which faces northeast towards the botanical garden, recently underwent a conservation intervention aimed also at removing the patchy green patina caused by SABs. After a few months, the plastered wall experienced a biological recolonization, prompting the consideration of not pursuing further removal actions. It is therefore important to understand and monitor over time the biofilm behavior and its impact on the plastered surface, to support the decision of preserving it instead of removing it again.

2. Materials and methods

2.1 Laboratory limestone samples

A dual-species SABs composed of the phototroph *Synechocystis* sp. PCC 6803 and the heterotroph *E. coli* ATCC 25404 were grown according to the protocol reported by Villa et al. (2015) [13] modified as follows: the stone samples were immersed overnight in the planktonic culture composed of cyanobacteria and *E. coli* cellular suspensions in a 1:1 ratio. Then, the liquid culture was removed and the BG11 medium [15] was added and maintained at 3 mm above the bottom of the samples. After 5 days with a 16/8 day/night photoperiod, the SABs were mature and ready for the tests. The commercial limestone samples (7.5 cm x 2.3 cm x 1.0 cm) consisting of 90% of calcite and dolomite and with a porosity of 8.91% ± 0.78 [12] were used. Images captured using the digital microscope DinoLite Premiere AM7013MT were processed with the freely available software GIMP (GNU Image Manipulation Program, Berkeley, California) to calculate the extent of surface colonization.

After biocolonization, the samples were dried in the oven at 40°C for 24h before starting the tests.

Wettability was assessed through static water contact angle (WCA) measurements conducted on both biocolonized and uncolonized (control) samples. WCA measurements were determined using a benchtop instrument (Data Physics OCA 150, equipped with a Liquavista Stingray camera and a Liquavista LED light source for background illumination). After dosing a drop of distilled water on the surface, a video was recorded. Single frames were isolated from the video and analyzed with the software OpenDrop (GitHub, Inc., San Francisco, CA, USA). The contact angle of a water droplet decreased slowly to zero for biocolonized samples and very quickly (less than 5 seconds) for uncolonized samples. The WCA was then determined on the first frame (frame rate of 62 FPS) after the droplet touched the surface, assuming that at that moment, absorption is still negligible [11]. Furthermore, based on the number of frames, the time until complete absorption was determined.

Standard capillary water absorption tests were also performed, according to the UNI EN 10859:2000 [16].

2.2 *Casa a Ponente of Palazzo Rocca*

Two different areas were selected, named A01 and A02. Both have a colonized part and a non-colonized one and the plaster seems macroscopically different. The on-site investigation of the recolonized plastered wall was made by portable digital microscopic observation using a digital microscope DinoLite Premiere AM-7013MT. The percentage of recolonized surfaces was calculated as described in 2.1.

The Mobile Surface Analyzer (Krüss GmbH, Hamburg, Germany) was used for contact angle measurements: a droplet of distilled water was dosed onto the target surface and a 60 s video was recorded (frame rate of 10 FPS). The WCA was calculated similarly to the laboratory measurements, using the software KRÜSS Advance (Krüss GmbH, Hamburg, Germany) for each colonized area and compared with the non-colonized ones. Each measurement was repeated at three different points of the same area.

The contact sponge test was also used for the evaluation of the water absorption [17].

3. Results

The cyanobacteria *Synechocystis* sp. PCC 6803 with the heterotroph *E. coli* ATCC 25404 developed a thin green biofilm on the stone surface, with good adhesion to the substrate. The biofilms resulted quite homogeneous with limited areas that appeared more whitish or yellowish compared to the rest (Fig. 1a). The percentage of colonized surface of limestone samples is 91%±5.

In the case study, the SAB on the plastered wall exhibited a relatively uniform coverage of the binder, while being very thin or absent over the aggregates (Fig. 1b). The percentage of the colonized surface of the A01 and A02 areas were respectively 88%±3 and 78%±23.

The contact angle value of biocolonized samples at lab-scale was 102.5°±2.0, which was significantly higher compared to the control ones with a value of 25.6°±1.34. Moreover, in biocolonized samples, the absorption rate ranged between 5 min and 7 min, whereas the untreated limestones exhibited immediate absorption, taking less than 5 seconds for the drop to be absorbed.

A similar trend was observed in the in-situ investigation of vertical plastered colonized surfaces (Fig. 2). In this case, the presence of SAB significantly increased the contact angle. The measured contact angle value for the A01 area was 134.24°±2.2, while for A02 was 130.04°±3.4. In comparison, the uncolonized area exhibited contact angle

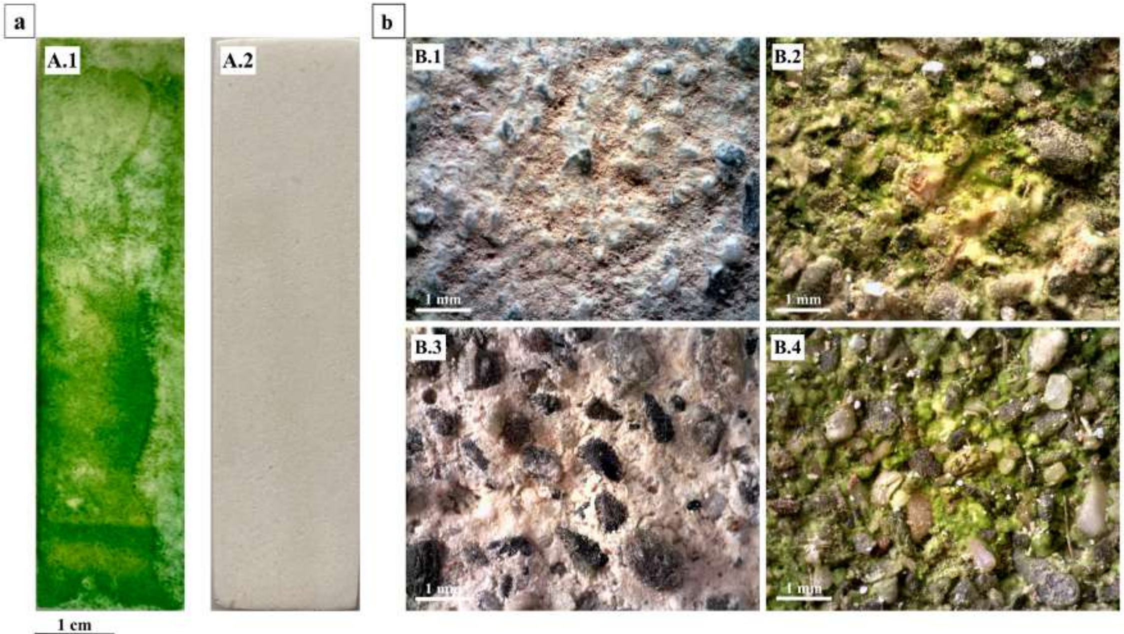


Fig. 1 (a) Macroscopic images of the limestone samples: (A.1) colonized with the dual-species biofilm and (A.2) a control sample; (b) In situ microscopy documentation of different areas of the plastered wall of *Casa a Ponente*: (B.1, B.3) without biofilm (B.1 area A01; B.3 area A02) and (B.2, B.4) biocolonized (B.2 area A01; B.4 area A02).

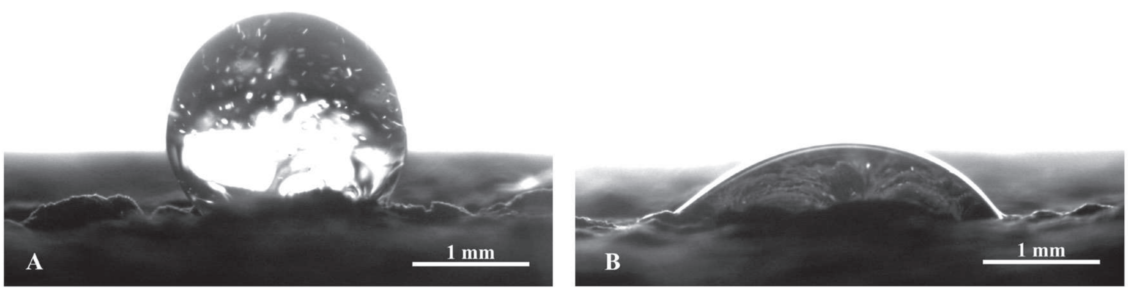


Fig. 2 First WCA. Microphotograph of (A) A01 area with green biofilm and (B) A01_NC area without biofilm.

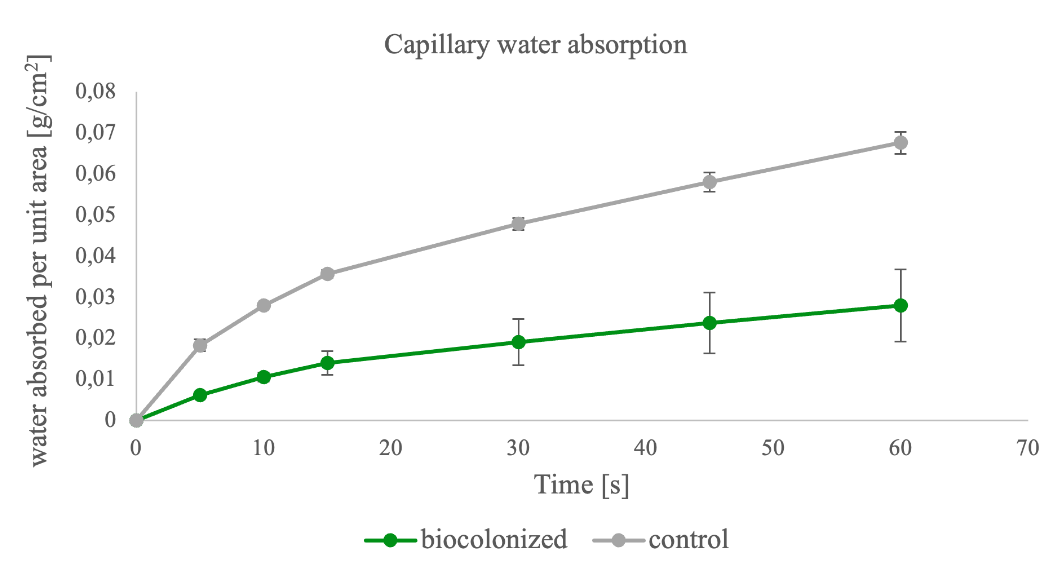
values of 45.3°±8.5 and 52.4°±8.1, respectively; the high standard deviation obtained on the areas without biofilm may be explained by considering the remarkable roughness and heterogeneity due to the inherent plaster composition. Therefore, it can be affirmed that the presence of SABs confers water-repellent characteristics to the surface [18]. Moreover, in the uncolonized areas, the water drops were absorbed by the surface within a few seconds, whereas in the biocolonized areas, the drops remained unabsorbed even after the 60-second duration of the recorded videos. In some cases, the drops volume and shape appeared almost unchanged by the end of the video.

Preliminary results of capillary absorption tests confirmed that the absorption rate in the first 60 seconds is slower in biocolonized laboratory samples than in the control ones (Graphic 1).

Similarly, in biocolonized areas, A01 and A02, of the plastered wall, the results of the contact sponge test in situ showed a lower absorbed water amount [g/cm2] compared to the uncolonized areas (respectively 14% and 42% less).

4. Conclusions

Liquid water is directly involved in many weathering mechanisms affecting masonry surfaces, and it contributes to the colonization of microorganisms. Consequently, it is fundamental to study the interaction between water and biocolonized surfaces. The contact angle measurement has been confirmed as a powerful tool for studying the surface wettability of biocolonized stones, both in laboratory and in-situ settings. The results showed that the dual-species SAB developed at lab-scale on limestone samples induced a near-hydrophobic characteristic to the surface. Similar results were also observed on the recolonized plastered wall of *Casa a Ponente* of Palazzo Rocca in Chiavari.



Graph. 1 Capillary water absorption as a function of time (first 60 s), with the control in grey and the laboratory biocolonized limestone samples in green.

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The 'health record' of the church of Santa Maria Assunta in Pontecurone: contamination between historical knowledge and non-destructive testing results

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Abstract

The historical architecture of the church of Santa Maria Assunta in Pontecurone (Alessandria, Italy), of late medieval origins and with significant transformations until the 20th century, is a clear palimpsest of different construction and decorative phases. Nowadays, although used as a parish church, it shows a critical framework of alterations. The need to best rearrange the data in preparation for a wished restoration program required the involvement of a team of experts from the Politecnico di Torino – as members of a protocol agreement – to verify the current state of conservation of the building.

Between 2019 and 2022, the study focused on examining rich but dispersed and fragmented historical sources, which provided important information for the knowledge of architectural components. In the meantime, an NDT diagnostic campaign to understand non-visible phenomena and structural problems was carried out. In particular, infrared thermography allowed the comprehension of the vaulted systems laying, the mapping of fissures and the reading of the stains caused by infiltration and rising dampness. Moreover, thanks to an innovative application of this technique, it was possible to evaluate the heating system's effectiveness through the survey of the distribution of hot air flows in the room context and on the surfaces. Instead, endoscopic inspections revealed the stratigraphy under the floor level, which is completely damaged, and resistograph analysis verified the quality of the antique roof trusses at some significant points.

The contribution will deal in detail with the systematization of the data in the health record, a tool already tested in other contexts (such as at Chambord Castle, to which this project refers) that can be constantly implemented and easily consulted. Furthermore, it easily communicates and records the knowledge about the building, relating historical information with results obtained from the application of non-destructive testing.

Keywords: church of Santa Maria Assunta in Pontecurone, cultural heritage, NDT, health record, building conservation, infrared thermography.

Methodological foreword. The 'health record' as a knowledge management tool

In the field of restoration, the conservation process of cultural heritage requires a good knowledge of the materials and the history of monuments and sites. For this reason, the approach we are going to explain in this paper, referring to the experience of the church of Santa Maria Assunta in Pontecurone[1] (Fig. 1), represents a method that can be suitable to systematise all the data about the building in light of a hoped restoration programme. Moreover, the development of the several steps of the study is also an example of collaboration between territorial public bodies and scientific experts that work together[2] to discover and highlight the pathologies and problems of the stratified palimpsest. It is urgent to underline that investing in cultural heritage as a promotional factor also means investing in knowledge and detecting complex situations that require planned monitoring and intervention to prevent the development of decay and the irreversible loss of material testimonies[3]. With this aim, the results of all previous studies and campaigns about the church, even if carried out with different methods, have been catalogued, translated and made available in a synoptic and implementable database, here called the 'health record', thanks to which it is possible to define the state of conservation and the priorities for safeguarding the building.

The case study between historical information and restoration yards

The 'health record' information system arises from the assumption that any new operation on cultural heritage should be profitably based also on its previous conservation history. For this reason, between 2019 and 2022, the research focused on the dispersed and fragmented historical sources, which provided important information for the knowledge of architectural components and previous restoration yards.

In short, the church of Santa Maria Assunta is a clear palimpsest of several construction and decorative phases: it was built around 1175[4] and it revealed subsequent and significant transformations[5] unraveled up to the 20th century, when a series of interventions were achieved with the aim of structural consolidation, conservation of the architectural organism and the preservation of interior decoration (Fig. 2). The analysis of these restoration yards constitutes the heart of the research because they offer the possibility of identifying returning problems and operational interventions that have already proved effective on the building. Chronologically, between 1925 and 1929, the church was closed to the public due to static problems, so the first structural monitoring was carried out to determine the importance of the overturning phenomena, which led to the installation of a steel beam at the extrados of the nave to which chains were anchored to stop the façade from overturning[6]. On the same occasion, a restoration of the roof took place, with the replacement of some wooden elements and tiles and the installation of new channels for collecting rainwater. In the 1930s, the external plinth was rebuilt entirely to protect the masonry from dampness[7], the existing single-lancet windows were restored, the 18th century semicircular windows were closed and new windows were opened on the façade and the side elevations.

Subsequently, documents attest to the work on the bell tower, the insertion of chains in the naves and extraordinary maintenance works on the roof between 1974 and 1977. In 1979, the problem of dampness was again evident, so a ventilation space with vents along the perimeter walls was built in an attempt to restore the perimeter masonry from rising damp. Finally, the last structural intervention dates back to 1982: it involved the construction of reinforced concrete beams along the perimeter walls and the chaining of perimeter walls and arches of the minor naves with metal tie rods.

Fig. 1 The façade and the South-East flank of the church of Santa Maria Assunta in Pontecurone (2022).

Fig. 2 The chains in the left nave during the restoration yard of 1974-1977 (Parish Historical Archive).

NDT diagnostic campaign

In addition to traditional disciplinary knowledge, competence regarding new tools for diagnostic investigation nowadays occupies a central role in the definition of the conservation program on the built heritage. The restoration project, in addition to the traditional knowledge campaign, the historical study of the sources, and the architectural and decay survey, cannot ignore tests and analyses in advance of the choices of intervention, which allow for in-depth analysis of the state of conservation, in particular where visual examination and the study of archival sources don't provide suitable results[8].

In this case study, the NDT campaigns were conducted in 2020-2021 using remote visual inspection, infrared thermography, and resistograph analysis, focusing on several issues: instability of the flooring, decay in masonry, and strength of the wooden beams of the roof system.

Endoscopic inspections were performed inside the disconnections in the cement tiles floor and showed no cracks, bulges, or moisture on the bedding layer of the damaged tiles.

Thermographic acquisitions, conducted with protocols different (active or passive) depending on the objectives, made it possible to identify the textures of vaulted systems, locate cracks and plaster detachments (Fig. 3),

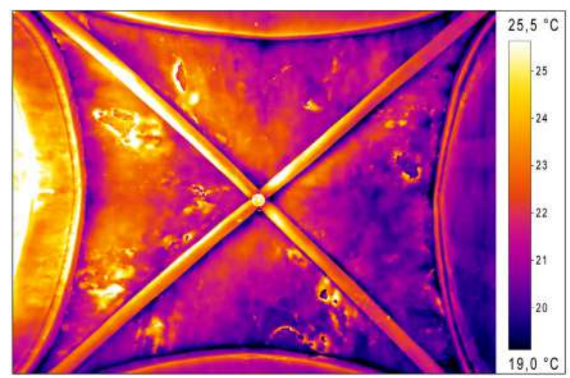

Fig. 3 Right side nave, 4th bay. Active IR scan: gaps and plaster detachments (February 24th, 2021).

Fig. 4 Central nave: Infrared microclimate analysis. Scan at 1h45' after the start of heating (April 14th, 2021).

and map evaporative fronts caused by infiltration from the roof and rising dampness. Since the evaporation front is subject to variations, the IR evaluation took place in different seasons and was correlated with the weather and microclimate data acquired over the whole period.

Resistographic testing was applied to a sample of three trusses out of the ten covering the nave to obtain a qualitative indication of the wood element’s preservation state. Each truss was analyzed in the most structurally stressed sections. At the same time, the wood’s surface moisture was measured using a penetration hygrometer. The results do not reveal any specific critical problems.

In addition to the more common aims of the NDT surveys, an experimental IRT campaign[9] was undertaken to verify the efficiency of the current heating system in the church[10]. On seven strips of cardboard that were fixed to the chains of the three naves and fixed to the floor, the superficial temperature distribution was evaluated over time following the heating (Fig. 4). This method allowed, at the same time, assessing the thermal comfort of the worshippers depending on their position (in space and standing or sitting) and the thermal stress to which plaster and wooden furnishings are subjected, especially in the higher areas.

The systematisation of data in the ‘health record’ as a critical working basis for conservation

As mentioned in the foreword, the study presented in this paper is part of a research program concerning the preliminary investigation of the church of Santa Maria Assunta conservation program. Referring to the debate on knowledge management processes and taking some case studies as examples[11], the work focused on the definition of a tool that collects historical notes about construction, information about restoration yards carried out since the 19th century and the synthesis of the current state of alteration of the monument[12]. Often, in the operational context of restoration, it happens that data on the state of conservation, diagnostic investigations and previous interventions performed are in a fragmented

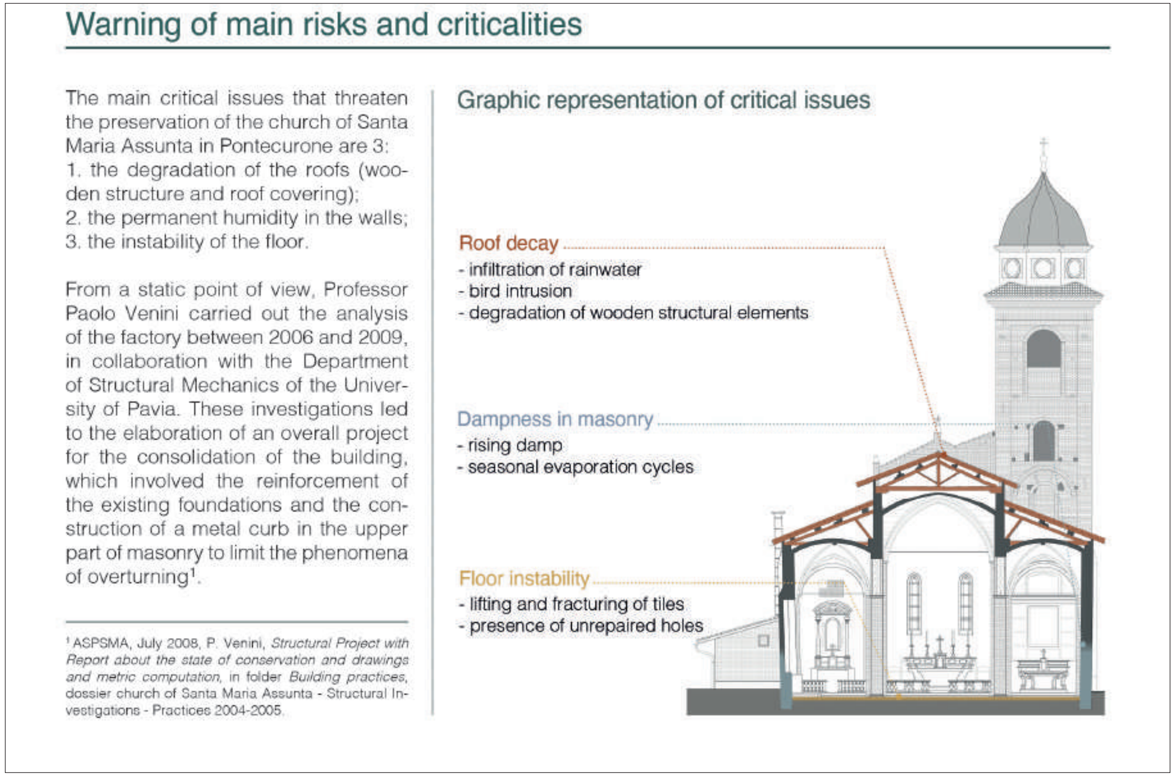

Fig. 5 The three main criticalities of the church summarised in the last section of the 'health record'.

and dispersed state as to be unusable. For this reason, the systematisation of all information is necessary to preserve experience and integrate historical research with the technical-scientific analysis from the diagnostic investigations. The whole of these fundamentals is the basis for the description of monument identity and for the development of its 'health record': a critical working basis essential for the definition of a preservation process, that becomes a precious database over time, also useful for the periodic monitoring of the health of the architecture[13].

In the case of Santa Maria Assunta, the research tries to translate this theoretical reflection into a concrete tool that represents a process innovation and can be constantly implemented and easily consulted, in which all the mentioned aspects, from historical analysis to the results of NDT diagnostic campaigns, are put together to offer a synoptic scientific reading of the monument and to underline its critical issues and main problems (Fig. 5).

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Notes

This paper is the result of the joint work of the authors. In particular, however, the foreword is shared, the section on the case study is written by Giulia Beltramo, the one on the NDT diagnostic campaign by Monica Volinia and the one on systematization of data in the 'health record' by Monica Naretto.

[1] Pontecurone is a town in the province of Alessandria, located in south-eastern Piedmont.

[2] In 2020 was activated a Protocol Agreement between researchers and technicians of Politecnico di Torino, the Diocese of Tortona, the Soprintendenza Archeologia Belle Arti e Paesaggio per le Province di Alessandria Asti e Cuneo, the Centro Conservazione e Restauro "La Venaria Reale" and the owner of the building.

[3] Gasparoli 2023.

[4] Year in which the first catalogue of the Diocese of Tortona parish churches attested its existence.

[5] Festuccia, Franco, 2021; Vanni, 2023.

[6] The same problem is still evident today: direct survey operations have revealed the overturning of the masonry on the main façade (Vanni, 2023).

[7] As in the previous note, the problem of dampness issue represents another analogy with current decay and the criticalities because it has required restoration work also in the past.

[8] Fiorani, 2009.

[9] Camuffo, Bertolin, Fassina, 2010.

[10] Air heating with vents located in the upper part of the presbytery and directed to the naves.

[11] Calò, Cavagnini, Riva 1999; Bartolomucci 2004; Coccoli, Scala 2006; Janvier-Badosa, Beck, Brunetaud, Al-Mukhtar 2013.

[12] The research about the Chambord Castel (Janvier-Badosa, Beck, Brunetaud, Al-Mukhtar 2013) is a significative reference for the development of the 'health record' of the church of Santa Maria Assunta in Pontecurone.

[13] Treccani 2006.

Italy-Switzerland Interreg Project shares methodologies for knowledge of Cultural Heritage

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Abstract

Nowadays the relevance of Building Information Modelling (BIM) in construction design and Non-Destructive Test (NDT) on architectural heritage is well known. Commonly recognized in the field of Cultural Heritage the methodology is most properly named Historic Building Information Modelling (HBIM).
The aim of this paper is to show the potential of combining non-destructive investigations for the diagnostics with HBIM for analyzing historical buildings. Authors refer the results obtained within the project "Interreg ConValoRe" that was developed in collaboration among the Italian municipality of Tirano, the Switzerland authority of the Bernina Region (CH) and other partners. Italian and Swiss methodologies of analysis and prescription from standard codes for the safeguard of cultural heritage were combined and applied to three significant case studies on the Swiss territory: 1) San Vittore Church, 2) Samadeni House, 3) San Romerio Church.
Firstly, a laser scanner survey analysis allowed the team to obtain the overall geometries of the buildings. Then a diagnostic investigation was performed with the use of NDT to define material properties. Both these were developed using HBIM modeling, where information about typologies, damages and characteristics of materials were implemented. Furthermore, the outcomes of geometries and diagnostic investigations have allowed the implementation of numerical models of the buildings in order to perform a specific static and seismic structural analysis. The paper presents the effectiveness of the implementation of the HBIM models with NDT information in order to log all the information necessary to ensure conservation and maintenance of Cultural Heritage Buildings.

Keywords: HBIM, NDT, diagnostic, laser scanner, structural assessment.

Introduction

Safeguard of cultural heritage is a topic of great interest but also a difficult goal to achieve. In recent years the need of interaction among different disciplines and skills has become clear.

This paper refers the results obtained within the project "COnVAloRE" that was granted by the EU under the Interreg program, a cross-border cooperation between Italy-Switzerland and developed in collaboration among the Italian municipality of Tirano (SO), the Switzerland authority of the Bernina Region (GR) and other partners. The aim of the project was to share information and experience between the partners. Two approaches to the analysis of existing buildings, Italian and Swiss, were considered, evaluating both the prescriptions from standard codes and the status of art of the operative methodologies. The activities were applied to three case studies in Switzerland: i) San Vittore Church; ii) Samadeni House; iii) San Romerio Church.

One of the goals of the project was that in an organic framework of skills many different subjects have contributed to create a synergistic diagnostic campaign which has allowed to obtain a homogeneous knowledge base on all case studies. The activities done are summarized in Tab.1.

Analysis of an existing building is a difficult discipline due to the large amount of unknown factors. So in order to be conservative in structural analysis, Italian codes define different levels of knowledge that can be achieved. To define the geometry laser scanner technique, drawings from historical research and visual inspection were combined. To define constructive details, visual survey and execution of tests at "extended" level consisted of specimens integrated with NDTs in order to extend the data and evaluate the homogeneity of the materials. All information is collected and combined in a HBIM model, and then used to implement the model for the structural analysis.

In recent years HBIM methodology was used on historical buildings: i) to perform structural analysis (Cardani et al 2014); ii) to synthesize quantitative information on the existing damage that can be exported for the structural assessments (Balin et al 2021). Correlation between flat jack test and sonic test is investigated in (Binda et al 2007). This correlation was used in the diagnostic analysis to reduce the impact on the building.

In this paper the authors show the potentiality of combining NDTs and HBIM to ensure conservation and maintenance of Cultural Heritage Buildings, dealing in particular with the application of the methodology to San Vittore Church.

Laser scanner survey and point cloud

A Terrestrial Laser Scanner (TLS) allows for the collection of a large amount of geometric measures of a building in a short time. TSL has facilitated (for the case studies), the accurate detection of the geometries, such as thickness of vaults, horizontal elements, and masonry walls. Furthermore, thanks to the technologies used with a camera integrated in the instrument, it was possible to proceed in the post-production phase to color the point cloud, thus enriching it with material information. The number of scan positions necessary to obtain a complete model depends on several factors: dimensions, geometry, number of elements inside the buildings, and level of detail required.

The TLS was integrated with aerial photogrammetry by drone and consequently, a points network of known coordinates (topographic polygonal), was achieved and used to link data coming from the laser-scanner and drone surveys. The point cloud produced by the drone does not allow one to achieve the precision of the clouds obtained with TLS, but it is useful to complete all information such

		S.Romerio	S. Vittore	Samadeni
Historical analysis		X	Z	Z
Laser scanner survey			Z	Z
Structural Diagnostic test	Single and parallel flat jacks test			Z
	Sonic test on masonry		Z	Z
	Penetrometric tests on mortar joints	X	Z	Z
	Penetrometric test with resistograph	X	Z	Z
	Structural monitoring	X		
Surface diagnostic test	Microclimate monitoring	Y	Y	Y
	Thermographic surveys	Y	Y	Y
	Humidity test	Y	Y	Y
Archeologic survey activity	Radar surveys	W	W	
	Dendrochronological investigations	W	W	
Stratigraphy analysis		Already present		
Inspection report			Z	Z
BIM model			Z	Z
Structural seismic vulnerability analysis			Z	Z
Z= Done by Switzerland authority of Bernina Region (GR)		Y = Done by Politecnico di Milano		
X = Done by Italian municipality of Tirano (SO)		W = Done by Archeologic service		

Tab. 1 Activities done on the three case studies for the Intereg COnVA-loRE project.

as thickness of the roof and other geometric measure.

The last step of laser scanner survey process is to elaborate, check, and collect the data to obtain a geo-referenced point cloud that collects all the information. The final product is the starting point to implement an accurate BIM model of the building.

HBIM model

The acronym BIM (Building Information Modeling), describes a technology capable of implementing, through the exchange of information, a single system that during the whole life cycle of the building helps in the decision-making process, and the interaction between the different subjects involved in the design process. It is a methodology and a tool, capable of collecting the entire information system, which can be exported or consulted in an unambiguous and updated way.

The HBIM methodology applied to an existing building uses 3D modeling of the Real-Based type, which makes it possible to reprocess the data collected during the survey phase and to create a three-dimensional model that accurately reconstructs the characteristics of the architecture. The process involves the design of a digital model from which it is possible to obtain different architectural draw-

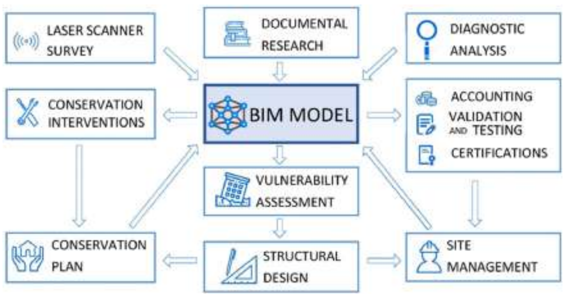

Fig. 1 HBIM process for Cultural Heritage.

ings in different restitution scales. The HBIM allows to superimposing the point cloud on the preliminary BIM model. This makes it possible to analyze and better model the deformations of beams and trusses, the irregularities of the walls and vaults, to measure the structural deformations, and to analyze in detail the geometries of the structural elements. Referring to S. Vittore Church and Samadeni House, the model is therefore geometrically very detailed and implemented with the stratigraphy of structural and non-structural elements. The data taken from the diagnostic phase such as structural details and the characteristics of the materials were implemented in the HBIM model through the modeling of "mass" elements. These elements are characterized by different shapes based on the type of investigation and allow the correct identification of the test location in the three-dimensional space of the model. Similarly, the distribution and position of the detected crack pattern have been entered into the HBIM model through the three-dimensional parameterizable elements enriched with all the information characterizing the crack. The modeling of the cracks in a three-dimensional model is fundamental for the correct interpretation of the instability phenomena of the building.

Non-destructive test

In the field of Non-Destructive Tests (NDTs), a preliminary visual survey is necessary to establish the state of conservation by detecting crack patterns and choosing the elements that require more in-depth investigation. Then an in situ diagnostic campaign is strictly related to the structural aspects. When combined with Minor Destructive Tests

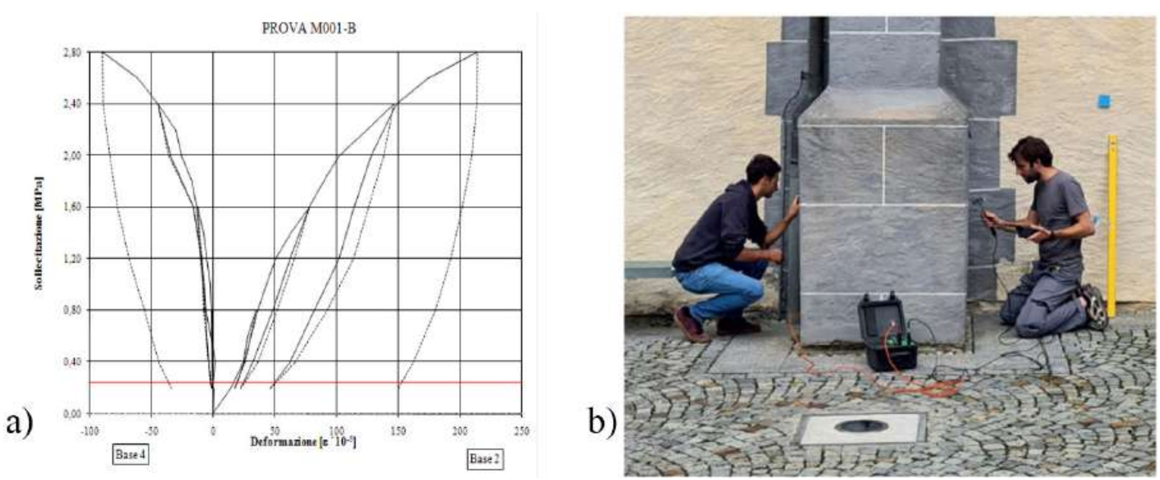

Fig. 2 diagnostic campaign: a) Flat jack test b) Sonic test.

(MDTs) for more precise mechanical values and NDTs, more extensive information without a significant impact on the building can be achieved.

The following processes were carried out on the three buildings during the diagnostic campaign: i) Visual survey of the crack pattern; ii) Laser scanner survey; iii) Thermographic surveys; iv) Arrangements of masonry units survey (SM); v) Single flat jack test (M1); vi) Two parallel flat jacks test (M2) Fig. 2a; vii) Penetrometric tests on mortar joints (MM); viii) Sonic test on masonry (UT) Fig. 2b; ix) Penetrometric test with resistograph (PL).

Due to the specific value of the church, the MDTs were performed only in Samadeni House. They consist in single flat jack test, which allow one to measure the state of local stress, and two parallel flat jacks test, which allow one to determine the characteristics of deformability of a representative structural sample of masonry. Then NDTs, such as thermographic surveys and sonic tests, were carried out to extend and compare information for the buildings. Thermographic surveys by detecting the thermal conductivity of different materials also help to analyze the texture of masonry walls. Sonic tests provide the measurement of the velocity propagation of a pulse in the material that can be correlated with the strength that is also investigated with penetrometric tests on mortar joints. For wooden elements, penetrometric test with resistograph, where a thin needle is forced to drill into the wood by rotation at a constant velocity, allows to obtain the variation of twisting force that defines a change in the wood density. This also allows to identify areas with cracks, brown rot or biological attacks that compromise the mechanical behavior of the element.

Structural Modelling & Seismic Vulnerability Assessment

In compliance with the current Italian building codes, the seismic vulnerability assessment of a structure allows for the identification of its safety level by expressing the result of the analysis in terms of the Seismic Risk Indicator (SRI). This indicator, tagged as ζE, is expressed in terms of the ratio of accelerations and have to be $\zeta E \geq 1$ in order to consider the structure seismically adequate.

The modeling and the analysis level were chosen in relation to the structural typology and geometry of the case studies. Four different procedures of structural analysis were taken into account: i) Local static analysis, for S. Vittore; ii) Global static analysis, for S. Vittore and Samadeni; iii) Local seismic analysis, for San Vittore and Samadeni; iv) Global seismic analysis for Samadeni. A specific local static analysis for S. Vittore was performed

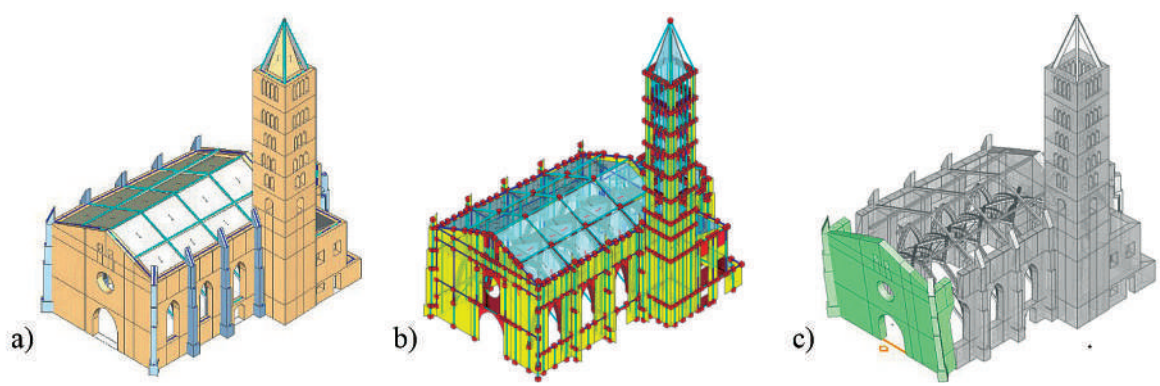

Fig. 3 a) Structural Model, b) Equivalent Frame Model, c) Kinematic Analysis Model for San Vittore Church in Poschiavo.

to properly analyze curved shells such as stellar vaults. In this analysis ribs were considered as structural elements. Instead, the webs of the vaults were considered as dead load. The vaults were consequently discretized in different arches, analyzed according to Heyman hypothesis (Heyman 1995). The outputs of the vaults analysis were used as input data in the global equivalent frame model and were adopted for analyzing state of safety of the buttresses.

Conclusions

The paper presents the effectiveness of a combined methodology that follows the path of knowledge highlighted in the current Italian legislation to ensure conservation and maintenance of Cultural Heritage Buildings. The data were managed through HBIM model that allowed the implementation of laser scanner survey, analysis of the damage and cracks pattern, NDTs test information on materials and structures. This allows for the collection of all the information necessary for a specific static and seismic structural analysis that is performed even for complex building such as S. Vittore Church. Furthermore, the correlation between different diagnostic information allows a design team to maximize the effectiveness of the diagnostic campaign. This paper has presented specific case histories that were developed during the project "COnVAloRE" and proposes an useful procedure to follow when faced with cultural heritage buildings.

Acknowledgements

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Knowledge coordination tool for the conservation of the church of Sant'Agata

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Abstract

The BIM (Building Information Modeling) approach to the construction sector is now well-established, both theoretically and practically, thanks to a legislation that encourages the use of such systems. In line with international trends, DM n. 560 of December 1, 2017 (as amended by DM n. 312 of August 2, 2022) envisions the mandatory use of BIM for public interventions, defining a road map based on the total amount of public works from 2022 on. This logic encompasses all interventions, including restructurings and restorations, which account for a significant portion of the Italian building sector.

This contribution proposes an experimental application on the church of Sant'Agata in Brescia, where an ongoing structural monitoring process has been activated, and a series of non-destructive investigations were conducted on the main roof structure. The numerous collected data denounce an evident malaise of the building and they are functional for the development of the restoration project.

The accessibility of the analysis' results and the need to coordinate many different professional figures, as frequently happens in case of restoration projects, has suggested the study of an HBIM model supporting the design activity, the knowledge management process and the planned future conservation practice. The procedure has implied a preliminary evaluation about the type of available information and then unconventional modeling solutions have been identified on the basis of the BIM available tools, creating a flexible and dynamic model, that offers the possibility of implementing and coordinating the data over time.

Keywords: HBIM, knowledge management, planned conservation, monitoring.

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The knowledge management activity related to an architectural valuable building constitutes the preliminary step when consciously approaching cultural heritage and its attainment implies to operate a reliable and functional organization of the whole acquired heterogeneous information, with the aim of creating a dynamic project environment. This purpose can be operatively pursued exploiting the tools offered by the BIM (Building Information Modeling) technology, whose primary application concerns the new constructions, experiencing the potential and the versatility of the method when implemented on historical buildings (HBIM). The case study concerning the church of Sant'Agata in Brescia has represented a fecund field for practicing a series of different information management solutions, in order to suggest a guideline to deal with an innovative and still poorly explored branch. The relevance of the building in the urban historical scenario, its compromised structural condition – denounced by a visibly important cracking framework mainly affecting the vaults and the under-roof walls – and the huge amount of available documentation have been thought to be appreciable features for the study's purposes. In particular, with reference to the treated information, the main source has been represented by the outcomes of the qualitative and instrumental investigations that had been performed on some portions of the structure by the engineering company (Foppoli Moretta e Associati S.r.l.) commissioned for the execution of current extraordinary maintenance interventions aimed to improve the building's seismic behavior.

Creation of the model and representation challenges

The most critical feature of the HBIM application lies in the need of dealing with existing buildings showing peculiar and complex geometries to be modeled, therefore one of the experimental values proper of the study lies in the research and in the definition of alternative techniques to the ones which are generally used for the representation of new structures having regular profiles. The non-standard approaches that should be pointed out rely on the same tools and functions provided by the modeling software and conceived for more commonly faced issues. These complexities sometimes risk to compromise the functionality of the method, leading to its marginal application in case of historical buildings. In this regard, the conducted work aims to provide an operative example based on solutions that seek their feasibility in the compromise between a sufficiently good level of representative accuracy and a limited processing time, in compliance with the general economy of the project. In this context, a significant parameter is represented by the definition of a level of detail which can vary within the same model according to the focus to be adopted. In the specific case, the attention has been set on the under-roof portion of the church, which is the area where the most of the investigations have been carried out, as well as the most significant region from the point of view of the structural impairment of the building. The modeling process has been developed by means of Revit software, supplied by Autodesk® company, a worldwide used support to the BIM applications. The modeling activity has been performed on the basis of the point cloud corresponding to the under-roof portion of the church, that was previously aquired by the commissioned geomatics company by means of 37 static scans executed with a laser scanner and aligned in a single rigid point cloud. The creation of the BIM model has relied on various techniques depending on the different structural elements to be represented; one of the most elaborated procedures has been carried out for the representation of the eight Palladian trusses composing the roof structure, which has

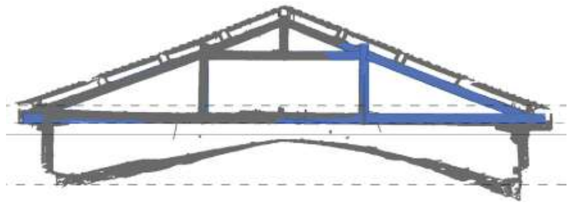

Fig. 1 Model adaptation to the point cloud.

involved the generation of new parametric families.

The model representing the generic truss has been created on the basis of dimensional parameters whose value could be modified in order to change the whole configuration of the structure allowing its adaptation to the actual geometry of the different trusses; the process has lead to the achievement of a good level of superposition between the model and the point cloud (fig. 1 Model adaptation to the point cloud). Besides, another significant representative solution has relied on the complementary use of Autocad software – supplied by the same aforementioned company – with the aim of creating a series of meshes corresponding to the internal surfaces of the considered structural element (such as the arches and the vaults), that have been subsequently loaded in Revit as local masses and conceived as references for the generation of the corresponding volumetric elements. Some modeling approximations and discretizations have also been assumed to limit the elaboration time and the size of the project file, allowing in this way the overall feasibility of the method (fig. 2 Final model and under-roof insight).

Knowledge management possibilities

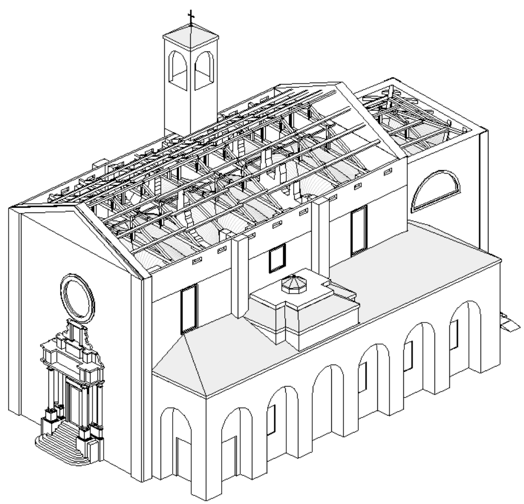

Fig. 2 Final model and under-roof insight.

Considering the discussed case study, the knowledge management process, aimed to relate all the collected knowledge to the already built 3D model, has been implemented on several fronts; first of all, it has dealt with the historical documentation that has been retrieved both from the Superintendence archive and from the one of the parish, in order to recap the most significant constructive events involving the building and its components. Besides, another kind of treated information has been supplied by a series of surveys and investigations carried out by the commissioned company in the under-roof area, including the qualitative analysis about the state of conservation of the wooden trusses, resulting in the so-called 'degradation mapping'. Moreover, the BIM model has been supplied with the information related to the structural monitoring system based on linear displacement sensors that has been installed by the same company in order to register the width's variation of the most relevant cracks detected on the external surface of the vaults and on the under-roof walls. Finally, some non-destructive or low-destructive instrumental investigations have also been performed on the trusses to quantify some physical parameters: ultrasonic tests, humidity detections, penetrometric tests with resistograph and samplings aimed at defining the essence of the wood. For each of these categories of treated information, the management procedure has relied on three main working phases: a prior collection of the suitable documents, including photographic references, technical relations, and numerical data sheets, a following logic organization of these documents in folders on the on-line platform of Google Drive and a consistent association of the links with the corresponding elements in the model. The choice of uploading the documents on a shareable storage is coherent with the idea of data accessibility, also due to the implementation of a standard structure for each one of the databases related to a different branch of the whole knowledge, promoting in this way the reiterability of the method (fig. 3 Structure of the documents' folders). Concerning the historical documentation, it has been catalogued, organized and then integrated in the model by means of simple URL-type parameters associated to the modeled structural elements, reporting the directory of the corresponding folder of documents; instead, the treatment of the other types of collected information has implied more demanding and customized procedures. Indeed, both the degradation mapping and the cracking framework subjected to structural monitoring have been represented in the model by means of properly created adaptive families to be anchored on the surfaces affected by the superficial or structural damage; the modelled adaptive elements have also been provided by a series of text-type and URL-type parameters; the periodically recorded measurements of the monitored cracks' width and the corresponding temperature values have been plotted in linked diagrams.

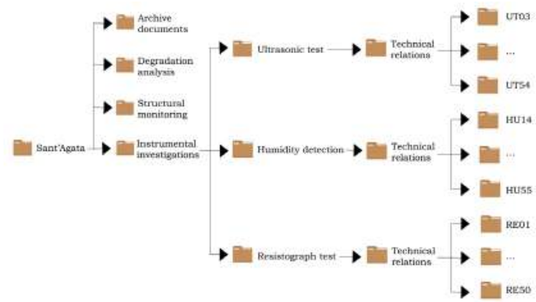

Fig. 3 Structure of the documents' folders.

Instrumental investigations and parametric families of placemarks

The analysis have included penetrometric tests (50), humidity detections (15), ultrasonic tests (15) and wooden samplings (4), that have been performed in some precisely selected points over the trusses corresponding to the most degraded portions or to the regions subjected to high structural solicitations, as the lower ties' ends and the lateral supports. From the HBIM point of view, the definition of a functional method allowing the correlation of these investigations and of their outcomes with the model has been a quite challenging point. One of the main purposes was to supply a graphical representation of the performed tests in the model, so that they could be easily identified just by looking at the 3D view. Furthermore, the intuitiveness of the chosen representative method was thought to be essential in order to promote an easy readability of the model, thus the different typologies of performed tests needed to be distinguished on the basis of simple criteria. At last, it was required to precisely localize the executed tests on the interested structural elements. A unique solution satisfying all these needs should be pointed out according with the functions available on Revit software; for this reason some possible approaches have been dismissed due to their unsuitability with respect to one or more of the outlined requirements. As an example, a possible solution could have been represented by the use of the labels: in this case new families of labels could have been created adopting different symbols to differentiate the tests' typologies. Moreover, the labels associated to the modeled elements could have been georeferenced on the single instances to precisely localize the investigation points. Nevertheless the illustrated approach exploiting the tags' functionality has a relevant disadvantage in the framework of the aforementioned needs: actually, the tags belong to the annotation category on Revit and, given their informative nature, they can be seen just in a specific 2D view of the model, as a plan, a section or a front view. This feature is a very limiting factor since the immediate visualization of the investigation points on the 3D view of the model was thought to be essential. Hence, another approach has been finally identified in the creation of new families of generic models representing, by means of conventional symbols, the different investigation types. In this case, the 3D created elements could be seen in the main project from any perspective in all the visualization modes, being full-fledged part of the model. The test based on the sampling of wooden cores from some of the trusses has represented an exception in the information treatment approach: for sake of simplicity, it has been introduced in the model by means of a new text-type parameter assigned to the trusses' family and dedicated to the definition of the wood species that have been detected through the macroscopic analysis of the collected samples: in all the analysed cases, the detected wood species is the *Picea abies* (also known as *Abies alba*), a type of conifer. Concerning the other tests, the choice of the 3D symbols that had to be developed in the family creation workspace has been based on the principle of full accessibility and intuitiveness (fig. 4 The placemarks in a zoom on the under-roof). It has also been necessary to define a method allowing to link the created placemarks to the corresponding interested portions on the trusses in order to precisely localize the investigated points. Therefore, it has been necessary to generate an additional family of adaptive generic models to create a physical link between each one of the introduced symbols and the related survey point. This connection has been represented by a very thin extrusion with circular section generated on a reference straight line having two adaptive points at its extremes. In order to correctly positioning the investigation points on the concerned beams, each truss has been isolated one by one to simplify the procedure: the exploitation of the adaptive points at the ends of the connecting lines allows to firmly and punctually fix the placemarks to the structural elements of the model. The introduced symbols are not mere icons, but they have been actually equipped with a

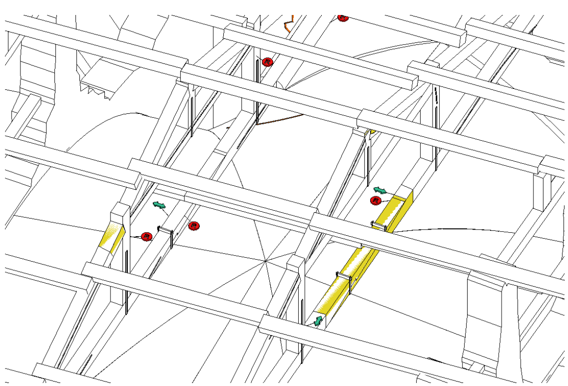

Fig. 4 The placemarks in a zoom on the under-roof.

series of parameters linking the information related to the specific test they represent. All the detection points have been listed in tables – one for each investigation type – that have been created as 'abacus' in a pretty unconventional way: it is possible to modify or update the parameters directly in the tables' cells and to extract the desired information for a long-term monitoring and conservation approach. Moreover, to improve the accessibility of the model, the placemarks have been provided with colours distinguishing the various investigation types; the colour assignment has relied on the creation of specific visualization filters based on rules (i.e. all the generic models whose parameter 'investigation type' is equal to 'humidity test' are painted in blue). The method is thought to be easily repeatable in case different kind of investigations are performed, just by conceiving a representative symbol to shape the new corresponding parametric family.

The illustrated management expedients, defined with non-standard modeling techniques, are though to allow the full readability of the model and to suggest a method to implement the information in a punctual and intuitive way, preserving the three-dimensional value of the data. The consistency of the documentation storage systems is intended to promote the data sharing and consequently the interoperability of the involved professional figures. At last, the limited required elaboration time suggests the feasibility of the method, which is expected to encourage the programmed conservation of cultural heritage.

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X-Ray analysis of Winged Victory

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Abstract
In the midst of the pandemic, the Winged Victory, a famous bronze statue from the Roman age discovered in the early 1800s and which has become a symbol of the city of Brescia, returns home after a careful two-year restoration.
The report aims to present the radiographic investigations carried out on the work during the restoration period with particular attention to what are the precautions necessary in the inspection of three-dimensional works such as the statues.
Compared to the analyzes of two-dimensional works (whether on wood or canvas), those on statues and other works with a complex structure require a specific and accurate study of the projections in order to understand the position and entity of what is observed.
In the case of the Winged Victory, a 300kV portable rx source was used together with a computed radiography system which, thanks to the use of flexible plates, made it possible to acquire images of reverse projections, both crossing the entire body and a "single wall".
The activity led to the execution of about 160 x-rays and the post-production work then made it possible to reconstruct partial and complete images of the work so as to be able to carry out in-depth analyzes of delimited areas and at the same time have an overview.

Keywords: Winged Victory radiography, radiografia Vittoria Alata, complex object radiography.

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The report aims to present the radiographic investigations carried out on the work during the restoration period with particular attention to what are the precautions necessary in the inspection of three-dimensional works such as precisely the statues.

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Dealing with a complex inspection

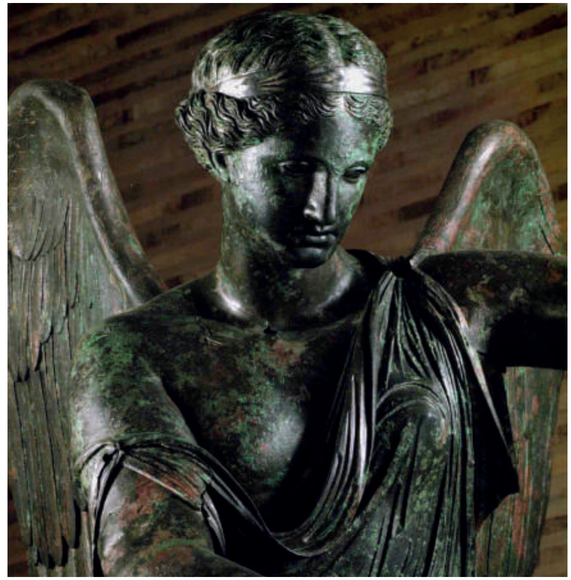
As anticipated, the radiographic technique necessary to inspect a large three-dimensional work is far from simple.

The easy choice would be to use a tomographic system in order to reconstruct the three-dimensional radiography of the work; however, as in this case, such big statue cannot fit in most of the tomographic systems and this makes its 3D reconstruction almost impossible (see report IDN 39 for comparison of digital radiography technologies).

For the analyses, it was therefore decided to use a computed radiography system that would allow maximum inspection flexibility: a Dürr CR 35 NDT combined with a 35x43cm phosphor plate and with a 300kV monobloc source.

The acquisition of the radiographic images then took place in various ways, ie by varying the direction of the source several times and the location of the radiographic plates with respect to the statue which was placed lying on its back.

The radiographic analyzes were carried out after the inside of the statue had been emptied of the nineteenth-century filling, above all in order not to invalidate the results of the analyzes carried out on the residues of the fusion earth in order to obtain useful information both on the construction technique and on the state of conservation of the statue.



The projection

Before starting to perform the radiographs it is essential to establish whether there is or not the will to assemble them in order to obtain a single image.

If this were the case, it will be of fundamental importance not to vary the position of the radiographic source to obtain images that are congruent with each other, ie with the same projection.

For the creation of the radiographic overview of the front and sides of the statue, the source was therefore placed about 3 meters away from the work, while the

radiographs of smaller details gave the technicians the opportunity to approach the source.

The hips

First of all, the source was placed laterally to create the radiographic overview of the sides of the body.

By placing the source on one side of the statue and the plates on the opposite one, it was possible to obtain the entire profile of the work but the image of the left side and the right side were superimposed.

Thanks to the use of the computed radiography system, it

was later possible to insert the plates also internally in order to obtain separate information from the two sides of the statue.

Front view

Subsequently, the source was placed from top to bottom in order to perform the frontal radiography of the body.

Also in this case the plates were first placed underneath (obtaining the combined x-ray of the front and back of the work) and then inside the statue to acquire separate images of the front and back.

Arms and wings

Keeping the source from above, wings and arms (that were separated from the rest of the body) were inspected by placing the plates only on the back and not internally.

Furthermore, the arms, which could be easily rotated, were inspected by varying their position according to the X-ray beam in order to have information on both the frontal and lateral parts of the two limbs without variating the source position.

Other projections

More radiographs were taken placing the source from the bottom upwards and the plates inside the statue so as to have indications on the lower part of the body and on the head.

Finally, the source was placed at 45° degrees with respect to the statue in order to provide elements of knowledge also on parts of the body and wings that had not been possible to analyze with other angles of the incident beam.

The radiographs in numbers

In total, about 160 radiographic images were taken, obtained by varying the acquisition parameters according to the different thicknesses of the material analysed.

The choice of parameters was carried out following the creation of some test images which led to establishing constant kV and mA (300 and 5 respectively) for all radiographs and varying the exposure time, from 10 seconds for the thinnest parts up to 120 seconds for the thickest parts.

Post-production

Some exposures such as the head, feet and chest were obtained from a single image, others instead were edited together in post-production in order to obtain the radiographic general of the different parts such as for the body, arms and wings.

The resulting images were subsequently saved with different contrasts in order to obtain information on both the thinnest and thickest areas.

Results

The radiographic images have brought to light various information of which, for simplicity, we report the main ones:

- differences in density (variations in thickness and alloy in the walls),
- identification of square-shaped holes probably for venting the bronze casting,
- melt porosity (air bubbles trapped during cooling),
- signs of previous restorations (higher density material incorporated in some repairs),
- support elements of higher density material installed during the 19th century restoration in the head, left arm and right wing
- defective jet of the flight feathers (the left one is broken just below the middle and was re-welded in the fifties of the last century with strong brazing
- joint lines of the waxes on the left arm.

Comparison of radiographic techniques for Cultural Heritage

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Abstract

Radiography has long been one of the most interesting methods of control for cultural heritage and, thanks to the advent of new technologies (which have brought countless advantages over the classic film), its diffusion has further increased.

In fact, the ability to investigate layers of material underlying the visible ones, analyze the structure and materials of an artwork, as well as verify its state of conservation, are of fundamental importance for undertaking a correct restoration campaign.

For decades, albeit with limited potential, film was the only existing radiographic technology and, consequently, the one used; now, however, there are several digital radiographic technologies, each with its own peculiarities, advantages and disadvantages.

The report aims to present the new radiographic methods: computed radiography, direct radiography and tomography, analyzing them and comparing their strengths and weaknesses in detail to understand, depending on the needs, which technique is to be preferred and why.

I already warn you that, as normally happens in non-destructive testing, an absolute technique, always applicable and able to provide all the necessary data, does not exist and, precisely for this reason, it is important to choose the most suitable one with awareness for the individual case.

Keywords: digital radiography, tomography, radiografia digitale, tomografia, flat panel, dda.

Radiography has long been one of the most interesting methods of inspection for cultural heritage and, thanks to the advent of new technologies, its diffusion has increased further.

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Below I present the main radiographic technologies for the analysis of cultural heritage with advantages and disadvantages.

The conventional film

By now almost everywhere supplanted by more modern systems, for decades it was the only existing radiographic technology and, consequently, the one used.

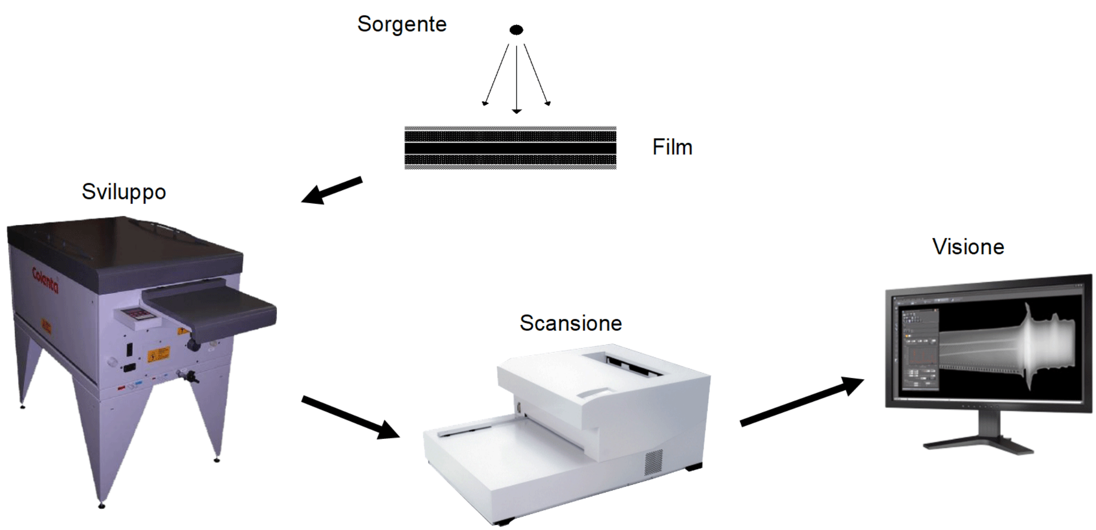
Thanks to the flexible support and the simplicity in giving it the desired shape (cut and fold), it has often given the operators the opportunity to obtain the desired information.

The major limitations of this technology are as follows:

- very limited radiographic range (possibility of inspecting several densities with a single exposure and having a margin of error on exposure),
- need to develop in a darkroom (environment without white light, illuminated only by red lamps),
- use of chemicals,
- impossibility of transferring the X-ray image without sending the only existing physical copy,
- complicated and non-lasting archiving,
- impossibility to perform post-processing to optimize what is of interest or to assemble several X-rays images.

The digitization

A first solution to overcome the disadvantages associated with archiving and data transfer is offered by



digitization systems. These scanners, specially designed to read industrial radiographic films, allow those to be transferred to digital format.

In addition to not solving the other critical issues related to the traditional method, digitization lengthens the process and the resulting file, having undergone a digital transformation process, is less accurate than the original X-ray.

The computed radiography

The CR (Computed Radiography) is the only technique that, to date, allows to fully replace the use of traditional films.

The reason is simple and linked to the fact that it uses special phosphor films called plates available in all formats and flexible like films.

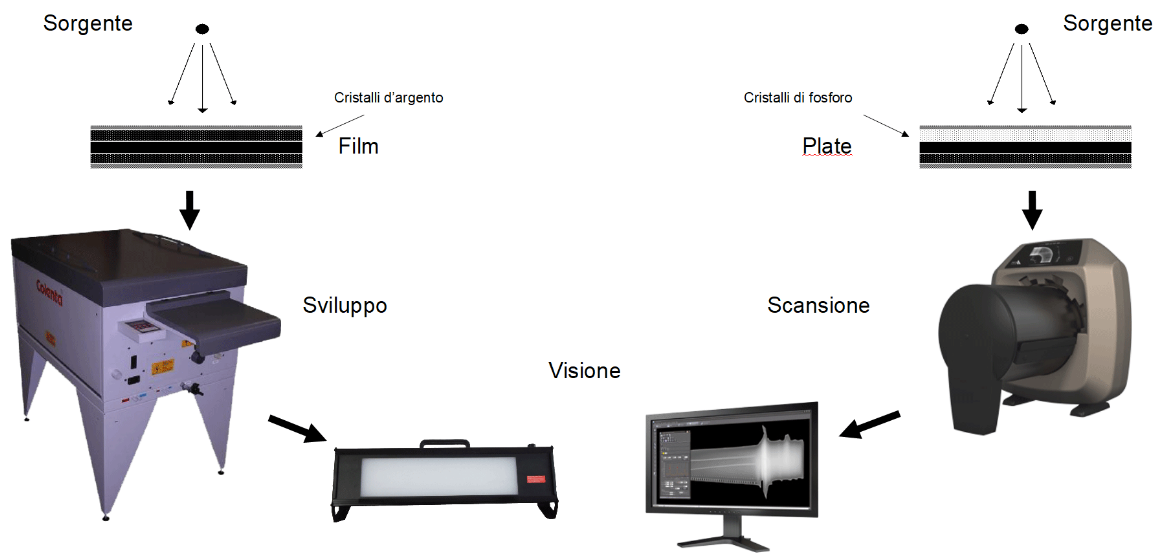
The exposure is carried out as always by placing the plate inside a protective envelope.

The envelope, unlike for films, has the main purpose of protecting the plate from mechanical damage and not from light; in fact this is not impressed by exposing it to ambient light, but is canceled (slowly). However, as it is made to be reused, it's important that it does not get damaged during use.

After exposure, it is necessary to acquire the image through the scanning process: once the desired parameters have been set, the plate will be hit by a laser beam to release the acquired radiation in the form of light which will then be transformed into bits of gray for reading.

The final phase of the scanning process is the cancellation of the plate in order to be able to reuse it (the number of reuses of the plate depends on various factors but it can be considered on average around a thousand exposures).

Compared to conventional film radiography, computed radiography offers advantages from every point of view while it is worthy of comparison with other digital methodologies.



The direct digital radiography

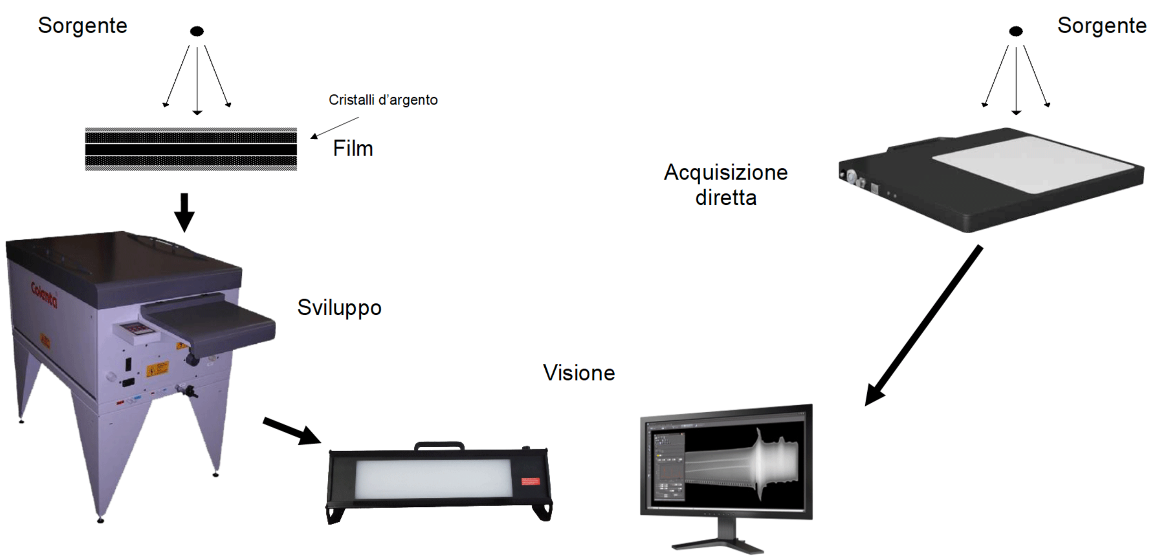
DDR (Digital Direct Radiography) is the direct descendant of analog x-ray videoscope: those systems that were once composed of radiation-fluorescent panels whose light was captured by video cameras and transmitted onto a monitor, are now made in monocoques with Linear Array technology or DDA (Digital Detector Array).

These systems are directly connected to the computer and allow images to be taken in (almost) real time, they are ideal for use in cabins and automatic systems but are also used for certain on-site applications.

The major advantages over film and CR-type systems are:

- speed of use,
- possibility of automation,
- superior radiographic quality (if with the same spatial resolution as CR systems).

On the other hand, they are not flexible and have unchangeable characteristics of format and resolution, so different activities may require the purchase of different panels.



The tomography

Tomography makes it possible to reconstruct a three-dimensional radiograph of the work under analysis.

This is done by performing a certain number of x-rays by varying the inspection angle.

Normally these scans are obtained through the use of a rotating table capable of moving along the vertical axis on which the piece is placed while the source and detector remain stationary (systems for large objects instead keep the work in rotation and move the source and detector on the vertical axis).

Acquired the images from various angles and for the entire height of the object, the software reworks them to obtain the 3D.

This three-dimensional vision is mainly advantageous for works that have a shape that develops over 3 dimensions such as statues, pottery and similar, while it does not offer particular advantages in the case of paintings on various supports.

On the other hand, tomographic systems are bulky and often have severe limitations in analyzing large works due to physical limits of space and power: compared to any other radiographic method, for the same

object to be inspected, the radiographic voltage is necessarily higher.

In conclusion, there is no radiographic method that can be defined as the best from every point of view but, simply, the most suitable for the specific needs of the laboratory for which it is intended.

To learn more about methods and technologies, you can contact me freely at the following addresses:
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Application of Virtual Wave thermography for the inspection of paintings

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Abstract
Active thermography is used more and more for the inspection of paintings. Many progresses have been made in both signal and image processing and thermography NDE techniques to deal with complex, potentially fragile, and unreplaceable samples such as paintings. For instance, to allow the inspection of historical artworks by using low-power heating sources, pulse-compression thermography schemes have been developed and successfully used in the last years by the authors. However, there are still many steps to do to reconstruct a thermal stratigraphy of a painting with good depth resolution, as the diffusion nature of heat mixes the information about the thermal properties of layers at different depths. To face this issue, in this paper we investigate the application of Virtual Wave approach in combination with pulse-compression. Virtual Wave maps the diffusion heat transfer problem into a wave-propagation one, increasing the capability of discriminating the information coming from different layers. We applied the Virtual Wave to a set of items (panel, canvas and wall paintings) and compared the results before and after its use, highlighting the benefits it provides in evaluating the different layers.

Keywords: active thermography, paintings, virtual wave, pulse-compression.

In recent years, active thermography has been used to inspect both easel and wall paintings to investigate the support and the layers underneath the pictorial one, even in combination with other NDE techniques such as hyperspectral imaging, IR reflectography, THz imaging, etc. In almost all cases, heating is provided by a light source and two main challenges must be faced: 1) how to achieve high SNR values while avoiding overheating the paintings' surface, to prevent any possible damage or alteration of the pictorial layer; 2) how to improve the reconstruction of the stratigraphy of the of the sample under test (SUT), which gives important information to conservators and restorers.

To address the latter point, the pulsed thermography (PT) is the most used method [1-2]. This is since a single excitation frequency as in lock-in analysis provides not enough information about multi-layered structures. However, PT is not the best solution for the first challenge. The information is extracted by studying cooling over time after lighting the painting with a single flash provided by high power lamps leads. The energy is delivered in a very short time leading to a large and rapid temperature increase of the sample surface. The peak power must be thus kept under a certain value to avoid thermochromism, thermal/mechanical shocks, etc., hence limiting the SNR.

In this scenario, to overcome the limits of PT for paintings NDE, some of the present authors developed a pulse-compression active thermography scheme (PuCT) exploiting pseudo-noise sequences that enable the analysis of artworks using low-power LEDs excitation apparatus. In the last years, PuCT has been applied to a set of mock-ups and historical paintings, including both panel, canvas, and wall paintings. Some of the results are reported in [3-6].

The excitation system used consists of a low-power LED source (200-300W) whose intensity is modulated by a binary pseudo-noise sequence. A series of thermograms is collected during the excitation, which is twice the time required for the heat to reach a desired depth, and then processed pixel-wise along the time dimension - the pulse-compression step. At the output of the procedure an equivalent long-pulse thermography (LPT) response is retrieved [7].

The theory at the heart of this procedure and the experimental details are not reported here, the reader being referred to [3-6], and we consider henceforth the output of the PuCT procedure the starting point for the Virtual Wave (VW) application.

At the same time, various approaches have been pursued for the reconstruction of the thermal stratigraphy of the sample, which could provide important information for the sake of conservation, restoration and characterization of the materials and the realization techniques. Nevertheless, due to the diffusion nature of heat transport, the information coming from different depths is mixed in the thermal images hampering the process.

In this paper, we investigate the use of the VW approach introduced in [8] to map the thermal diffusion signals in a virtual domain where the thermal response behaves like a propagating wave.

To gain insight of this procedure, let us consider an ideal PT experiment on a homogeneous sample having an isolated defect at some depth. The sample is excited by a short pulse and a time-sequence of thermograms is collected. As is well known, the defect affects the thermal time-domain response of the pixels in correspondence to it, by modifying the expected trend of a sound point. However, the contribution of the defect on the time trend is not limited to a short time interval, but it is generally a smooth variation lasting for a long time. This is since different frequency components diffuse with different velocities, as expressed in Eq.(1), where v_p and v_g are the phase and the group velocities respectively,

$\alpha = \frac{k}{c\rho} [\frac{m^2}{s}]$ is the thermal diffusivity and

$\mu = \sqrt{\frac{\alpha}{\pi f}}\,[m]$ is thermal diffusion length.

$$v_p(f) = 2\pi f\mu = 2\sqrt{\pi f\alpha}\,;\; v_g(f) = 4\sqrt{\pi f\alpha} = 2v_p(f), \quad (1)$$

It is thus not possible to easily associate a depth to a “defect” unless a specific processing of the data is used. For example, the well-known Thermal Signal Reconstruction method [9] can determine the depth of a defect by applying a proper fitting function by exploiting the theoretical solution of an ideal PT experiment. Unfortunately, this is unlikely to work for painting inspections, since:1) the structure of paintings is complex and largely unknown in term of thicknesses and materials; 2) the interest is focused on reconstructing the painting structure itself and not (only) on detecting isolated defects. It is then necessary to develop methods that can better associate a given signature in time trends to a given depth, so as to allow a 3D reconstruction of the sample. One of the most promising techniques is the Virtual Wave, which has already been applied to NDT of industrial samples [10].

Virtual Wave

The temperature distribution inside the SUT as a function of space and time in an ideal PT experiment is the solution of diffusion equation reported in Eq.2:

$$\left(\nabla^2 - \frac{1}{\alpha}\frac{\partial}{\partial t}\right)T(r,t) = -\frac{1}{\alpha}\frac{\partial^2}{\partial t}T_0(r)\delta(t), \quad (2)$$

where: ∇ is the Laplacian, α the thermal diffusivity, assumed to be homogenous, $T_0\,(r)$ the source-term that defines the initial temperature distribution immediately after the short pulse.

The associated “virtual wave” $T_{VW}\,(r,t)$ is defined as the solution of an ideal “Pulse-echo” experiment, formally represented as the solution of the wave equation reported in Eq. 4. In this case $T_0\,(r)$ represents the initial displacement immediately after the pulse and c is an arbitrarily chosen velocity of propagation, usually set equal to one.

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)T_{VW}(r,t) = -\frac{1}{c^2}\frac{\partial^2}{\partial t}T_0(r)\delta(t). \quad (3)$$

It can be seen [9] that $T(r,t)$ and $T_{vw}(r,t)$ are related by the following Fredholm equation,

$$T(\mathbf{r},t) = \int_{-\infty}^{\infty} T_{virt}(\mathbf{r},t')K(t,t')dt', \qquad K(t,t') \equiv \frac{c}{\sqrt{\pi\alpha t}}exp\left(-\frac{c^2t'^2}{4\alpha t}\right)\; for\; t>0 \quad (4)$$

where $K(t,t')$ is the kernel.

If we discretize $T(r,t)$ and $T_{vw}(r,t)$ in space and time, so that $T(r,t)$ becomes the matrix containing the time-trends of the pixels sampled at the frame rate of the thermocamera, Eq.4 can be written in matrix form as:

$$[T]=[K][T_{VW}] \quad (5)$$

The matrix $[T_{VW}]$, containing all the virtual waves associated to each pixel, can be then obtained solving Eq.5 as $[T_{VW}] = [K]^{-g}[T]$ where $[K]^{-g}$ is the pseudo-inverse of $[K]$.

Due to the ill-posed nature of the problem, here $[K]^{-g}$ was calculated by using the damped singular value decomposition (DSVD) regularization method, and the damping was calculated automatically studying the curvature of the singular values decay.

Experimental results and conclusions

The following figures 1-4 compare PuCT images before and after the VW processing for the same paintings analyzed in [3], that is the "Crucifixion of Viterbo" attributed to Michelangelo's workshop and Mantegna's "The Resurrection of Christ". Similar results were found with other samples, here not reported for the limited space. It is worth noticing that $[\boldsymbol{T}_{VW}]$ is discretized in space and time as $[\boldsymbol{T}]$, but for $[\boldsymbol{T}_{VW}]$, the time is mapped into depth by using the velocity *c*. It is also important to stress that:

1) PuCT already increases a lot the SNR starting from the raw data, allowing many details of the stratigraphy and structure to be identified, as reported and detailed in [3-6];
2) the application of the VW increases some more the SNR, especially for hidden layers, but the larger gain it is found in the stratigraphy reconstruction capability. This is evident looking at the results after VW: the painting scene, which persists for a long time in PuCT time sequence hampering the analysis of the subsurface features, almost disappears in VW. The wood grains have a significantly better resolution after VW and their evolution with the depth can be monitored. Specific features barely or not visible in PuCT, become visible after VW

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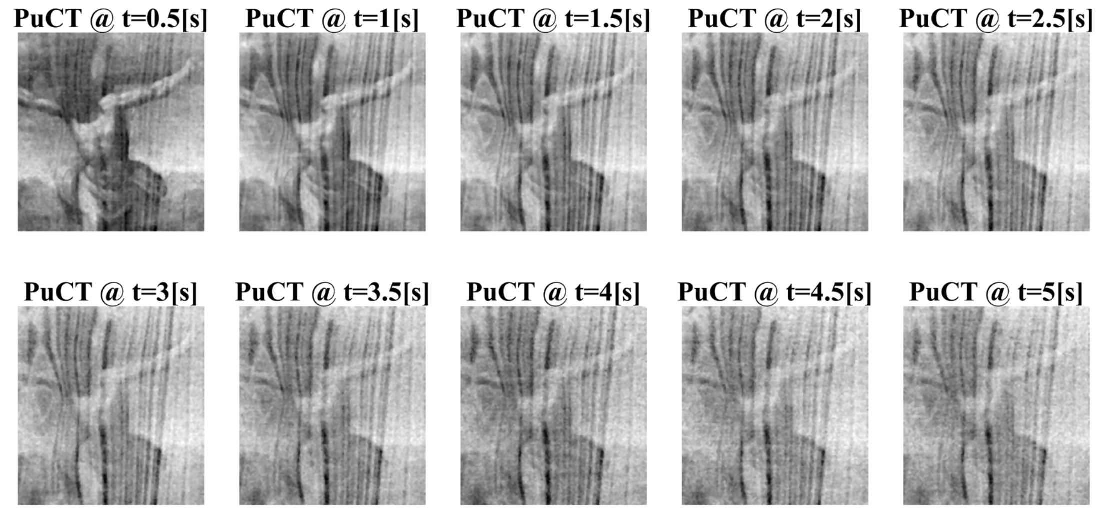

Fig. 1 PuCT images at different times: as the time increases, the detail of the wood grain becomes more visible, even if the scene (Christ's crucifixion) of the pictorial layer persists for a long time.

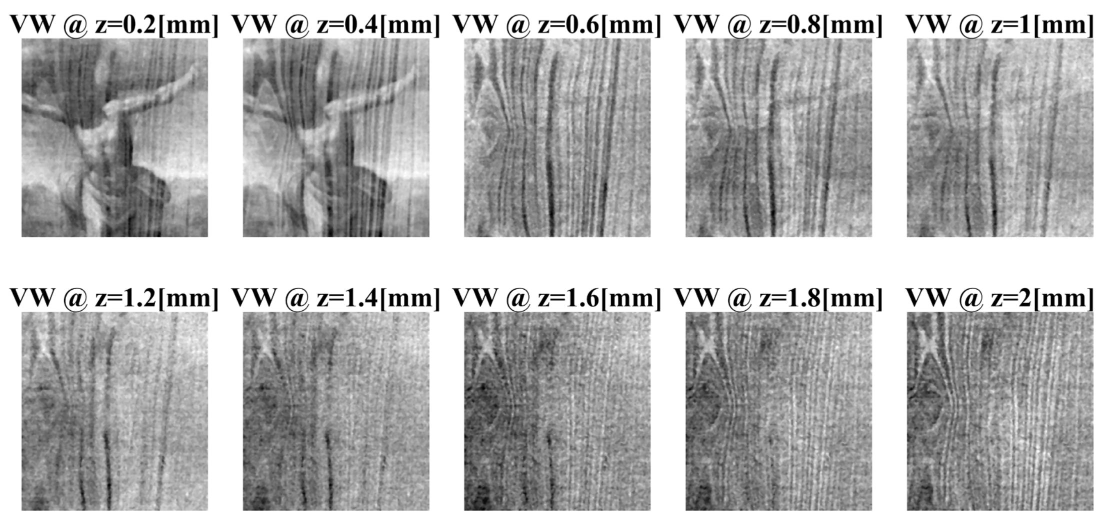

Fig. 2 Images at different depths after the application of the VW to the PuCT data of figure 1. The pictorial layer scene disappears early in depth and the evolution of the wood grain with the depth are clearly visible. For instance, the grain patterns are different from z=0.6 (ticker) to z=2 mm (finer), and the latter are not visible in PuCT images.

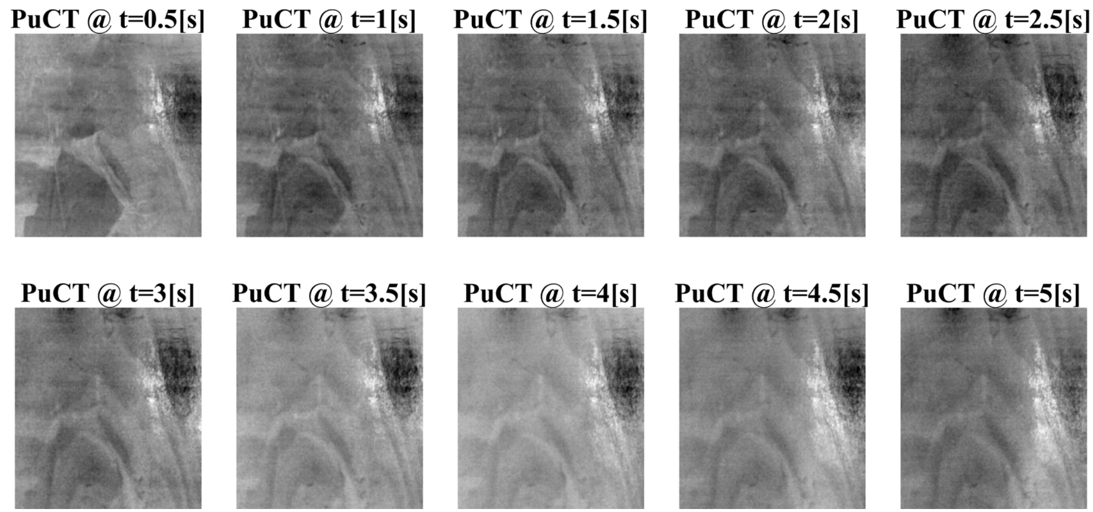

Fig. 3 PuCT images at different times for the Mantegna's "Christ's resurrection". As for Figure 1, the details of the underneath structure are unveiled when time increases. However resolution decreases with time and the "shadow" of Christ's figure superimposes with the wood grain.

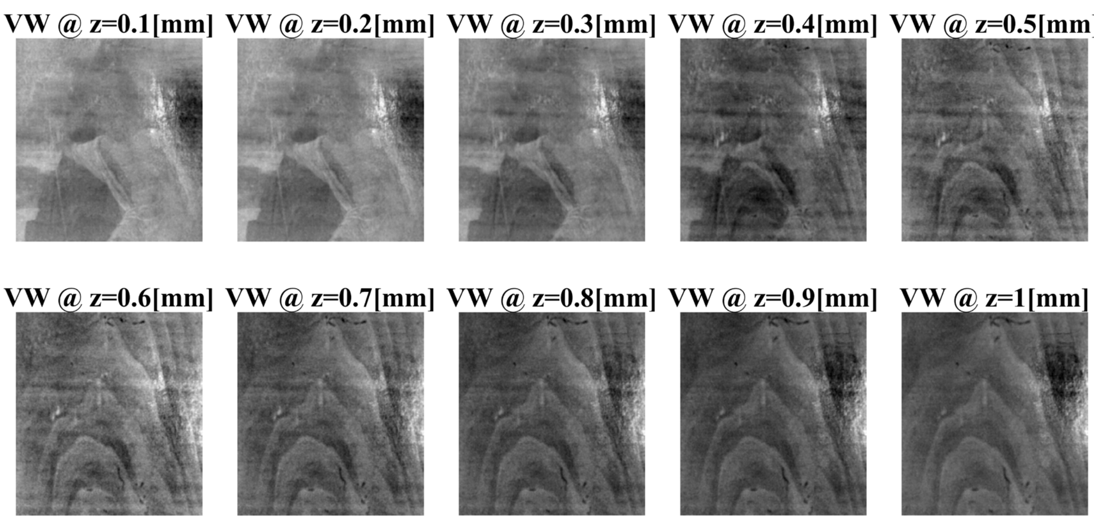

Fig. 4 VW images of Mantegna's "Christ's resurrection". The enhancement of the stratigraphy reconstruction is evident with respect to figure 3. Further, from z=0.4 to z=0.6mm, a pattern of horizontal can be seen. These are supposed to be related to the strokes of the ground layer, and they are visible in PuCT images in [3], but not for this part,of the painting.

Inspection and documentation of the condition of historic timber structures

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Abstract

Caring about historic buildings is not only important for preserving a society's cultural heritage and for attracting tourists, but also brings many other benefits: a 700-year-old roof structure of a church in Germany, for example, not only teaches us how to build stably and sustainably, but also what needs to be done to ensure that such a structure survives for centuries without significant damage. A special combination of conventional inspection (visual and tapping) with electronically regulated, high-resolution resistance drilling showed to be affordable and efficient in order to reliably determine the condition of the wood. But, it is critical to use the proper drilling technique and then to present the results in a comprehensible way, so that architects, engineers, and repairing carpenters quickly understand the condition of the structure. For this purpose, we developed a concept for mapping the condition that is fundamentally different from just revealing defects. In hundreds of restoration projects since 1988 (church roofs, half-timbered buildings, bridges, towers, harbor structures, ...), our inspections typically lead to a reduction of repair costs of 50% or more and at the same time allowed to preserve significantly more historic fabric – mainly because the renovation measures can be well planned, organized and optimized beforehand based on the condition inventory maps. In addition, our results help designing better timber structures for future uses that last longer and have less defects.

Keywords: historic monument protection, timber structures, resistance drilling, damage mapping, condition inventory.

Introduction

In the 1980s, the Federal German Science Fund supported a joined project ("SFB 315") of several leading heritage research institutes. One of the early findings was that a technical method is needed for non-destructively assessing the condition of (not only historic) timber structures (SFB 1989). At the same time, micro-needle drilling resistance measurements have been developed at the dendro-chronology department of the botanical institute at Hohenheim University for measuring the density of latewood within tree-rings and for reconstructing past climate changes (Rinn 1988). As a side-effect it was found that the drilling resistance profiles do not only reveal tree-ring density changes (Rinn et. al 1989) but also defects, caused by fungi or insects (Rinn 1992).

Applying this technology for inspecting historic timber structures quickly showed that it is critical how to present the findings: the results of the SFB315 clearly showed that the established damage inventories had not been a reliable base for structural planning, and not enough for executing and controlling the required repair work.

Thus, in addition to the technical diagnostic methods, a concept for documenting the results needed to be developed.

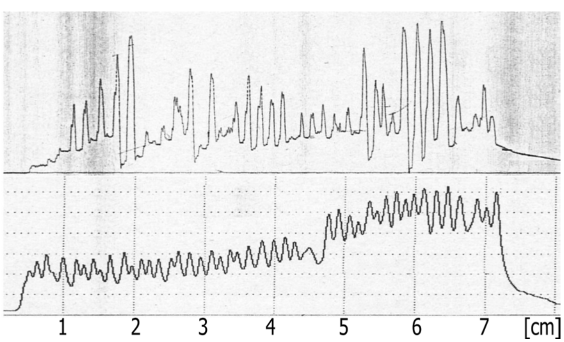

Fig. 1 Profiles of two resistance drillings obtained at the same position of an intact (dry) conifer beam. The bottom profile was measured by an electronically regulated, high-resolution resistance drill, clearly revealing the intact tree-ring density variations. The top profile was measured with a drill with a mechanical recording mechanism: it drops down to zero several times suggesting local defects (by fungal decay or insects) although the wood is totally intact. Such profiles are misleading and do not allow to reliably evaluate wood condition.

Micro-needle drilling resistance measurements

Since the first public demonstrations of the micro-needle-drilling-resistance devices (Rinn et. al 1989), more than 20 different kinds of resistance drills have been seen on the market, provided by at least 7 manufacturers (www.resistograph.com). These devices differ strongly in precision and resolution as well as in reproducibility (Rinn 2016) and many of them are not suitable / not precise enough for reliably determining the condition of historic timber structures. Thus, the drill subsequently described in this paper is just one of many different types of resistance drills. It is allowed to be labeled with the internationally registered trademark "Resistograph" because it fulfills the corresponding conditions (Rinn 2012, 2013, 2015):

- a spatial resolution of at least 25 measuring points per millimeter,
- a signal (resistance) resolution of at least 10bit;
- a correlation between profile value and density of penetrated wood of at least $r^2 > 0.8$.

Fulfilling these conditions is prerequisite for obtaining profiles that clearly reveal tree-ring density variations (Rinn 1996, 2016) and at the same time, for allowing to differentiate between intact and decayed

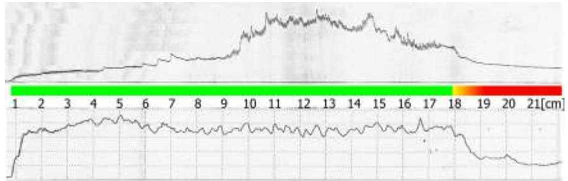

Fig. 2 Two resistance drilling profiles measured in a few millimetre distance. The bottom profile, obtained by a high-resolution electronically regulated resistance drill correctly reveals wood condition (Green = intact, red = decayed). The top profile, obtained with a simple resistance drill, using a spring-loaded recording mechanism, does not allow to correctly evaluate wood condition.

wood, thus for reliably detect defects that are structurally relevant in terms of load-carrying capacity and durability.

The importance of this aspect of selecting the right type of drilling resistance device is illustrated by the following example: the historic roof of a castle in Germany was technically inspected and the expert concluded that the entire structure needed to be replaced because he found evidence of insect damage in practically all drilling resistance profiles. In contrast, a follow-up inspection by another expert using an electronically controlled and high-resolution drilling resistance measuring device revealed no evidence of any significant damage and therefore no need for repairs. The first expert opinion was fundamentally wrong because the drilling resistance measuring device used systematically delivers faulty and misleading profiles (similar to Figure 1).

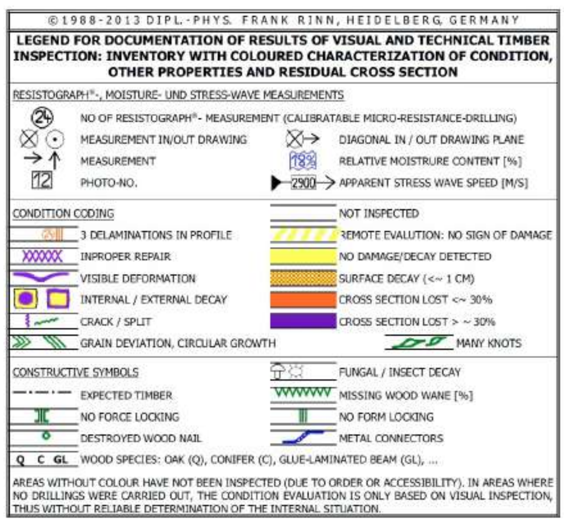

Fig. 3 Typical legend for timber structure condition maps.

Documentation of inspection results

The long established damage inventories usually marked defects either with black patterns or typical colours, such as red. That means, there was no differentiation between the areas that are intact and the ones that have not been inspected. Consequently, by looking at the inventory, the architects, engineers and carpenters did not know, whether the non-marked beams or beam-sections are intact or not inspected. This uncertainty systematically led to unnecessary work and costs.

Thus, the biggest and probably most important step forward in our documentation concept was to clearly differentiate by colours between the areas that have not been inspected and the beams that have been found to be intact (Fig 3).

Practical application in the real world

Typical steps of our inspections are:

1. Preparation
   a. Clear definition of restoration targets.
   b. Clarification of precision and scope of inventory plans and intensity of the condition inspection.
2. Making up a new or corrected version of an existing inventory plan / sketch.
   a. Coordinate system for the building.
   b. Drawing up a new inventory: prefer overview drawings rather than many single axis

plans. All beams of a facade in one plan, all roof-rafters in one plan.

3. Examining the timber construction
   a. Visual evaluation and documentation:
      i. Obvious external damage.
      ii. Missing parts of the construction.
      iii. Deformations of beams and joints.
      iv. Multiple use of building parts.
      v. Improper previous repairs.
   b. Use of traditional skilled handcraft inspection methods (hammer, ...).
   c. Use of technical devices, when and where necessary (moisture content, drill resistance, stress waves). We drill as often as required to be sure about the condition, thus more often into invisible beams.
   d. Coloured documentation of the results of the examination in the inventory sketch.
   e. It is critically important that the measured results are interpreted on the spot and that the evaluation of the wood condition is documented by colouring the corresponding beam in the sketch on site (because you never know more about the wood than when standing in front of it with the measurement results in your hand!)
   f. Determining animal or fungal decay and the cause of damages.
4. Report with maximum one page of pure text to read - all relevant information should be clearly drawn in the coloured inventory. One good plan or sketch explains more than 10 text pages (handcraft workers normally do not read long reports and damage lists, but they check and understand the coloured plan). The coloured sketch needs to be self-explaining in terms of what has to be replaced.
5. Constructional evaluation of results as drawn in the coloured inventory plan.
6. Planning and inviting of tenders for measures based on coloured inventory plan.
7. Execution of the reconstruction work.
8. Control and examination of the repair work according to the coloured condition inventory plans.

Fig. 4 Typical condition map showing the results of a one-day inspection of a historic fassade in Southern Germany. The colours easily and quickly indicate, what needs to be done for restoring the building.

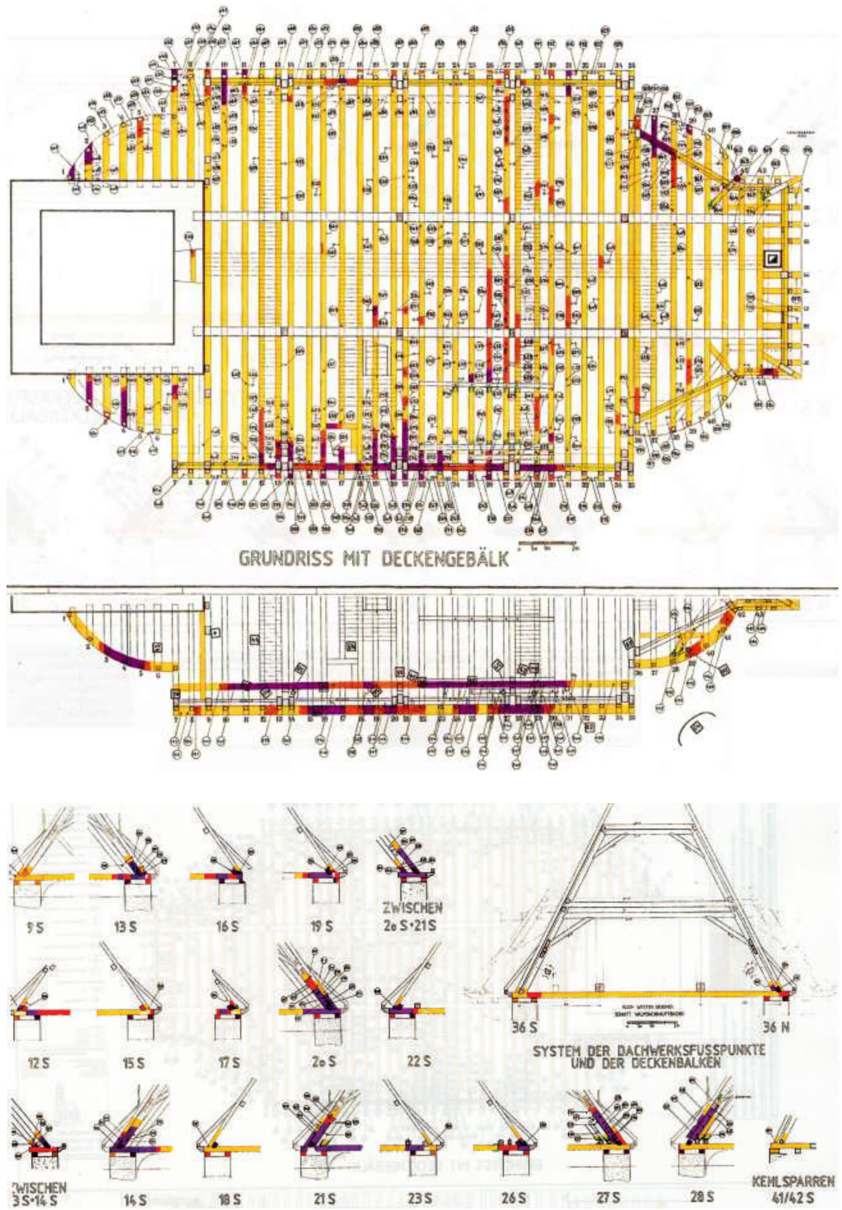

Fig. 5 Coloured condition map of the ceiling beam level and uprising construction of a historic church roof truss near Frankfurt, clearly indicating what needs to be done for repairing the structure.

Results and conclusions from hundreds of restoration projects since 1988:

1. Conventional, only visual inspection
   a. mostly found less than 30% of total damage,
   b. overestimated the extent of visible defects
   c. underestimated the amount of internal / hidden defects,
   d. leads to:
      i. increasing costs during restoration
      ii. increased loss of historic fabric
      iii. need for re-restoring after a few years because internal decay was not found but reactivated later by moisture.
2. Proper application of NDTE, especially resistance drilling, allows, on the one hand, to find also hidden damage and, on the other hand, to reduce the scope of restoration works to the really necessary extent:
3. Based on our inventories
   a. Restorations were usually carried out in time and in the frame of the estimated cost plan.
   b. Cost reductions typically about 50% or more
4. Our inspections led to savings in total costs of typically 5 to 10 times the inspection charges.
5. Much more historical building material has been preserved (at lower costs).

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The potential of Thermal Quasi-Reflectography to advance the Non-Destructive Testing image-based protocol in Cultural Heritage

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Abstract

Thermal Quasi-Reflectography (TQR) is a recent imaging technique, introduced by the authors and well-accepted by Heritage community, based on the acquisition of reflectance information in the MWIR thermal region. Using an optical calibrated imaging set up and an optimized image data pipeline, the MWIR signal from the artwork surface is acquired in quasi-reflectance approximation, namely, by minimizing the spurious thermal emission at room temperature. The carried information is related to the response of the artwork surface. As such, TQR provides an additional tool to probe the surface materials (characterized by a MWIR fingerprint, e.g., organic matter) as well as of the surface structure features (matched by resolution sensitivity, e.g., cracks defects).

We briefly discuss the potential of the TQR in the NDT of mural paintings and book heritage, taken as exemplary case studies of effective integration of the technique in the conventional diagnostic protocol.

1) In the first case, MWIR quasi-reflectography is used in dual-mode approach with thermography for the analysis of Leonardo frescoes (Sforza Castle in Milan). TQR allowed sharp imaging (close to optical diffraction limit) of surface defects and restoration patches, at 500 μm resolution, that can be exploited to spatially register thermography. The result was a mosaic mapping of the sub-surface fresco detaches, referenced to the visible surface, that was used by the restorers for the intervention.

2) In the second case, TQR was integrated in the conventional imaging protocol of manuscripts to investigate the *Vergilius* palimpsest (Biblioteca Capitolare of Verona). This case, TQR was used in multimodal approach, providing complementary information to the UV-VIS-IR reflectance-luminescence imaging platform, concerning the non-homogeneous distribution of conservation products in the surface layer.

Keywords: thermal quasi-reflectography (TQR), infrared imaging, thermography, integrated diagnostics, mural painting, manuscripts.

1. Infrared imaging of multi-layered artworks and the Thermal Quasi-Reflectography technique.

Infrared (IR) imaging turns to be a versatile tool for the investigation of multi-layered artworks. An optimized setting of different acquisition modalities and the selection of proper IR bands allow us to probe in full field both the structural and the matter response at surface and subsurface levels. Reflectography in the near-IR (up to 2.5 μm), especially in a multispectral fashion [Striova 2020], enables the sharp imaging of features underneath the surface, thus unlocking drawings in paintings or hidden text in book heritage, as well as information on (some) materials distribution. Information is obtained based on the reflectivity response and optical transparency of the painting matter in the near-IR. Differently, IR imaging in the thermal bands MWIR (3-5 μm) and LWIR (7-15 μm) is being performed in emission modality (namely, thermography), thus allowing the detection of subsurface "defective features", i.e., discontinuities in materials distributions like detachments. Quantitative information can be obtained by processing the surface temperature response (spatiotemporal) after a controlled heat stimulus [Mercuri 2017].

An integrated multi-modal protocol based on reflectance and emission-based imaging provides a more comprehensive diagnostics of the artwork, towards a multi-layered model, which should go beyond the simple practice of jointly using the techniques. On the research methodology side, the topic of implementing integrated protocols is open, calling the heritage community to a discussion. Difficulty is concerned with the non-possibility of standardizing the target object: an artwork is a unique case-study for which it is difficult to conceive a general methodology, or, often, this is not the priority when supporting the conservator.

Recently, a novel tool for IR imaging of artworks, named Thermal Quasi-Reflectography (TQR) was demonstrated by the authors [Daffara 2012, 2018] and well received by the heritage community.

In principle, TQR is based on the acquisition of the reflectance information in the MWIR thermal region. It was shown that using an optical calibrated imaging set up and an optimized image data pipeline, the MWIR signal from the artwork surface is acquired in quasi-reflectance approximation, namely, by minimizing the spurious thermal emission at room temperature. By triggering a proper source to the MWIR (InSb) radiometric camera, the emissive contribution is negligible (about 1%) with respect to the reflective one and a calibrated MWIR reflectance map can be obtained. Thus, the carried information is related to the response of the artwork surface, and the TQR provides an additional tool to probe the materials characterized by a MWIR fingerprint (e.g., organic matter). Furthermore, TQR imaging has proved to have high contrast sensitivity and high resolution (near the diffraction limit), thus enabling the mapping of fine features in the surface structure (e.g., cracks defects).

Here, we briefly discuss the potential of the TQR to advance the non-destructive testing (NDT) of Cultural Heritage by taking as exemplary case studies two effective integration of the technique in the conventional diagnostic protocol. In the first case, MWIR quasi-reflectography is used in dual-mode approach with thermography on mural paintings, while, in the second case, TQR is integrated in the conventional imaging protocol of manuscripts.

2. Integration of TQR and thermography to advance the NDT protocol on frescoes

MWIR quasi-reflectography was used in dual-mode approach with thermography for the analysis of the *Monocromo* by Leonardo at the Sforza Castle, in Milan [Daffara 2021]. The masterpiece was subject

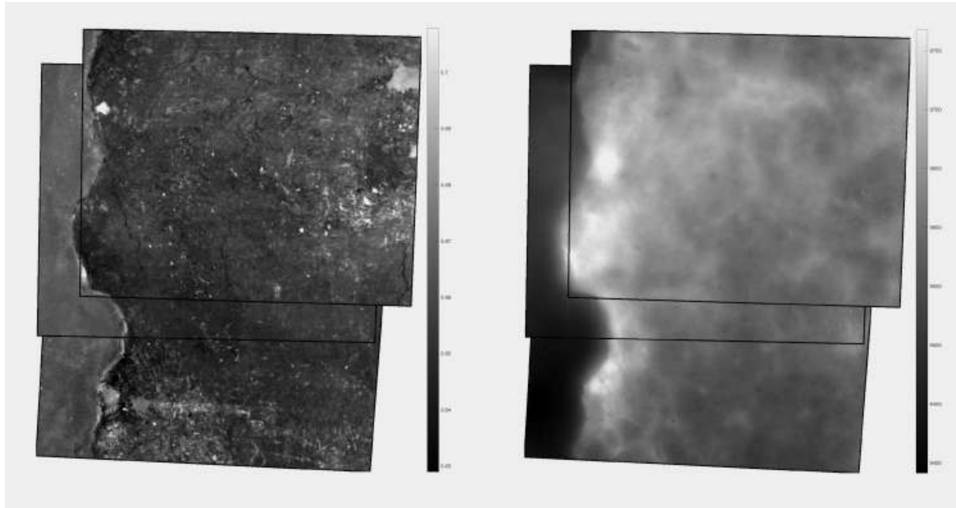

Fig. 1 Example of dual-mode dataset: TQR reflectance map (left) and the thermogram in the MWIR (right) are mutually registered. TQR detects surface features like restoration materials and saline patinas, while thermography detects subsurface detaches.

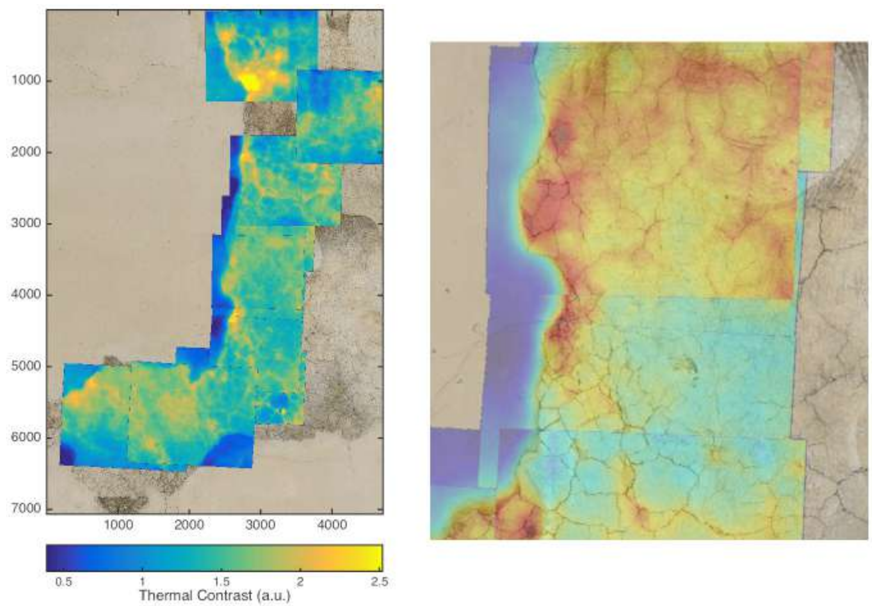

Fig. 2 Thermal mosaic registered to the visible surface (500 µm pixel size) for precise mapping of the detachments.

to restoration by Opificio delle Pietre Dure, during which several diagnostic campaigns were carried out [Palazzo 2017].

An example of results is reported in Fig. 1 and Fig. 2. In the dual-mode approach, two mutually registered datasets are acquired in reflectance and emission modality, the TQR map and the thermographic sequence. TQR allowed sharp imaging (close to optical diffraction limit) of surface defects and restoration patches, that were exploited to spatially register thermography. The result was a mosaic mapping of the sub-surface detaches, referenced to the visible surface, that was used by the restorers for the intervention.

The precise mapping of frescoes detachments is recognized to be an important and difficult task. The key role of TQR, carried out in dual-mode with thermography, for advancing the diagnostic protocol on frescoes concerns the possibility of scanning large surfaces at high resolution thanks to the possibility of creating the mosaic in the reflectance MWIR domain. In case of the Leonardo painting, subsurface defect mapping was referenced to the visible surface with submillimeter accuracy (500 μm pixel size).

Fig. 3 From left to right; top: VIS and TQR imaging in the MWIR (3–5 μm). Bottom: IR reflectography with CMOS (0.8–1 μm) and InGaAs (0.9–1.7 μm) sensor. TQR is highly sensitive to surface materials.

3. Integration of TQR and optical imaging to advance the NDT protocol on manuscripts

TQR was integrated in the conventional imaging protocol of manuscripts to investigate the *Vergilius* palimpsest at the Biblioteca Capitolare of Verona [Cimino 2023]. The palimpsest contains several traces of reagents and conservation treatments. The effectiveness of MWIR reflectography and thermography in manuscripts diagnostics has been reviewed in literature [Orazi 2020]. In this case, TQR in the MWIR was used in a multimodal approach, with a customized setup, with the aim of providing complementary information to the UV-VIS-IR reflectance-luminescence stack acquired with the available imaging platform (Phase One).

An example of results is reported in Fig. 3. The high contrast sensitivity of TQR imaging enabled the discrimination of the thicknesses of the product layer as well as of the different lacunae integrations with Japanese paper and modern parchment. TQR in the MWIR range was shown effective and complementary to UV-based and IR-based imaging, especially concerning the investigation of the conservation history.

Given the complexity of palimpsests, the key role of the use of TQR for advancing the UV-VIS-IR protocol on manuscripts concerns the spatial mapping of materials with fingerprint in the MWIR range, allowing to supervise the characterization with punctual IR spectroscopy.

4. Conclusion

Thermal Quasi-Reflectography (TQR) is a recent technique, which is not part of the routinely used diagnostics protocol. We reported a short discussion on the topic by summarizing exemplary results from this research group on frescoes and on manuscripts. Based on the acquisition of the MWIR radiation in reflectance modality, the TQR technique allows a sharp imaging at surface level and provides complimentary information to conventional techniques, like thermography and optical imaging. The case studies on notable masterpieces demonstrated the potential of TQR for advancing the image-based protocol in Cultural Heritage. A systematic research plan on the topic is desirable.

Acknowledgements

on-field diagnostics on Leonardo frescoes of the Sforza Castle was supported by Dr. Francesca Tasso (Soprintendenza of Castello Sforzesco, Milan, Italy). The dual-mode experiments on the Monocromo was co-supervised by Paola Ilaria Mariotti from Opificio delle Pietre Dure for the conservation issues.

The experimental diagnostics at the Biblioteca Capitolare was conducted in the framework of a collaborative project at Univ. of Verona, co-supervised by Prof Paolo Pellegrini for the philology issues; the measurement session on the palimpsest was carried out by Dr. Giacomo Marchioro.

The project manager, Dr. Timoty Leonardi, and the president, Mons. Bruno Fasani, of the Foundation of the Biblioteca Capitolare of Verona are acknowledged for the access to book heritage.

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A fast procedure for the assessment of historical floor timber beams in presence of pictorial decoration

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Abstract

With the aim of defining a procedure for the rapid and easily reproducible investigation of timber structures, such as historical wooden floors with pictorial decorations, it is intended to present the methodology applied during a test campaign on floor timbers, with some limitations on the investigation. The floors analysed belong to a Baroque aristocratic palace open to the public and used as a museum: the space and time available for the investigation were therefore very limited. Diagnostic instrumental investigations (ambient humidity and resistance drilling) were carried out at selected points, following visual observations of the state of preservation of the wood and paint, wood species identification, construction technique, type of support and geometry, possibly deformed and/or damaged (maximum deflection along the profile), in order to minimise interaction with the historic timberwork. It was possible to take a sample of material from the damaged areas to check for the possible presence of pathogenic micro-organisms.
The intention is to be able to calibrate an operational method that allows the comparison of as many similar structures as possible, knowing that, for various reasons, it will not always be possible to carry out exhaustive and extensive surveys on all of them, as would be preferable. However, these investigations must be able to provide sufficient data for structural evaluation, but also for their correct maintenance and conservation, both within the same building and in similar timber structures.

Keywords: timber floor beams, NDT investigation, visual inspection, pictorial decoration, resistance drilling.

Introduction

The importance of accurate diagnostics of existing timber structures (floors and roofs) in cultural heritage is well known and there are numerous texts and regulations that help to carry out analysis procedures correctly and systematically. This analysis is important to save historical timber beams that are too easily replaced, unfortunately in many cases, with other types of structures. Some wooden floors are very old and show the signs of time, and despite deformations, biotic attacks, brittleness and torsion, they are still able to perform their structural work and retain their historical and cultural value, also because of the carpentry techniques used. The construction characteristics and pictorial decorations, the quality of the elements and their connections, the solutions adopted over time to locally repair the structure, and all the historical events, which have affected it, mean that each structure is different from the others also in terms of its state of preservation.

Obviously, this capacity has to be demonstrated, not so much from the point of view of their morphology and design, which is unlikely to be wrong if the ancient structures are still functional, but from their maintenance over time o the variation of the current structural scheme from the original one (due to changes in use, stresses, renovations), which may have changed their functionality. Wooden structures, if well preserved, have proven to have high durability, provided that they are kept in a constantly dry environment, avoiding damage from moisture infiltration and stagnation in the walls, particularly near the headboards. In addition to degradation caused by insects and fungi, mechanical damage can also occur, represented by cracks and deformations, with sometimes safety-critical effects.

Correctly assessing the condition of timber structures is an essential requirement to guarantee the quality of the intervention project and its compliance with the requirements of the building's function. Unfortunately, it is not always possible to collect all the data required by specific standards and guidelines [1, 2, 3, etc.], particularly when dealing with floors with historic pictorial decorations and/or covers. In fact, these coatings often cover the knots and, in the absence of degradation/lacunae, it is not even that simple to identify the wooden essence.

For these reasons, a specific expeditious investigation procedure was applied for wooden floors with pictorial decoration, which was minimal but sufficient to allow a structural assessment of the state of conservation of the main timber elements.

Survey experience at Palazzo Viani Dugnani in Verbania

The customers, with a view to restore the two-storey palace, built in the second half of the 17th century and since 1914 Landscape Museum [4], requested, in agreement with the designers, a series of diagnostic investigations prior to the final restoration design and strengthening of Palazzo Viani.

Among others, investigations were carried out on the wooden structures on the first floor. The first floor of the museum is characterised by polychrome wooden ceilings from different centuries, while the walls have been renovated with thick garnet red paint; each wooden ceiling is accompanied by a painted band on the walls of different height. The majority of the wooden ceilings feature repeated decorative modules, while on the Via Ruga side, there are two beautiful ceilings with non-repetitive decorations and ornaments that create a unicum on the entire ceiling ("a passasotto" decoration); they are painted in lime with many gold brush strokes in the style of the 17th-18th century. In other rooms, the ceiling, with polychrome lime tempera decoration, ap-

Fig. 1 Palazzo Viani Dugnani: decorated timber beam near the decorated wall support with angled cracks. The beam presents localised decayed decoration (infiltration, colour alteration, dark stains, washouts and gaps). The lacunas in addition allow to observe the direction of the fibres.

Tab. 1 Example of a survey template for a timber floor according to the presented fast procedure.

<table>
<tr><td>Building name:</td><td>Survey of the morphology and of the alterations/decays</td><td>Date of inspection:</td></tr>
<tr><td rowspan="4">Number of the room and of the floor (add a map):

</td><td colspan="2">Structural Typology:
i.e. Double-beam ceiling with rulers and fine pictorial decoration.</td></tr>
<tr><td colspan="2">Support:
Heads when embedded in masonry on both sides</td></tr>
<tr><td colspan="2">Corbles:
Presence or absence of corbels and in what material (wood, stone, or other)</td></tr>
<tr><td colspan="2">Wood species:
indicate the wood <u>species</u>, the <u>geometry</u> of the section and the presence of stain with description. The recognition of the wood species, geometric features and decay was carried out by visual inspection and according to the national standard on Cultural heritage, Wooden structures [1 and others indicated here inside].</td></tr>
<tr><td colspan="3">State of conservation: (Fig. 2a,b)
1. Report the presence of <u>cracks</u>, their location and direction. Also in correspondence of the supporting wall. Report the presence of any additional support.
2. Indicate the presence of <u>knots</u> if they can be seen through the paint.
3. Indicate the presence or absence of <u>biotic attack</u>.
4. Indicate the presence of <u>deflection</u>, where it is maximum and quantify it (Fig.3).
5. Report the relative <u>humidity</u> of the environment and the humidity of the beam.
Remarks:
Any peculiar information related to the specific situation of the floor or that may help to understand the causes of floor damage, such as the state and use of the room where the floor is located, the condition of the vertical support structure, etc. (For example, see Fig. 2c).</td></tr>
</table>

pears to be of a more recent, possibly 19th-century phase with repetitive lacunar modules. The ceiling shows minimal general degradation from water infiltration; loss of the paint film, tannin stains, decohesion of the paint film on the more fragile colours and dark retouches. On the below plastered strips, the degradation is shown by a general matting due to accumulated dirt deposits, punctual damage from leakage, salt efflorescence, holes and incompatible punctual plastering.

The fast procedure adopted for the timber structures

The survey must be carried out by specialised and qualified technicians, adopting the procedure, as described in [1], and provides for the collecting and processing of the minimal data actually required for static assessment calculations and the design of any strengthening interventions, so the level of detail is adapted to the requirements defined by the designer.

The presence of the paint film, however, does not allow all the observations required by the procedure to be carried out. In the case study reported here, in fact, it was not possible to correctly define the mechanical quality class, nor the microscopic recognition of the wood species, which was however carried out macroscopically thanks to the advice of a local expert on site.

The presence of pictorial decorations can help highlight further degradation along the beam, such as marks left by percolating infiltration water that dissolves the tannins in the wood and part of the pictorial decorations. These can leave dark stains, particularly on their outermost edges. Or exposure degradation is more evident where the pictorial decoration has been lost (Fig 1).

A template resumed in Table 1 for each observed timber beams was thus developed containing the items beside.

a b c

Fig. 2a, b, c a) General view of the beam, which is warped, with a few small chamfers and dark spots of moisture; b) Detail of the beam rotation near the support on the spine wall, but with straight corbel, metal bands can also be observed; c) View of the roof truss above the same room with the metal bands supporting the tie beam investigated and visible from the below room, which turns out to be the tie beam of the roof truss.

It is important to include pictures in the form in order to understand the type of floor, the details and its unique characteristics (Fig. 2). The beam in the apparently worst condition is selected and the deflection data measured at different points with the various instruments available is reported. The focus is usually on the midpoint, but it may happen that the midpoint is not always the point of maximum deflection, as in the example in Fig. 3.

In the case shown in Fig. 2, an inspection on the upper floor confirmed that the beams are not part of a floor slab, but rather of decorated tie beams of king post roof trusses left exposed on the lower floor.

With regard to the quantification of decay and determination of effective sections, penetrometric investigations were carried out with an instrumented drill (resistance drilling devices [5]), in order to detect the homogeneity of the section, the presence of cracks and superficial or internal deterioration of the wooden material, presence of moisture, paying due attention to the signs that can be caught with difficulty in the pictorial decorations. This device provides a densiometric profile along the investigated section and it can also non-destructively provide the geometry of a beam even when covered by a decorated plank. Being a local test method, timber components in existing buildings often require multiple measures, depending on specific problems to investigate (e.g., beam ends threatened by moisture due to masonry contact, presence of decay, cracks), to have statistically more reliable results [6] and to compare different observed situations along the same beam, so it is useful for a global calibration of the timber element.

The results of the penetrometric tests should indicate two dimensions: the drilling depth (Total Profile Pt) the estimated resistant profile (Resistant Profile Pr). With these data it will be possible to achieve an index obtained from the ratio of the calculated resistant profile (Pr) to the length of the investigated profile (Pt). Pr/Pt ratios tending towards a value of 1 refer to profiles in which no degradation conditions are found. So, it is possible to group the profiles into two classes: 1) class 0 - tests that provided the following ratio: $Pr/Pt > 0.7$; 2) class 1 - tests that provided the following ratio: $Pr/Pt < 0.7$. These data should be accompanied by the graphs ob-

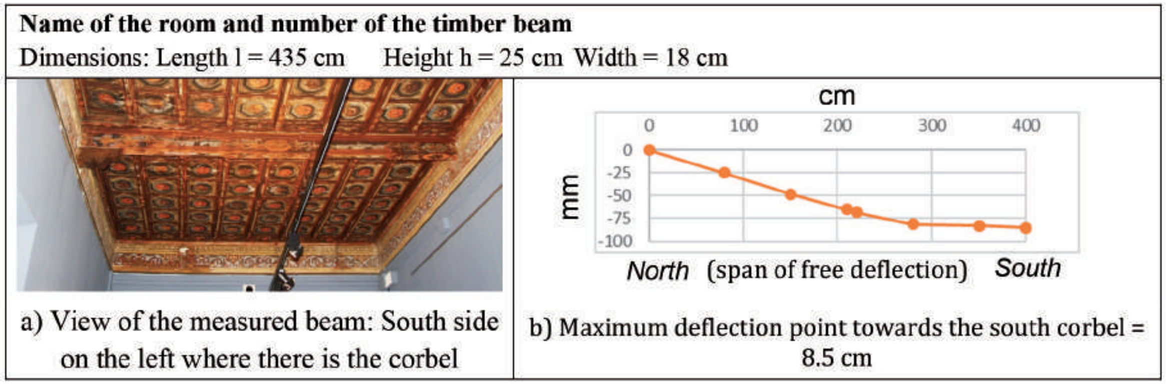

Fig. 3 Example of a survey with indication of the quantitative deflection data, here not in the middle span, as attended, but towards one of the timber heads.

tained from each test, with the interpretation of the acquired profile trend and some photographs illustrating the test position. The classification into two classes allows a quick identification of critical areas to be inspected directly to explore the type of damage/defect. This classification is based on experiences gained in testing timber structures by the research group once coordinated by Prof. Luigia Binda of the Politecnico di Milano.

A model table is provided, showing the average size of the tested element and the depth reached by drilling, thickness of the element at the test point, in the case of pass-through holes (Table 2). These measurements do not always coincide, given the geometric irregularity of the wooden elements. Temperature and humidity data of the environment and of the wooden element are also reported.

Conclusions

Objectives, limits and methods for carrying out the diagnosis of historic wooden ceilings must be clearly defined by the competent technical designer. Greater difficulties arise when historic ceilings are entirely covered with a pictorial decoration that hides many of the natural characteristics of the wood, or there is even the presence of a decorated planks covering the beams. A good knowledge of load-bearing timber structures certainly helps the structural engineer to decide on the necessary structural intervention, punctual and/or localised, if necessary, with considerable cost savings when compared to the complete replacement of the load-bearing structure, guaranteeing sustainability and safety. Strengthening costs can be many different in fact.

For beam classification, in some cases, visual inspection can only provide partial information on chamfers

Tab. 2 Example of a table with the results of the quick classification of the deteriorated area of timber structures obtained from penetrometric tests.

Test profile	T °C	H (%)	Tested Element	Dimensions (cm)		Testing trajectory	Pt (cm)	Pr (cm)	Pr/Pt	Class
				Base	Height					
L 1.04-R1	20	14.5	Beam	14	26	90°	25	25	1	0

Classification: 0 = insignificant profile reduction; 1 = significant profile reduction.

and fibre inclination if they coincide with cracks and deformations. A comprehension of the structural and load diagram suggests the most significant points of further investigation. The degradation of the painted decorations and the presence of any lacunae are useful areas for the macroscopic recognition of the wood species and for the execution of resistance drilling profiles that, repeated at several points on the same beam, can provide indications on the homogeneity of the geometry, density characteristics of the timber element, as well as providing statistically more reliable data. The ratio of resistant section to total section deduced from the resistance drilling profile allows an immediate reading of critical areas. In addition, integration with complementary investigations such as ultrasonic tests, can help to refine the investigation and, in some cases, may indicate whether it is suggested to perform load tests. A recent promising development in the use of densiometric resistograph data could be to report it as a non-dimensional value with reference to a sample of known class [6]. Another interesting application derives from correlations with the density measured in the laboratory to derive the dynamic modulus of elasticity of the material under test by means of ultrasonic measurement [7].

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Masonry dome spandrels in an early 16th century church in Piacenza: non-destructive approach by inspection and infrared thermography

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Abstract

The pendentives of a dome connect the pillars with the generally circular shape of the base line of the dome, above the pillars. The pendentives can appear in various visible shapes. However, their real shape and configuration is often hidden. Moreover, as the ring of the tambour or dome is a circle inscribed in a square, or other shape, the pendentives also perform a consistent structural function, protruding from the walls between pillars, supporting heavy loads of the dome.

With reference to the Renaissance basilica of *San Sisto*, in Piacenza, there is no information about the design and construction nor about the technical details of its 2 domes. However, it is known from historical documents of the church's reconstruction time (early 16th century), that these domes should be the work of Alessio Tramello, a skilled architect, who had earlier possibly worked with Bramante, in Milan. In this outstanding church with 2 transepts, the first just at the rear of the façade, the second in classical position, the 2 domes, both circular in plan-view and similar in diameter, without lanterns, appear different at the intrados.

In a quest for deeper knowledge about these domes, the pendentives, the drums and domes were subjected to careful visual inspections followed by thermographic tests, from inside the church. The extrados of the domes are not visible as encased in *tiburiums*, not accessible.

These investigations have revealed some of the details about materials and technical solutions adopted by the designer in relation to the pendentives, which look different for each of the two domes. The contribution intends to shed some light on these 2 interesting construction elements showing example images from the inspections.

Keywords: pendentive, spandrel, dome, visual inspection, IR, thermography, NDT, masonry, cultural heritage.

The pendentives of a dome – also called spandrels - connect the pillars, placed according to a geometric polygonal shape in plan-view, with the generally circular shape of the base line of the dome, above the pillars. At the angle between two walls above the arches that connect the pillars, the pendentives can have various visible shape (Colla, 2022). However, their real shape and configuration is often hidden. Due to the ring of the tambour or dome being a circle inscribed in a square, or other shape, the pendentives also have consistent structural function, protruding from the walls between pillars, having to support large portions of the dome's load.

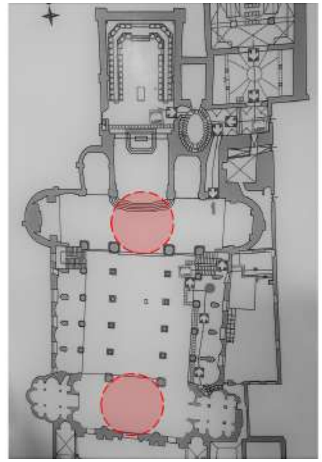

Fig. 1 Domes' position in plan-view.

Fig. 2 Internal views of south and north domes.

Work objectives

In a quest for greater knowledge about the domes of St. Sixtus' basilica in Piacenza, the pendentives, drums and domes were subjected to careful visual inspection. These inspections were followed by non-invasive thermographic tests, from inside the church, with particular focus on the domes' pendentives. The contribution is meant to shed some light on the spandrels' construction technology and to show examples of the recorded images.

Case presentation

Piacenza, a Roman colony with anti-Gallic function, at the fall of the Roman Empire was dominated by the Goths (476-553), by the Langobards (570-774) with a Byzantine short while, then by the Franks (774-888). In 853, Angilberga, wife of Lodovico II the Pious, the Langobard king, decided to found a monastery of Benedictine nuns with a church dedicated to Saints Sisto and Fabiano and to the Resurrection. The monastery was conspicuously endowed with land, villas and farms and became a true centre of power. In 1112, the nuns were replaced by monks, also Benedictines. In 1285, the role of "commenda" was attributed to the monastery, preserved until 1425. The church housed the relics of both Saint Sixtus (San Sisto) and St. Barbara, object of pilgrimages from both France and Germany and therefore had "an economic income". However, the Commendatory status had reduced the abbey to a state of total abandonment. In 1425 the abbey was handed over to the Cassinese Congregation of St. Giustina of Padua. Due to the severe decay state of the construction, at the end of the 1400s, the religious were forced to begin work for the reconstruction of the church as it is today. In the 2nd phase of this Renaissance church's reconstruction, Alessio Tramello, a skilled architect from Piacenza (earlier he had possibly worked with Bramante, in Milan) was in charge: he intervened from 1505 to 1514 and was responsible for the roofing of the whole church (Ganz, 1968; Ganz, 1983; Arisi, 1977). This elegant church is in the shape of a Latin cross, with 3 naves and lateral chapels. There are 2 transepts: a south one, just at the rear of the façade; another one to the north,

Fig. 3 East view of southern *tiburium*.

Fig. 4 East view of northern *tiburium*.

in classical position, to give shape to the transversal arm of the cross. The intrados of the 2 domes, both circular in plan-view and similar in diameter, without lanterns, appear different (Fig. 1-2). The domes' extradoses are not visible as encased in *tiburiums* (Fig. 3-4). The 3-nave crypt is the largest in Piacenza, with 4 chapels and choir (restored in 2005). Unfortunately, there is no information about the basilica's design or construction nor about the technical details of the 2 domes.

IR method

Infrared (IR) thermography tests exploit the thermal energy that each material naturally emits when not in thermal balance with its environment. Hence, it is a predominantly passive technique that merely records the heat emitted by the surfaces in the areas framed by the IR camera. The achievable resolution is influenced by the capacity of the instrument used (its thermal sensitivity and number of pixels, first and foremost) and it is a function of the tested materials' characteristics and of the intensity and speed of temperature changes taking place in the environment (Colla et al., 2008), (Argnani et al., 2022). Furthermore, due to the very short wavelengths of thermal signals, the ability to investigate in depth is normally limited to no more than a few centimetres. In Saint Sixtus church, the IR data acquisition campaigns were carried out in different seasons, starting in 2021 and employing 2 different IR cameras: a 76800-pixel camera and a higher resolution 300000-pixel camera.

Experimentals

Inside the church, the visual investigations were affected by poor and unfavourable light conditions (both natural and artificial) around the domes' intrados and pendentives as well as by the exceeding distances (>10m) between viewpoints and areas of interest. However, for the spandrels of the southern dome, thanks to decay signs such as fine cracks and rust points, it was observed a vertical line in the centre of each pendentive (Fig. 5). At a more careful check via zoomed-in photos, this line appeared to be a vertical metal rod, probably square in section, disappearing above in the drum's lower frame (dotted mark in Fig. 6). At some distance away from this point, at both left and right side, two sorts of hooks or rod's ends were also just distinguishable (smaller circles in Fig. 6). Thus, it is possible that 2 further elements, similar to the central one, are also meant to help to support the leaf of brick masonry of the spandrel. The IR tests have shown – but only barely visible in some pendentives – the presence of the described central vertical element (see arrows on right pendentive in Fig. 7) and of its lower-end anchor point (see dotted circle on right pendentive in Fig. 8). Likely, this anchor point ties-in through a tie-rod in the masonry pillar behind the pendentive. These vertical metal elements are possibly anchored at the top in a further metal piece running all along the base of the drum. Because of the out-projecting spandrels, a tie-system is needed to anchor the whole weight of this masonry material and of the above leaning drum and dome, which are exerting strong vertical and rotating forces on the pendentives.

From the roof attic space, inspections to the drums' outer surfaces, were only partial because large areas were inapproachable; as well, the domes' extrados remained inapproachable. Notwithstanding the difficult access to only 2 faces of the drum of the south dome (N-E and S-E sides), at the base of drum the inspection has revealed the presence of metal pieces sticking out in horizontal radial direction (Fig. 9-10). These are the anchor points of multiple metal tie-rods present in radial horizontal direction for every pendentive, confirming the hypothesis of a tie-system made of radial tie-rods with pulling support function for the masonry parts.

Otherwise, the pendentives of the north dome show different configuration: first of all, each pendentive area is hollowed by a niche (containing a painted terracotta hollow figure bust, Fig. 11) and a ring is contouring the hollow space. Some fine cracking revealed the size of this metal ring of the niche showing squared section (arrow series, Fig. 12 centre). At the top, this ring appears tied to some other element, via a metal piece connection or hook (single arrow, Fig. 12 right). Therefore, the presence of a larger metal ring running just above the pendentives, and connecting them, was expected in the lower frame of dome's drum. Although this could not be detected visually nor via IR, it was sensed by using a strong magnet. Sadly, the IR tests were not conclusive enough, because very little further information could be added to visual inspection findings (Fig. 13): the example IR image shows an anchor point for a vertical metal piece in the pendentive area's centre (dotted circle's centre, Fig. 14).

From the roof attic space of this dome, inspections were again only partially undertaken, due to impossible access to some parts. Nonetheless, the anchors of metal tie-beams were observed and proved similar to what described above for the other dome (Fig. 15-16).

Fig. 5 North spandrel of southern dome.

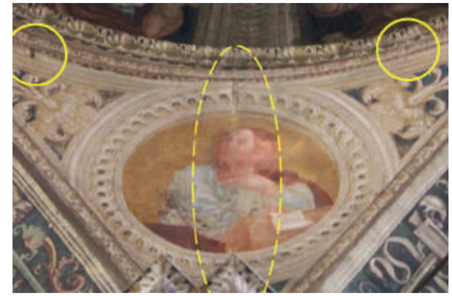

Fig. 6 Detail of top part of a spandrel.

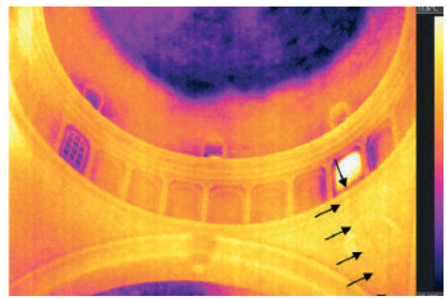

Fig. 7 IR of N-W side of southern dome

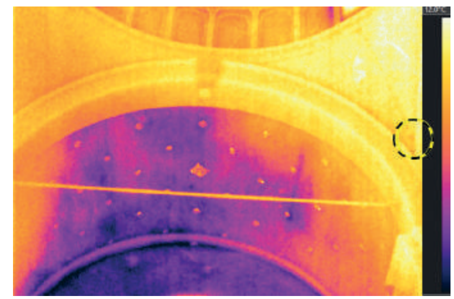

Fig. 8 IR of southern dome's lower part.

Fig. 9 East side of south drum with metal anchor.

Fig. 10 Eyelet detail of a radial tie-rod.

Fig. 11 North spandrel of the S-W northern dome.

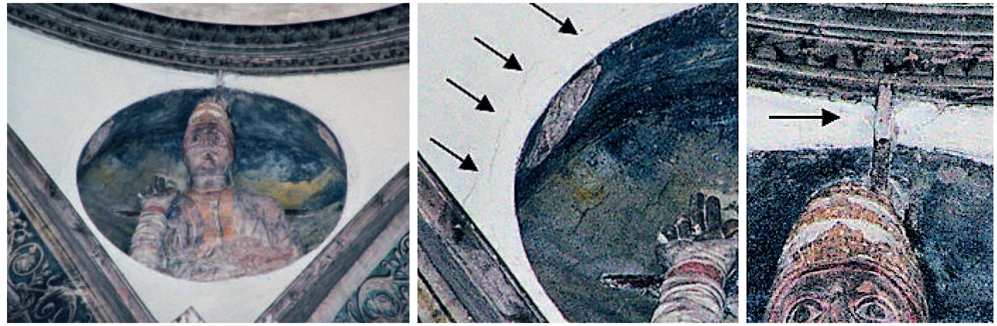

Fig. 12 Details of north spandrel.

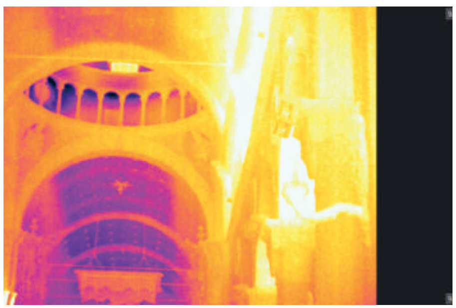

Fig. 13 IR view of the northern pendentives.

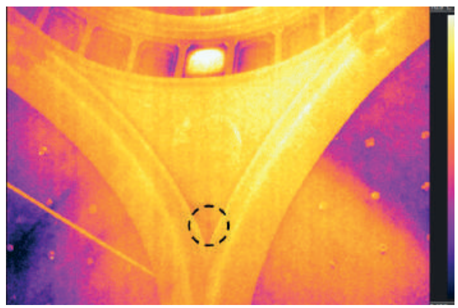

Fig. 14 Detail of north spandrel.

Fig. 15 View of east side of main dome.

Fig. 16 Detail with metal tie-rod.

Discussion

Regarding the IR tests, as it is often the case with historical buildings, the internal thermal conditions were not favourable to IR tests due to rather stable temperature values. For the investigated case, this problem was observed in the various seasons. When investigating large volumes, such as churches with high ceilings and domes, with no chance to use active IR, nor to create warm-cool air drafts nor to exploit winter heating (as it was the case, here), the testing conditions may become prohibitive for IR. Hence, it becomes mandatory to inspect multiple times the site before starting IR tests, in order to study the sun irradiation from windows, according to the testing season and the times of day when the less-worse environmental temperature gradient is present.

The IR investigations conducted in march 2021 with high-resolution thermal camera could not provide decisive nor complete information about the domes' construction. Still, the recorded images hinted to metal elements, their location and shape in the pendentives of the domes.

Conclusion

The visual and thermal investigations carried out on the domes and pendentives of the church of St. Sixtus in Piacenza were able to give evidence of the construction details about materials and technical solutions adopted by the designer in particular in relation to the pendentives. Although of similar size, the pendentives look and are different in the two domes. Quite particularly, images from the data collection campaigns on these 2 interesting renaissance domes show not only how important it is to carry out careful and multiple visual inspections, but also let us know that in the considered historical period, dome design was in strong evolution with designers experimenting different solutions.

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Detecting masonry types in historical buildings by infrared thermography and the case of Maria Luigia's theater in Piacenza

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Abstract

Infrared thermography (IR) is a powerful and fast NDT technique allowing varied applications in many fields. In the practice of architecture and civil engineering, there is still a lack of confidence in adopting this methodology for structural applications. However, in relation to historical or existing buildings diagnose, detecting for example the type of load-bearing masonry below the walls plaster can be undertaken via IR tests for the purpose of obtaining valuable information for the building assessment. I.e., plastered brick or stone masonry can be detected via IR, as well as various types of these masonries can be distinguished. Furthermore, information for masonry quality indexes is readable in IR output. This contribution's purpose is to provide clear examples of masonry type detection in real buildings and to present duchess Maria Luigia's stables, in Piacenza.

The stables were built around 1840 on the site of the ducal theatre, which burned down at the end of 18th C. Stables and lodgings still form an inseparable complex. The building, part of large military barracks, has not been in use for many years and it is not accessible inside. Very little is known about its history and characteristics. The single room with 3 naves which housed the horses, about 30 m long, is elegant and outstanding, divided by stone columns with marble troughs and wrought iron mangers for the horses. It is a solid masonry structure, with walls of consistent thickness. But what type of masonry is hidden under the thick plaster? A thermographic survey, carried out from outside, has shown unusual masonry facings for the area: stone & brick mixed masonry, in which bricks courses alternate with bands of rounded almost unworked stones. More interesting details are described herein.

Keywords: masonry, brick, stone, IR, thermography, theatre, historical building, heritage, diagnose, NDT.

As mentioned in the Italian National Guidelines for Risk Reduction to Architectural Heritage (2018), the structural diagnose of historical buildings is a complex methodology made of an interdisciplinary approach involving many specialists and a number of information-collection steps that need to be tailored on the specific case and on the territorial characteristics of the site. Dramatic events such as earthquakes have repeatedly shown that even in recently restored historical buildings the suffered damages were extended, even up to partial or total collapse, when only the surface embellishment (facades restoration) but not the structural performance was cared for, or when the intervention was not based on the real knowledge of the specific building characteristics and behaviour. Therefore, before thinking of designing any intervention for a historical building, an excellent prior knowledge of the building is essential, related in particular to its materials, construction techniques, transformations and structural damages.

The evaluation of the Masonry Quality Index (MQI) may greatly simplify the process, because it allows to evaluate the mechanical strength of a masonry based on its construction quality. Experimental research conducted on real masonry in Italy has shown a correlation between masonry mechanical strength and compliance with the "rules of art" transmitted by numerous ancient and more recent treatises or manuals or by oral tradition (Borri et al., 1982). The MQI allows to estimate the mechanical performance of any historical masonry (in terms of compressive strength, elastic modulus and shear strength, to which correspond the vertical loads, the out-of-plane stresses and in-plane stresses, respectively) by assigning MQI scores to each representative masonry of the building, subsequently converted into the strength value using a mathematical formula.

The MQI is in turn made up of the result of a further relation that takes into account 7 fundamental masonry characteristics: the mortar quality, essential for regularising the contact between the stone or brick units, distributing the stresses and ensuring masonry cohesion; the presence of diatons, i.e., elements passing through the "entire" wall thickness, responsible for the transverse connections between the masonry "leaves"; shape of the units: bricks or squared stone units ensure optimal contact between the units' faces and good friction coefficient, while rounded or irregular units transmit inclined internal forces that tend to separate the units and leaves, generating cracking, displacements or dangerous bulging; the units' size, because units with large dimensions perform a stabilising action thanks to their weight; the correct offset between the vertical joints contributes significantly to the effective meshing of the masonry (connection between masonry units) thus, i.e., distributing the concentrated loads; wall's horizontal rows of units distribute the loads evenly and during an earthquake they allows units' oscillation around horizontal hinges that do not damage the wall; quality of units: degraded, missing or weak units drastically reduce the resistance to vertical loads. Skipping further details, it can be added that the MQI may help or substitute experimental investigations (flat-jack tests or diagonal compression tests); it may provide strength values much more accurate than use of standard tables, especially for the case of unusual masonries. It is not destructive thus it complies fully with conservation principles. However, it has a fundamental limitation: since the assessment of the above 7 characteristics usually takes place by visual examination, the method requires excellent knowledge of traditional materials and construction techniques (Matteucci, 2022). Hence, the visibility of the masonry (inside, outside and possibly in section) is necessary. Instead of removing large portions of plaster (at least 1x2 m) or inspecting invasively and destructively the wall sections, high-resolution non-destructive testing (NDT) imaging techniques – i.e. GPR radar or IR thermography – can play a fundamental role.

Work objectives

Infrared thermography (IR) is a powerful and fast NDT technique allowing varied applications in many fields. However, in architecture and civil engineering, there is still a lack of confidence in adopting this methodology for structural applications. In relation to historical or existing building diagnose, detecting for example the type of load-bearing masonry below the walls' plaster could be undertaken via IR tests for the purpose of obtaining valuable information for the building assessment. Nonetheless, this is not acknowledged in the practice, not yet. Not only plastered brick or stone masonry could be detected via IR, but various types of these masonries could be distinguished. Furthermore, information for MQI is readable in IR output. Starting from the above aims, this contribution's purpose is to provide a few clear examples of masonry type detection in real buildings and to present the masonry case of duchess Maria Luigia's stables, in Piacenza.

Fig. 1 South view of ducal stables.

Case presentation

As early as 1561, on the Carnival occasion, in Piacenza the duke Ottavio Farnese used the great hall on the first floor of Palazzo Gotico, the medieval "broletto", as court theatre (Buttafuoco, 1842). In 1644, it was a theatre with 4 tiers of wooden boxes. However, by the end of 1600s it was replaced by the new Cittadella Theatre, next to the Ducal Palace, in Cittadella square. Although today it is one of the pavilions of the barracks of the 2nd Pontieri Engineers Regiment (Fig. 1), it was built in the 1680s and was joined to the ducal residence by an overhead walkway. Equipped with 5 tiers of 25 boxes, U-shaped in plan, it was the type of "Italian theatre" which, from 17th C., started to differentiate theatrical structures from the previous Greco-Roman model. This theatre was actually a multifunctional complex: it included a tavern and the so-called *Casino de' Virtuosi di Musica*, an accommodation intended for artists and impresarios. Dedicated to a noble audience linked to the Ducal court, this building kept activity until the end of 18th C. This theatre was short-lived, too: in 1798 it was destroyed by a fire. Otherwise, the Casino dei Virtuosi (which stood behind the theatre and still exists today) and the walkway (standing until Italy's Unification in 1861) resisted the fire. Until 1840, the area of the burnt theatre was used for outdoor performances in the "building shell" of the theatre, until Maria Luigia of Austria had the ducal horse stables built (Bissi, 2017). These stables were equipped with carriage house and with the squires' residence in the site of Casino dei Virtuosi. The stables were accessed from the right one of the 3 façade arches, with the left arch leading to a small courtyard and to the walkway to return to the Palace. Inside, the stables appear as a hall with 3 naves, about 30m long, divided by stone columns with capitals that support masonry vaults. The thrust of the vault arches is cancelled out by metal tie rods present in the 2 orthogonal directions. Along the longitudinal walls, each bay between the columns corresponds to large semi-circular windows above and, for each, below, 3 high niches each equipped with a large light-coloured moulded stone basin, with the function of horse's drinking trough, topped by a moulded wrought iron rack manger (Fig. 2). In 1998, the stables received indirect protection as a buffer zone for the Citadel and Farnese Palace (1089/1939 law) whilst only in 2004 they get direct protection. Stables and lodgings form an inseparable complex with the Citadel and Farnese Palace. The building appears to be a solid masonry structure, as it can be seen from the strong pillars on the facade and the consistent thickness of the window walls.

Fig. 2 Stables' internal view.

IR methodology

Exploiting the thermal energy (heat) that each material naturally emits when not balanced with its environment, IR is a predominantly passive technique merely recording the surface temperatures of the areas framed by the IR camera. In the output images, the achievable resolution is influenced by the camera sensitivity and pixel number, whilst the outcome readability is function of the tested material characteristics and of the intensity and speed of the temperature gradient taking place. Thanks to the very short wavelengths of signals, IR is a high-resolution imaging tool (Colla et al., 2015), (Colla et al., 2008). For the cases under consideration, an uncooled, 76800-pixel, short-wavelenght IR camera was employed.

Experimental phases

The building has not been in use for many years. Presently it is not accessible inside because owned by the Ministry of Defence. Outside, a quick IR survey was conducted in August 2021 and completed later. The main façade is facing S-W whilst the S-E front of the stables is flanked by high-trees. The remaining part of the S-E front was inspected in angled view due to reduced space from the Citadel (Fig. 1 & 5). In image post-processing, the recorded thermograms' temperature range was reduced for increased colour contrast and better readability of masonry layout and details under the plaster. Figures 3-6 offer some of the IR campaign output whilst Fig. 7 shows an approx. 1.5x2 m detail area of a wall corner, where the unplastered masonry is made of horizontal bands, approximately 0,5 m high.

Discussion

The IR campaign outcome from the stables' investigations has immediately shown a particular type of masonry layout, unusual in the area of the building or in Piacenza: it is clearly a regular mixed masonry built with stones and bricks, in which double courses of bricks with regular joints of mortar (presumably lime mortar) alternate with bands of uncoursed roundish stones, of irregular shape and size. Otherwise, the edges around the openings (windows, doors) and at the corners between walls are made of brick masonry. Thanks to the temperature differences read in the thermograms, shapes and sizes of features are observed and recognised (see i.e. Fig. 6) even before comparing with the visible situation in the only point where the damaged, modern plaster has fallen (Fig. 7): here it can be seen that the stones were used split and roughly worked on the wall facing. Almost all of the 7 masonry characteristics recalled earlier, can be distinguished in the IR images.

Nonetheless, how can it be said from the IR images that the nature of the masonry units is different? Usually, stones have much higher density than bricks and are not good heat conductors, therefore stones would take longer to heat up than bricks when irradiated by sun rays, as it was the case during this data collection. Hence, although behind plaster, stones would appear of lower temperature (darker colours in the chosen temperature legend) than brick units. In turn, if the user of the thermograms enjoys very good knowledge of traditional materials and construction techniques, the simple shapes composed by the false colours – different temperatures – will allow to recognise in the images the specific masonry patterns and layouts, their quality characteristics and other aspects.

For example, by looking at the 4 masonry examples provided in fig. 8-11, all from cases in the historic city centre of Bologna, it can be recognised – from left to right – a regular bond made of full-stretcher solid bricks, an in-fill wall made of modern hollow brick units, irregularly mixed stone & brick masonry, a mixed masonry alternating one course of bricks and one course of cobbles. In the last 2 cases, the stones appear again with lower temperature.

Returning to the case in Piacenza, the produced thermograms show not only the described masonry type but also the presence of vertical brick interruptions to the horizontal bands, aimed to create a dense brick masonry mesh

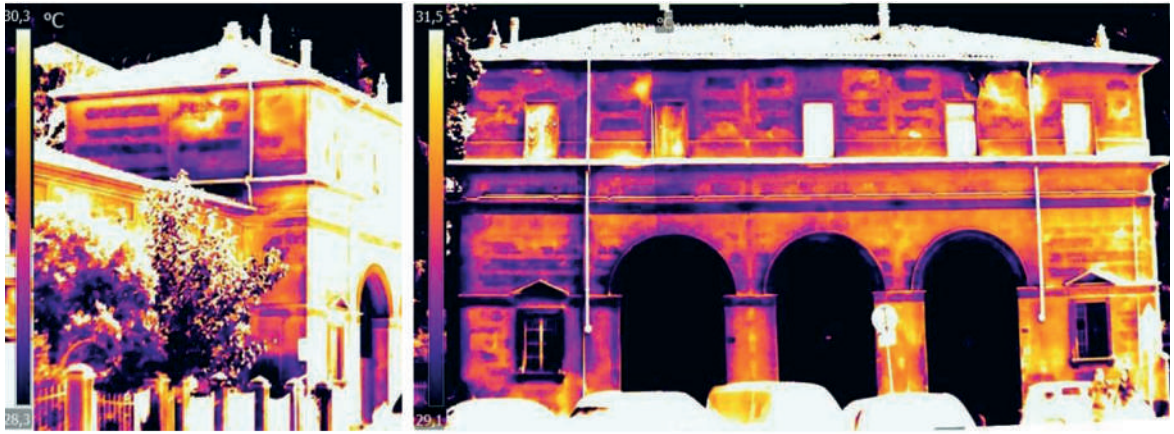

Fig. 3-4 The N-W front (left) and the S-W main façade (right).

Fig. 5 Part of S-E front.

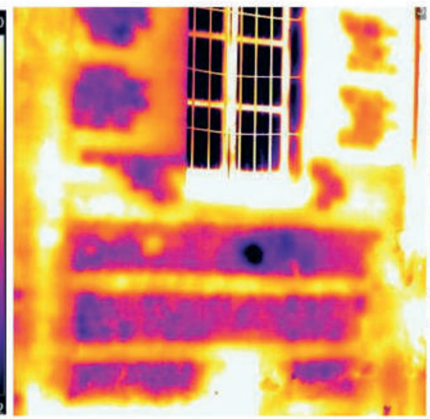

Fig. 6 Stables' masonry detail.

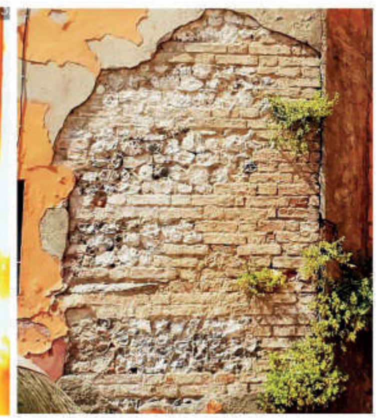

Fig. 7 Stables' corner detail.

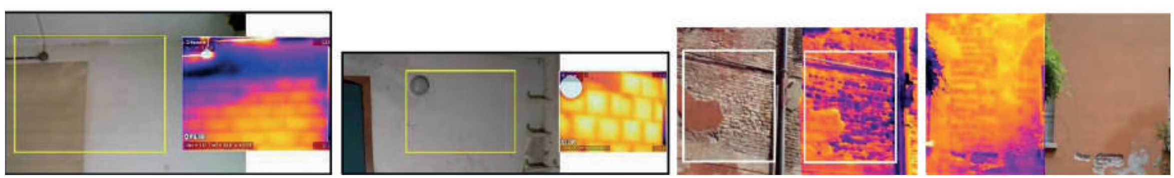

Fig. 8-11 Various masonry layouts detected via IR.

for improved safety and higher wall quality, where the brick masonry embraces and encloses the uncoursed stone masonry parts. Moreover, the presence of minor and major load-discharge arches above openings underlines a clear mastering of construction principles, too. Compared with architectural manuals of the time (Musso, 1894; Formenti, 1893), Fig. 12, the presented case not only is built according to contemporary construction rules ("a regola d'arte") but demonstrates even more attention to possible weaknesses of this type of economic but solid construction, given that the transition between bricks and stones is here more gradual. In fact, in case of surface decay, if not kept solidly in place by strong mortar, the unworked cobbles and stones may tend to move and rotate, generating wall damage. Therefore, it is important that a proper plaster covers and protects these masonry walls but only a lime mortar is compatible with these historic masonry materials.

Conclusion

A non-destructive thermographic survey, carried out on the outside of Maria Luigia's stables, built on the previous ducal theatre, has clearly unveiled the type of historic masonry below the thick plaster. Thus, this type of structural use of the IR methodology in the diagnose of existing buildings provides valuable information for masonry quality evaluation and for building assessment. Furthermore, this image diagnostic approach not only is conservative, time- and money-saver but provides also more complete information when compared to local destructive inspections or mechanical tests. The mixed masonry, where brick courses regularly alternate with bands of almost unworked stones, was rather unexpected for the building: a regular and dense brick net observed around the stone parts has been compared with 19th C. architecture manuals.

Acknowledgments

Mrs S. Allesti is gratefully acknowledged for proofreading the text.

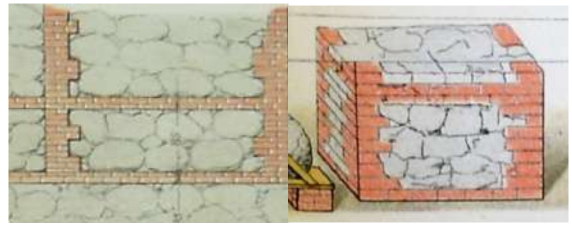

Fig. 12 Details from Musso,1884.

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Thermal evaluation of envelope materials in historical buildings through Non-Destructive thermographic Moisture Analysis

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Abstract
Among the factors affecting the structural integrity and energy performance of historical buildings, moisture within the building envelope emerges as a crucial but difficult variable to assess quantitatively with nondestructive methods, especially for large surfaces. Understanding how moisture affects the dynamic thermal characteristics of historic buildings, particularly in the context of calculating building energy performance, is crucial. Nondestructive methodologies are needed when there is the risk of damaging fragile heritage buildings. The presence of moisture significantly alters the thermal properties of the envelope, leading to less accurate assessments of energy performance and possibly compromising energy efficiency, thermal comfort and conservation. To address this issue, a novel nondestructive method was applied to quantify moisture content using infrared thermography, taking advantage of thermal inertia measurement. The novel approach has undergone laboratory testing and shows promising potential for future on-site-implementation within historic buildings.

Keywords: infrared thermography, bricks, thermophysical properties, moisture, building energy.

Introduction

The presence of moisture within the wall structure can alter the wall thermophysical properties, affecting both energy efficiency [Di Perna *et al.*, 2011] and thermal comfort [Aste *et al.*, 2009]. In refurbishment interventions of historical buildings, understanding the dynamic thermal behavior plays a crucial role in determining heating and cooling [Fedoruk *et al.*, 2015] energy requirements that is mandatory for a correct design of HVAC (Heating, Cooling and Air Conditioning) system. It is important to note that significant disparities between the actual and theoretical values of these parameters (up to 30%) can arise due to several factors. These may include incomplete knowledge of the historical composition of the building envelope, which can be addressed through historical research and on-site inspections, as well as variations in moisture conditions during different seasons. When subjected to periodic thermal stimulus on the outer surface, the wall transmits heat to its inner surface with a delay and attenuation that depends on its structural properties, as specified in standard [ISO 13786]. Attenuation indicates the ratio of the heat flux entering the room through the structure over that which is applied on outer wall. The phase shift, on the other hand, indicates the delay of the maximum external thermal stimulus on the inner surface of the wall. More attenuation would limit periodic temperature changes on inner surfaces. Cyclic temperature variations on the surfaces is recognized as a major driver for serious causes of degradation [Bernardi, 2008] such as salt crystallization, wet-dry cycles, and mechanical stress. Environmental comfort or well-being is defined as the condition of satisfaction perceived by individuals, resulting from various contributions, among which the microclimate stands out. Controlling the temperature of indoor surfaces, and its homogeneity, is one of the factors that contribute to thermo-hygrometric comfort. In modern buildings it can be carried out in several ways, for example, by ensuring good thermal insulation of the walls taking care to avoid or correct thermal bridges, by appropriately designing the type of air conditioning systems but, above all, by adopting "massive" brick envelope structures, capable of acting as a thermal flywheel by limiting the internal surface temperature fluctuations due to the normal intermittent operation of the systems. Regarding historic buildings, an assessment of the thermal characteristics of the envelope is even more necessary, especially when these can change significantly depending on the water content in the masonry. According to calculation based on standard methods and literature data of typical building materials [ISO 13786], the same building envelope wall (e.g., solid bricks, 30cm thickness) would have vastly different dynamic thermal properties depending on its water content. Moving from dry to wet conditions, the damping factor is halved, while the time shift increases its value by a quarter. Taking into consideration the significant impact of water presence in historical masonry, a non-destructive method based on active Infrared Thermography (IRT) has been developed for its assessment. The proposed method, presented in this paper, has been tested on brick samples.

Materials and methods

The aim of this work is to assess the moisture content in porous specimens (brick). To provide such an estimation its fundamental to evaluate the thermal effusivity of the brick, which is carried out by IRT via a comparative method [Grinzato *et al.*, 2008; Bison *et al.*, 2008]. This thermophysical property will be correlated with water content. A standard brick, measuring 12x25x5 cm, has been tested. To evaluate the sensitivity of the method, various levels of moisture content are measured. First, the brick is driven to complete saturation by submerging it, for enough time, in water; an easily removable plastic film is applied to avoid evaporation. The wet specimen and a reference material ("Pietra Serena" sandstone) are varnished with a high-emissivity paint in such a way to uniform optical properties of the surface. They are disposed on a table and subject to heating by activating a 1kW lamp (hung perpendicularly on them) for a brief period, typically around 30 seconds. The rising temperature profile for semi-infinite body, in function of time, is given by the following equation:

$$T(t) = \frac{2Q}{\varepsilon}\sqrt{\frac{t}{\pi}} \qquad \varepsilon = \sqrt{\lambda \rho c_p} \qquad (1)$$

where: Q is thermal power, t is time, ε is thermal effusivity, λ is thermal conductivity, ρ is density and c_p is specific heat capacity at constant pressure. Both the brick and the referring sample are thick enough to been considered as semi-infinite bodies, furthermore, they are placed one close to the other under the heat source with one of the long sides in contact to prevent external heat exchange. The IRT camera records the trend of the surface temperature with a frequency of 5 Hz. A three-dimensional matrix is obtained: referring to the scheme below (fig.1) a and b represents the spatial dimension; by following a (a; b) point through the n dimension ones can obtain the thermal profile in that point over time.

The average surface temperature is evaluated in the yellow boxes shown in figure 2 for both materials during the application of thermal stimulus. From the thermal effusivity of the reference material, the thermal effusivity of the unknown material is determined by means of the equation below:

$$\varepsilon_{unknown} = \frac{\varepsilon_{reference} T_{reference}}{T_{unknown}} \qquad (2)$$

Thermal effusivity varies in function of the water content of the brick. To provide such an estimation it

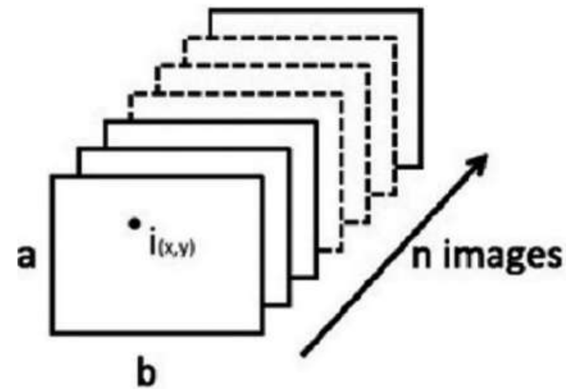

Fig. 1 A scheme of thermal acquisition is presented. Spatial dimensions correspond to a and b, the third dimension is related to time.

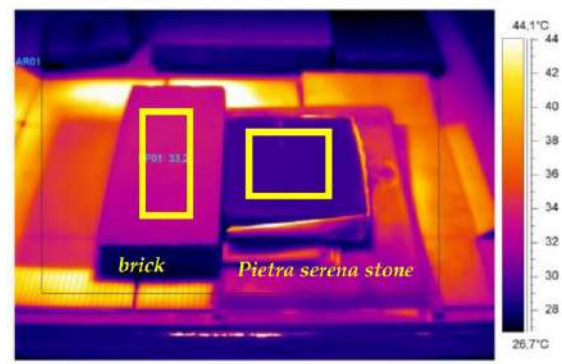

Fig. 2 Thermal image of the tested materials. The yellow boxes are the regions of interest where the average temperatures for each frame were collected. On the left is visible the unknown thermal effusivity brick, on the right the reference material.

is fundamental to model the thermophysical properties from which derives. In this study a simplified model is proposed: the brick is considered as a sum of three distinct parts, water, air and bulk material. Thermal conductivity and specific heat of the entire material are derived as a weighted average of the properties of the cited components. The moisture volumetric percentage and wet brick thermophysical properties are defined as

$$\Phi = \frac{m_{H_2O}}{\rho_{H_2O}V};$$

$$\rho_{wet}(\Phi) = \rho_{dry} + \Phi\rho_{H_2O} \quad (3)$$

$$c_p(wet) = c_p(bulk)\cdot(1-\chi) + c_p(air)\cdot(\chi-\Phi) + c_p(water)\cdot\Phi \quad (4)$$

$$\lambda(wet) = \lambda(bulk)\cdot(1-\chi) + \lambda(air)\cdot(\chi-\Phi) + \lambda(water)\cdot\Phi \quad (5)$$

Where χ is the open porosity percentage, it represents the volume that can be filled by absorbed water and corresponds to the volumetric water content at saturation conditions. To measure it a gravimetric analysis was performed. $c_p(bulk)$ and $\lambda(bulk)$ refer to the massive part of the brick and were derived from the value of $c_p(dry)$, $\lambda(dry)$ measured in laboratory. Thermal conductivity measurements were conducted via transient plane source method, according to ISO 22007-2 standard [ISO 22007-2]. $c_p(dry)$ was determined by means of Differential Scanning Calorimetry [ISO 11357-4]. $\rho(dry)$ was measured using the gravimetric method. ρ_{H2O}, $c_p\,(water)$, $c_p(air)$, $\lambda(water)$, $\lambda(air)$ are taken from literature.

Starting from this simplified model it is possible to estimate the thermal effusivity of a wet brick as a function of the water content, as stated in the following equation:

$$\varepsilon(wet) = \sqrt{\lambda(wet)\rho(wet)c_p(wet)} \quad (6)$$

Comparing the value of effusivity experimentally measured by IRT with the one predicted by the model, it is possible to estimate the moisture content percentage Φ. How to model in a precise way the thermal conductivity of a wet porous material is argument of debate and still under study. In this work we have also tested a more sophisticated model for $\lambda(wet)$ prediction presented in [Alsabry *et al.*, 2020] as an evolution of the studies presented in [Dul'nev *et al.*, 1987]. The results provided by the more complex model seem, for the specimen considered in this work, to be similar to the one obtained via the simplified model already described.

Results

The described methodology has been applied to the brick already characterized. The moisture content has been varied from saturation to approximately 15-20% of the sample volume. The experimental results are shown in table 1.

The obtained results are compared with the gravimetric method in order to validate the proposed method. As reported in table 1, IRT and gravimetric method are almost equivalent at high level of humidity (close to saturation), whereas IRT method produces a significant overestimation at low water content. In this moisture condition a humidity gradient can easily form inside the

	Brick Water Content [%]			
IRT method	33.9±0.3	29.8±0.3	26.4±0.3	20.7±0.2
Gravimetric method (reference)	36.1±0.3	27.9±0.2	23.0±0.2	15.8±0.1

Tab. 1 The results obtained by the presented method are shown in the first line. In the second are reported the values measured with the gravimetric method.

brick during the sample preparation. This phenomenon can affect the measurement of thermal effusivity and consequently can lead to a misestimation for low water contents.

Conclusions

In this paper, an innovative approach has been applied for the nondestructive evaluation of thermal characteristics of building envelopes using quantitative Infrared Thermography. Parameters such as dynamic thermal properties, variations in surface temperature, and temporal homogeneity are deemed crucial for assessing building energy performance and ensuring thermal comfort and conservation of historical buildings. The proposed methodology offers a viable means of gathering such a valuable information, even in the case of cultural heritage buildings, where the feasibility of destructive testing and inspections is limited due to potential risks to cultural heritage integrity. To validate this approach, laboratory testing and comparisons with conventional methods have been conducted on solid brick samples. The fundamental concept of this novel approach is centered on the modeling of thermophysical properties of materials as a function of their water content. The results obtained from this study have demonstrated promising outcomes through the utilization of simplified models. The experimental procedure has proven to be straightforward and may be implemented on-site with some optimization, particularly concerning improving the technology of the plastic film that have to be applied to inhibit evaporation, and at the same time it must guarantee adhesion, removability and to be harmless to fragile surfaces. Future steps in the research will deal with a more accurate estimation of thermophysical prosperities, moving from analytical formulations to an approach based on finite element modeling.

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Part Two – Microanalysis and Conservation of Cultural Heritage

The frescoes of the Novalesa abbey complex, from restoration to preventive conservation through non-destructive diagnostics

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Abstract

The work presented shows the initial results of an interdisciplinary project focusing on actions necessary for the implementation of strategic maintenance plans to achieve preventive conservation of heritage systems.
Started in May 2021, the project aims to assess and tune strategies for the prevention and mitigation of degradation phenomena affecting four historical buildings belonging to the architectonical site of the Novalesa abbey (Turin), with a particular focus on its medieval frescoes. It involves different professional actors (restorers, architects, conservation diagnostic scientists, and art historians) as well as the area's inhabitants.
Based on the results of studies conducted over time on the wall paintings in the Chapel of St. Eldradus, one of the most important examples of Romanesque art in north-western Italy, the work methodology was extended to other areas of the monastery complex in need of attention. The apse of the church, the Chapels of St. Michael and the aforementioned St. Eldradus, and finally the so-called 'Camera Stellata' are now the subject of research in terms of the correlation between environmental conditions and the deterioration of the wall paintings, through the use of scientific nDT techniques and various types of analysis.
The project deployed a system to collect the needed knowledge while managing the operations related to the preventive conservation plan (as i.e. salt extraction, local consolidation, etc.) and it is tended to be an asset supporting the project according to ICCROM and ICOMOS. Furthermore, the project is committed to involve the communities through dissemination initiatives.
The Novalesa project was activated in the framework of PRIMA initiative funded by Fondazione Compagnia di San Paolo, having also the financial support of Città Metropolitana di Torino and Benedettini Congregation. The project operates under the supervising of the Soprintendenza Archeologia Belle Arti e Paesaggio per la Città Metropolitana di Torino.

Keywords: preventive conservation plan, cultural heritage, infrared thermography, monitoring, risk assessment, risk management, data management system.

Introduction

The Compagnia di San Paolo of Turin, in early 2021, launched the PRIMA call, "*Prevenzione Ricerca Indagine Manutenzione Ascolto per il patrimonio culturale*[1]", for the structuring and implementation of planned maintenance and preventive conservation plans for heritage systems to encourage the spread of maintenance culture at the expense of implementing emergency restoration interventions.

With the project "*Gli intonaci dipinti del complesso abbaziale di Novalesa, dal restauro alla conservazione preventiva*[2]," the Congregation of Benedictine Fathers, the site's bailee, was the grantee. At the same time, the Metropolitan City of Turin, the entity that owns the complex, is the project's technical-economic partner. With the endorsement and supervision of the SAPAB-TO[3], the design and execution of the work are entrusted to Koinè Conservazione Beni Culturali s.c.r.l. The LabDIA of the Politecnico di Torino performs non-destructive diagnostics, and Kpeople Research Foundation is involved in setting up the platform to manage the maintenance plan. The interdisciplinary team of conservation experts is developing a three-year preventive conservation plan on four areas of interest within Novalesa abbey. These areas include the apse of the church with a notable fresco cycle, the Camera Stellata, and the chapels of St. Eldradus and St. Michael, where the pictorial cycles of rare importance for the very high artistic quality are among the oldest preserved in Piedmont. On these assets, an interdisciplinary team of conservation experts is using a tested methodology from European Commission research areas. A Data management system and platform have been created to support decision-making and management of targeted activities, following the principles of preventive conservation advocated by organisations like ICOMOS – ICCROM[4].

«secundum evangelica normam et regola dom[i]no Benedicto»: a brief historical introduction.

In 726, the patrician Franco Abbone, governor of Dora and Arc valleys, founded the abbey of Ss. Peter and Andrew in Novalesa adopting the Rule of St. Benedict[5]. The deed of foundation – kept in the State Archive in Turin – is the *ouverture* to a centuries-old history defined by symbolic episodes such as the visit of Charlemagne – real or not – in the battle against king Desiderius near the so-called *Chiuse longobarde* (773)[6].

Several events – already partially collected in the *Chronicon Novalicense* (half of the eleventh century) – outline an uncertain chronology characterized by a continuous reconfiguration of the abbey, as confirmed by the wall fragments re-emerged by archaeological investigations[7]. Indeed, archaeological studies have underlined multiple overlapping walls, so different redistributions and buildings orientations, various spoliation and reuses. This condition is also extended to the *sagrato*, i.e. church square, – partially investigated in 2008-2009[8] – and to the chapels of the Novalicense monastery: St. Eldradus, St. Saviour and St. Michael (*alias* St. Peter[9]) on the south and St. Mary Magdalene on the north.

Archaeological and art history studies about the Novalesa abbey have increased after the 19 April 1973, when the former Province of Turin – now Metropolitan City of Turin – bought the monastery[10]. In addition to archaeological excavations – largely completed in 1995 – the former Province started to restore and renovate all buildings shortly after the acquisition: the so-called *manica* of St. Lucy (until 1982) and the southern wing (1985-1991) but also the so-called *Palazzo Abbaziale* and the current archaeological museum (from 1997)[11]. These works became essential due to the various uses and modifications to the abbey in the ages, especially between 1855 and 1972[12]. The sale deed also mentions some undocumented pillage and demolitions that probably occurred during the Second War World[13]. The cyclic renovation – with demolition and rebuilding – also characterized the frescos of the abbey: removed, repainted, and remade with several administrations – abbots, priors, etc. – as we can observe in the presbytery where different *architecturae pictae* overlap the paintings by Antoine de Lohny and then were covered in white plaster maybe during the building renovation (1710-1714) of Antonio Bertola.

State of conservation of the frescoes and principal degradation factors

The frescoes subject to the preventive conservation plan and to the corresponding scheduled maintenance intervention exhibit different states of conservation, which are closely related to the environment in which they are located. The paintings in the apse of the church and the Camera Stellata are in better condition, as the last maintenance and restoration interventions took place in the early 1990s and early 2000s. The situation is more problematic for the chapels, as they have been subjected to restoration interventions, even in relatively recent years, due to the emergence and progression of relevant decay manifestations.

The most significant degradation phenomenon observed on the Novalesa paintings, in terms of both the extent of the affected surface and the severity of the consequences it can cause, is the superficial and subsurface crystallization of salts. This leads to a direct deterioration of the mural paintings, resulting in the disintegration of the plaster, flaking, and detachment of the paint layer (Fig. 1). The presence of salt efflorescence is particularly visible on the frescoes of the chapel of St. Eldradus. Given the high importance of the artwork, the removal of these salts from the paintings in the past fifteen years has been accompanied by a systematic monitoring campaign, which has helped to understand the underlying dynamics of salt migration within the masonry.

There are also other degradation phenomena identified on the assets in question, including dark stains mainly caused by the infiltration of rainwater from the exterior, colored patinas resulting from biological and microbiological colonization, detachment of plaster from the masonry, chromatic alterations affecting non-original materials, and coherent and in-

Fig. 1 Chapel of St. Eldradus (left and center) and Camera Stellata (right): details of the micro-flaking and decohesion of mortar caused by salts on three different areas.

coherent deposits, including traces of animal, insect presence and wind-blownd sediments. In many cases, the responsible risk factors have been identified, and planned operations are being carried out as part of the conservation and maintenance plan for the asset system.

Monitoring as a method of decay assessment

Given the value of the surfaces studied, the research team decided to use non-destructive diagnostic techniques on all the four assets to identify the causes of some of the degradation phenomena found, assess their evolution over time and check the effectiveness of any remedial actions. Moreover, as many of the observed alterations show a significant correlation with micro- and meteo-climatic conditions, installing a weather station in addition to the standard measurement of internal physical parameters was considered appropriate. Such a solution allows a detailed assessment of site-specific environmental conditions that cannot be compared to those detected by stations already in the region.

The comparative analysis of environmental parameters acquired over time was related to the degradation phenomena observed, allowing the identification of potential local risk thresholds. It also provided the data for defining targeted non-destructive diagnostic protocols. In this context, thermographic monitoring, in particular, made it possible to identify some localised issues that could be easily solved (water infiltration from the roof and windows) and could be included as routine checks in a planned maintenance plan. Others detected problems, on the other hand, require evaluations carried out over time. It is the case of the Chapel of St. Eldradus, where the results of infrared surveys conducted for over ten years highlighted the importance of the synergic evaluation of IR data with the environmental ones. These assessments allowed us to formulate hypotheses about some decay causes, rule out others, and begin experimental activities. The significant temperature variations observed by IR only on the south wall, the one most compromised by degradation, suggested the installation of an external thermal shield (Fig. 2), whose effects, in terms of the benefit to the conservation of the paintings, are under investigation.

Fig. 2 Chapel of St. Eldradus South wall. Natural thermal shield.

Initial results have been encouraging, but only long-term monitoring will provide significant indications of the experiment's effectiveness and the adequacy of the system implemented: in general, does the idea work? Is planting in pots with frost-tolerant but deciduous plants sufficient, or is there a need for more uniform but less reversible protection screens?

We try to answer these questions through the interpretation of the detected thermal signals together with a careful visual inspection related to any alterations that might occur on the painted surfaces due to the change in the thermal conditions of the wall.

The preventive conservation strategies fine-tuned for the site of Novalesa

Starting from the results of the H2020 STORM project, the methodology underlying the preventive and planned conservation developed for the Novalesa site also led to the creation of a platform dedicated to facilitating the management of the maintenance plan by the site's stakeholders in collaboration with various professionals. The aim is to identify and adopt direct and indirect intervention methods on the assets to ensure their optimal long-term preservation. The methodology followed for the Novalesa project consists of four fundamental aspects: data collection, risk assessment, risk management, and results evaluation. The basis of the work is the "data collection phase", during which existing documentation related to the assets (historical, descriptive, diagnostic investigations, and conservation status data) is gathered, aiming to obtain a comprehensive understanding of the conservation history of the artworks. The risk assessment is defined starting by identifying the principal vulnerabilities, causes, and dynamics of decay. The scientific data are also related to the qualitative characteristics of the materials, the extent of degradation, and the type of assets involved. The computer system includes an algorithm that assigns a numerical value to the risk, aiding in defining risk management and developing a scheduled maintenance plan. Risk management constitutes the operational part of the methodology, where specialized technicians execute the planned interventions. They can act directly on the artistic objects or, more often, on the conservation environment to minimize intrusive actions on heritage assets. That is the case, i.e., of the plants used as a natural shield in front of the south wall of the St. Eldradus chapel to reduce decay and thus the consequent use of consolidating products, in line with the principles of preventive conservation.

Direct maintenance activities are typically managed by two to three specialized restorers who constantly follow the planned preventive conservation strategy, using portable devices connected with the management application, allowing daily documentation of the work carried out, recording observations, and updating any changes encountered. Other stakeholders involved in the preventive conservation of the site can access the data asynchronously from network-connected stations. Lastly, periodic evaluation moments are scheduled during the implementation of the maintenance plan. These evaluations involve interpreting the data collected from various monitoring and assessing the conservation status of the structures and artworks. The critical data analysis becomes a crucial assessment point of the work done up to that point, aiming to adapt the strategy in line with the obtained results.

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Notes

[1] Prevention Research Investigation Maintenance Listening for Cultural Heritage.

[2] The painted plasters of the abbey complex of Novalesa, from restoration to preventive conservation.

[3] Superintendence Archaeology Fine Arts and Landscape for the Metropolitan City of Turin. Work supervised by Dr. V Moratti, whom we thank.

[4] Preventive conservation is defined as: "all measures and actions aimed at avoiding and minimizing future deterioration or loss. They are carried out within the context or on the surroundings of an item, but more often, a group of items, whatever their age and condition. These measures and actions are indirect - they do not interfere with the materials and structures of the items. They do not modify their appearance" (https://www.iccrom.org/projects/preventive-conservation).

[5] Blandino 1973, p. 51; Lomartire 2007, p. 320.

[6] Valerio 1866, p. 74.

[7] Cerri 2004.

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[9] Savi 1973, pp. 87-89.

[10] Blandino 1973, p. 73.

[11] Bruno 2004, pp. 125-133.

[12] L. 878 del 29/05/1855, art. 1.; Valerio 1866, pp. 14-15 and 84; Blandino 1973, p. 76.

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3D Printing of architectural elements of Cultural Heritage using Fiber-Reinforced Mortar: a novel approach for rehabilitation and conservation

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Abstract
The preservation and rehabilitation of cultural heritage are of great importance for the conservation of the history and identity of societies. In recent years, 3D printing has emerged as a promising technology for the restoration of architectural elements of cultural heritage that are beyond saving. In this paper, we present a novel approach to 3D printing the degraded elements of cultural heritage using a fiber-reinforced mortar.
The process begins with the scanning of the degraded elements by point cloud technology, followed by the modelling of the missing parts in a 3D interface. The missing parts or the highly degraded ones are then 3D printed using a fiber-reinforced mortar. Carefully selected pigments are introduced into the mortar mixture to reproduce the natural aspects of the original elements as much as possible.
The 3D printed elements underwent physical and mechanical analysis which showed remarkable results, ensuring in this manner their durability. The proposed approach presents an innovative solution for the restoration and conservation of cultural heritage elements, particularly those that are difficult to restore using traditional methods.
The use of 3D printing technology in the rehabilitation and conservation of cultural heritage elements is an exciting and rapidly growing field. This paper contributes to the advancement of the field by presenting a novel approach for 3D printing the degraded elements of cultural heritage using fiber-reinforced mortar. The results of this study offer a promising and sustainable solution for the preservation of architectural elements of cultural heritage for future generations.

Keywords: 3D printing, cultural heritage, conservation, architectural elements.

Introduction

Preserving and rehabilitating cultural heritage is crucial for safeguarding the rich history and identity of societies worldwide [1, 2]. As technology continues to evolve, innovative methods are emerging to restore architectural elements of cultural heritage that would otherwise be irretrievable. In recent years, 3D printing has emerged as a promising technology in this domain, offering new possibilities for the restoration and conservation of cultural heritage artifacts.

This article presents a novel approach to reconstruct the degraded architectural elements of cultural heritage by 3D printing utilizing fiber-reinforced mortar. The process begins with the scanning of the deteriorated elements using point cloud technology, enabling a comprehensive digital representation. Subsequently, missing or highly degraded parts are modeled in a 3D interface, meticulously recreating the intricate details of the original elements.

Through the utilization of a fiber-reinforced mortar, the missing or damaged components are accurately 3D printed. The mortar mixture can be enriched with carefully selected pigments, thus ensuring a faithful reproduction of the natural aspects found in the original elements. This approach not only aims to revive the visual aesthetics of the cultural heritage but also prioritizes the durability of the restored components.

To validate the efficacy of this novel approach, the 3D printed elements undergo rigorous physical and mechanical analyses. The results of these analyses reveal remarkable outcomes, establishing the durability and integrity of the restored artifacts. Consequently, this innovative methodology provides a sustainable and promising solution for preserving and conserving architectural elements of cultural heritage that are otherwise challenging to restore using traditional methods.

The application of 3D printing technology in the realm of cultural heritage rehabilitation and conservation represents a rapidly growing and captivating field. This article contributes to the advancement of this field by presenting a pioneering approach for 3D printing degraded elements of cultural heritage using fiber-reinforced mortar. The findings from this study provide an optimistic outlook for future generations, ensuring the preservation of architectural marvels that bear witness to our shared history and cultural legacy.

Materials

The cementitious mortars that were used in this study were prepared using natural quartz sand ranging from 0 to 1 mm in size, CEM II/A-S 52.5 R Portland slag cement, and limestone filler sourced from a local quarry basin. These main components were chosen in accordance with the standards CP 012-1:2007 [3], NE 013:2002 [4], GP 075:2002 [5], and ATE 004-07/1707-2022 [6].

In all the mixtures, 12 mm long monofilament polypropylene fibers were incorporated, with an equivalent diameter ranging from 21 to 34 microns. The manufacturer has specified a tensile strength of the fibers as ≥ 300 N/mm^2 [7]. Additionally, each mixture contained two types of additives. The first additive was a viscosity modifying agent, which consisted of an aqueous solution of a high-molecular-weight synthetic copolymer. The second additive was a superplasticizer, which facilitated rapid strength development during the early stages of hydration, even under low ambient and heat curing temperatures [8].

Fresh state properties and mechanical characteristics

The fiber-reinforced mortar used in 3D printing must possess specific properties in its fresh state, such as printability, pumpability, buildability, and open time.

Additionally, it should exhibit desirable mechanical characteristics once it has hardened.

The 3D fiber-reinforced mortar utilized in this study exhibited a flowability range of 40 to 60 mm, which played a pivotal role in ensuring the successful creation of resilient and structurally sound 3D printed mortar elements. Mortar mixtures with lower flowability may lead to insufficient compaction and compromised mechanical properties, while excessively high flowability can decrease cohesion and interparticle interactions, ultimately jeopardizing the strength and long-term durability of the printed components.

The 3D fiber-reinforced mortar used in this study has a slump flow of 150 mm, ensuring optimal material flow behavior during the 3D printing process. Mixtures falling within this range exhibit suitable viscosity and yield stress, enabling consistent material flow through the printer nozzle. Slump flow values below 140-150 mm indicate a higher yield stress, posing challenges for smooth mortar flow. Conversely, slump flow values above 160 mm indicate excessive fluidity, increasing the risk of material spreading and compromising structural stability during printing.

The 3D printed specimens underwent mechanical strength testing. Three-point bending tests were carried out on prism specimens following the standard [9], at 24 hours, 7, 14, and 28 days. Additionally, compressive tests were conducted on cubic specimens following the standard [10] at the same time intervals of 24 hours, 7, 14, and 28 days.

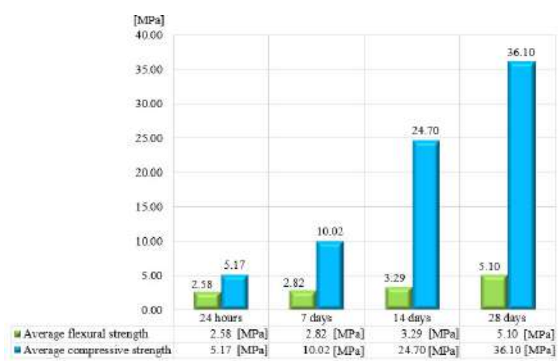

Fig. 1 Mechanical strength.

Methodology

The objective of this research was to develop an innovative approach for the restoration and conservation of architectural elements that are beyond saving through traditional methods. The methodology encompasses several stages, including the scanning of degraded .elements, 3D modeling of missing parts and fiber-reinforced mortar 3D printing.

Scanning of degraded elements

The initial step in the process involved the scanning of the degraded elements using point cloud technology. High-resolution 3D scanners were utilized to capture the geometry and surface details of the deteriorated architectural components. The scanning process was carefully executed to ensure accurate representation of the original element's shape, texture, and intricate features. Multiple scans were performed from different angles to capture a comprehensive point cloud data set.

3D modeling of missing parts

Following the scanning stage, a 3D modeling process was employed to recreate the missing parts of the degraded elements. Using specialized software, the point cloud data was processed to generate a detailed 3D model of the complete architectural component. Manual modeling techniques were employed to accurately reconstruct the missing sections, paying close attention to the original design and historical context. The resulting 3D model served as a reference for the subsequent 3D printing process.

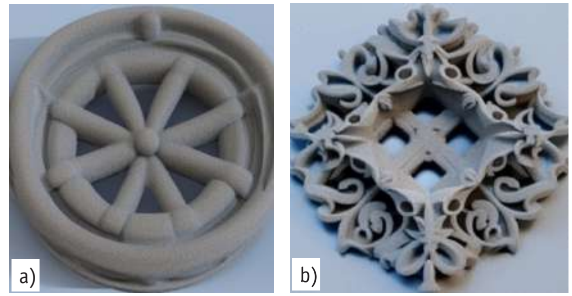

Fig. 2 Elements printed with different nozzles: a) 20 mm nozzle, b) 5 mm nozzle.

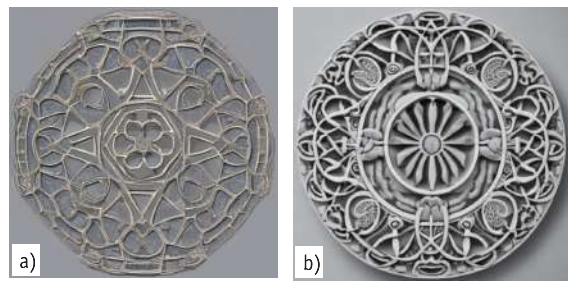

Fig. 3 Printing stages: a) image taken after the first two layers were executed, b) final element.

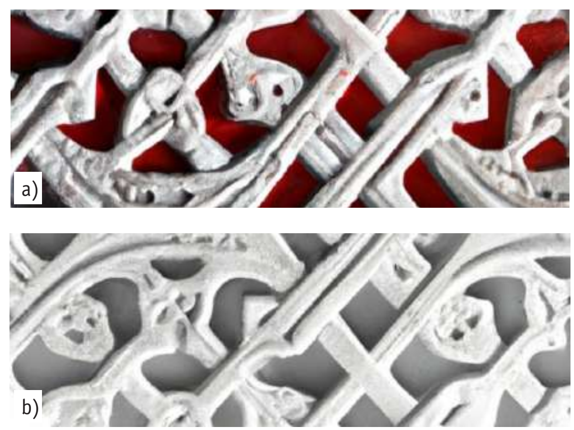

Fig. 4 Completing a degraded exterior decorative profile with 3D printed elements: a) remaining original part, b) 3D printed addition.

Fiber-reinforced mortar 3D printing

The 3D printing process was executed layer by layer, guided by the 3D model generated in the previous stage. The printer deposited the fiber-reinforced mortar material, following the intricate geometry and design details of the missing sections. Special attention was given to maintaining the structural integrity and preserving the original aesthetic qualities of the architectural element.

In the fiber-reinforced mortar 3D printing process, the dimensions of the nozzles and the layer thickness were varied based on the model that needed to be reproduced. This approach allowed for greater flexibility and control over the printing process, accommodating different geometries and complexities of the missing or degraded parts.

Different nozzle dimensions were utilized, ranging from 2 mm to 20 mm, depending on the specific requirements of each architectural element (Fig. 2). Smaller nozzles were employed for intricate details and fine features that required high precision and accuracy. Conversely, larger nozzles were used for printing larger sections or areas that required rapid deposition of the fiber-reinforced mortar material.

The selection of the appropriate nozzle dimension was determined by factors such as the size of the missing part, the level of detail required, and the desired printing speed (Fig. 3). By utilizing a range of nozzle sizes, the printing process could be tailored to match the unique characteristics of each architectural element, ensuring optimal results.

Furthermore, the layer thickness during the 3D printing process was adjusted accordingly. Thinner layers were employed for intricate details and complex geometries, allowing for a higher level of resolution and accuracy. On the other hand, thicker layers were utilized for larger sections, enabling faster printing speeds while maintaining structural integrity. Fig 4 illustrates both an original byzantine architectural element and a 3D printed reproduction, made by varying the nozzle and layer dimensions.

Conclusion

The presented research offers a novel solution for the restoration and conservation of highly degraded architectural elements of cultural heritage that are beyond rehabilitation using traditional methods. Based on the findings described in this work, the following conclusions can be drawn:

- The 3D printing process utilizing fiber-reinforced mortar allows for the accurate reproduction of arhitectural missing parts, ensuring the preservation of intricate details and historical context.
- The fresh properties of the 3D printed mortar contribute to the successful creation of resilient and structurally sound 3D printed elements.
- The mechanical strengths achieved by the 3D printed mortar, as validated through rigorous testing, ensure the durability and integrity of the reproduced architectural elements.
- This innovative approach provides a sustainable solution for the preservation and conservation of cultural heritage, safeguarding the history, identity, and legacy of societies.

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Converting an industrial hall into a Museum of Industrial Archeology: approaches and plans for the transformation of 'The Tobacco Storehouse' in Iaşi, Romania

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Abstract

The industrial archeology, a relatively new field in Romania, aims to shed light on the industrial heritage. It is an interdisciplinary field that studies the material or immaterial evidence of documents, artifacts, structures, human settlements, and urban or natural landscapes created for or by industrial processes. In this paper, we present the conversion of an industrial hall located in Iasi, Romania, into a museum of industrial heritage.

The original industrial hall, known as "The Tobacco Storehouse", was built in 1894 and measures 1427 sqm, disposed on three stories. The museum will permanently display machineries, steam powers, printing machineries, airplanes and motor vehicles. This paper presents the approaches proposed by architects, design engineers, curators, and experts for the conversion of this space. The conversion process involved careful consideration of the hall's historical and architectural value. The aim was to preserve its industrial character while creating a modern museum space that would attract visitors from all over the world. The proposed designs and plans take into account the building's existing features, such as the large windows, high ceilings, and exposed brick walls. The use of natural light, innovative display systems, and interactive exhibits will create an immersive and engaging experience for visitors.

One of the critical aspects of this process is the evaluation of the existing masonry structure and the identification of any defects that need to be addressed before the conversion. Non-destructive testing (NDT) techniques are used in this regard as they providing valuable information about the integrity of the structure without causing any damage. In this respect, both surface-based and volumetric assessments were performed. The surface-based analysis included visual inspection, surface roughness testing and surface drying testing, while the volumetric assessment consisted in ultrasonic testing by use of high-frequency sound waves to evaluate the internal condition of the masonry elements.

The conversion of "The Tobacco Storehouse" into a museum of industrial heritage is a significant project that will contribute to the promotion and preservation of Romania's industrial heritage. The museum will provide an opportunity for visitors to learn about the country's industrial history, as well as the social and economic context in which it developed. The proposed approaches and plans presented in this paper offer a valuable insight into the complex process of converting an industrial space into a modern museum while preserving historical and building value.

Keywords: masonry, heritage, NDT, convert, rehabilitation.

1. Introduction

As a preservation process, industrial halls often have historical significance as they represent the industrial heritage of a region. Converting one into a museum allows for the preservation and celebration of this industrial history, providing a valuable educational resource for visitors in accordance with TICCIH Charter «Charter pt.7-II, The International Committee for the Conservation of the Industrial Heritage».

This project respects all the principles about industrial heritage. Firstly it enables adaptive reuse (this approach promotes sustainability by repurposing existing structures instead of constructing new ones) and combines both exhibits and collections (showcase artifacts, machinery, tools, documents, photographs, and other items related to the industrial era -these exhibits provide a tangible and immersive experience, allowing visitors to understand the evolution of industries, technological advancements, and the impact on society- last Industry Chimneys time). It also propose various features such as interpretation and storytelling, educational value (serve as an educational institution, offering programs, workshops, and educational materials related to industrial history, technology, engineering, and innovation - schools, universities, and research institutions to provide educational opportunities for students and researchers). Beside the already mentioned features it represents a community engagement by converting an industrial hall into a museum can stimulate the community's involvement in preserving the history of the region. Regarding the architecture and design, the fea-

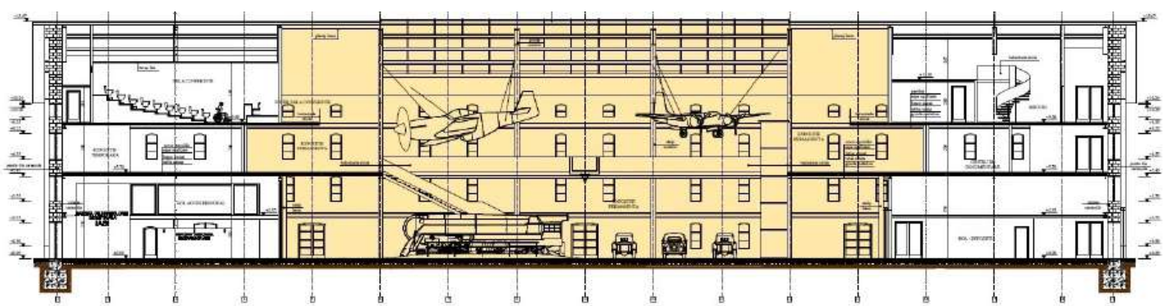


Fig. 1 Museum of industrial heritage.

a b c

Fig. 2 The localization of the Tobacco Storehouse: (a) map; (b) photo hall outside; (c) photo hall inside.

tures of the industrial hall can be highlighted and preserved, showcasing the industrial aesthetics and design elements of the era- can create a unique ambiance that complements the museum experience. Additional it involves accessibility and visitor facilities, future adaptability, conservation and preservation.

Converting an industrial hall into a Museum of Industrial Heritage presents an opportunity to honor the industrial heritage, educate the young people, and contribute to the cultural growth of a community.

2. Materials and methods

The foundations of the building follow the traditional approach of continuous stone foundations beneath the walls. The lower sole has a width of 1.30 m and is positioned at an elevation of -3.60 m. However, the foundations possess only partial rigidity to effectively transmit the operational demands to the ground. The load-bearing structure of the building consists of brick masonry walls arranged in two orthogonal directions. However, the brickwork lacks confining elements such as reinforced concrete pillars and belts, failing to meet the current requirements set by legal regulations. Inside the building, the load-bearing structure employs wooden frames with poles measuring 27x27 cm and spaced at 4.50 m intervals. The transmission of forces to the ground is achieved through isolated foundations positioned beneath the wooden poles. The floors are predominantly constructed with wood, although significant deterioration is observed at the time of assessment. The existing roof is framed type and exhibits degradation that permits water infiltration. The materials utilized in the structural elements are of unsatisfactory quality, meeting the standards applicable during the original construction but failing to comply with current legal norms. The qualitative evaluation of the "The Tobacco Storehouse" building aimed to assess compliance with general structural regulations and the detailing of both structural and non-structural elements. Consequently, the following conclusions can be drawn, categorized according to specific criteria.

Through an analysis aligned with prevailing regulations pertaining to resistance, stability, and operational safety, it is evident that the structural elements exhibit a significant degree of degradation. The degradation encompasses both structural and non-structural components, manifesting as follows: -structural walls exhibit vertical and inclined cracks, large areas suffer from the degradation

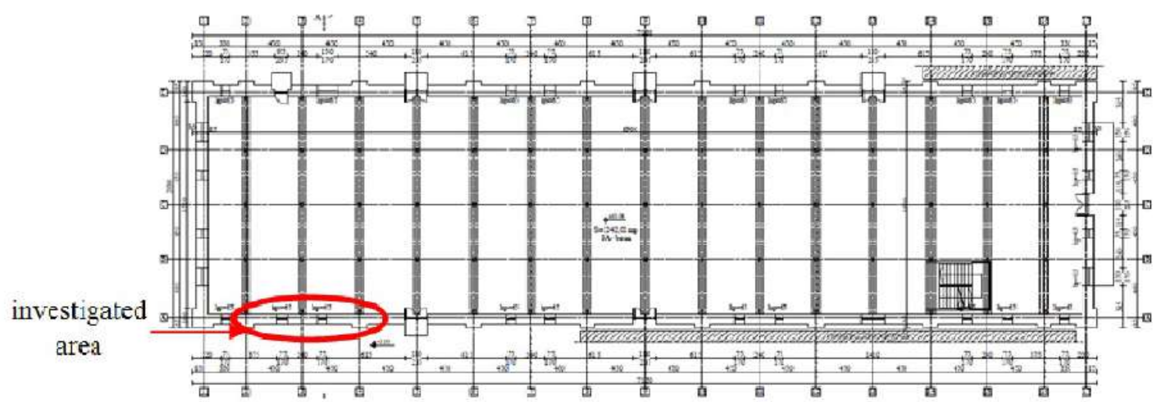


Fig. 3 Graphic representation of the industrial hall.

and collapse of wooden planks, deterioration of interior masonry is observed in localized regions, absence of metallic components necessary for the connection of wooden elements,interior and exterior plastering has deteriorated, local water infiltration from the roof is present.

To ensure the acquisition of pertinent research findings while considering the structural integrity, non-destructive methodologies were employed to obtain accurate and reliable results: visual and ground penetrating radar (GPR).

GPR is a geophysical method that uses electromagnetic pulses in the radar and microwave frequency spectrum (20-2000 MHz) to detect anomalies in underground utilities «R. Grimberg, et.al., 2011», and concrete substructures «G. Leucci, et.al., 2017»; «R. Grimberg, et.al., 2009». GPR is a well-defined and accepted NDT assessment method to obtain a high-resolution image of the subsoil and for accurately assessing the condition of structures. Using this technique, any buried object or any substructure that presents a contrast in dielectric constant (relative permittivity) from the surrounding environment can be efficiently mapped «D.J. Daniels, 2004».

2.1. Materials And Technologies

The proposed interventions for the restoration, renovation, and modernization of the building encompass various categories. Firstly, the restoration of brick masonry involves restoring the solid brick walls in the central space and gables, which will remain visible within the building. Secondly, masonry wall interventions include creating gaps in the walls for proper mortar casting with dispersed reinforcement, injecting the walls with reinforced fiber mortar within the ventilation layer, and renewing existing air layer walls by reinforcing the core masonry «D. Ungureanu, et. al. 2021».

Strengthening the structural walls is another aspect, which includes introducing connectors to enhance the stiffness of the walls after injection works and mortar hardening. The architectural works will primarily prioritize restoration using a combination of traditional technologies, incorporating both original and modern materials.

The objective of this study is to extend the operational-service life of the warehouse while ensuring cost efficiency and sustainability throughout the design stage and utilization period «Documentation for assignment of intervention».

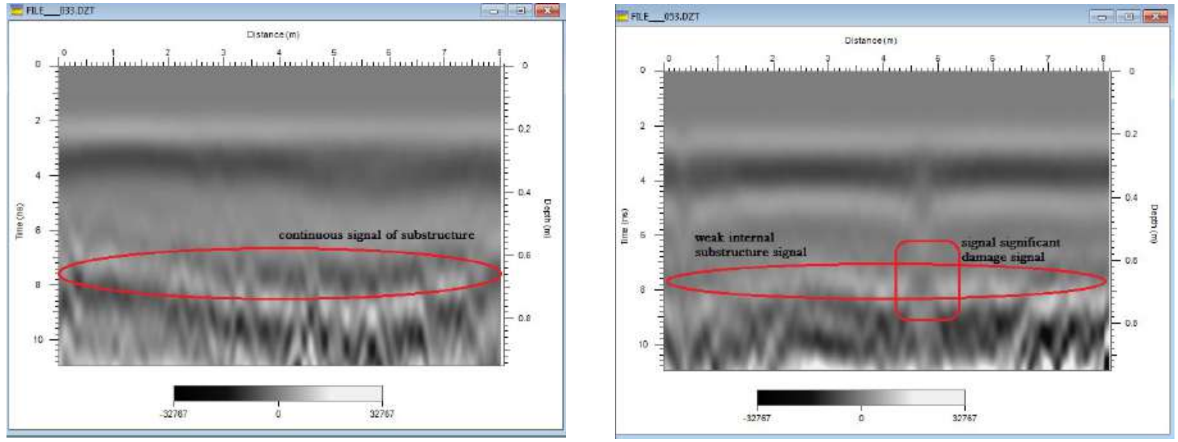
2.2. Equipments and methods

The data acquisition was made with Mala CX 11 which has built-in software for both data collection and on-site interpretation, tailored for high-frequency applications «https://www.malagpr.com.au/mala-cx12-concrete-scanner.html» and Utility Scan Standard System (Geophysical Survey Systems, Inc. GSSI, Nashua, NH, USA), with 400 MHz antenna «N.

a b c

Fig. 4 The areas of survey investigations: (a) outside; (b), (c) inside.

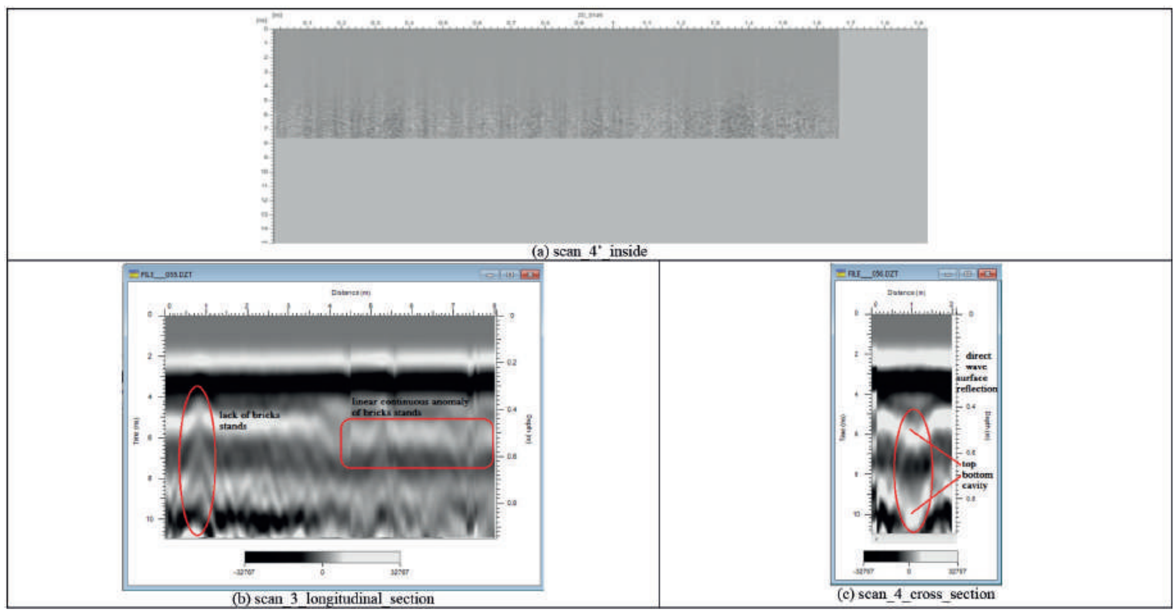
Fig. 5 The survey was done on the floor in the immediate vicinity of the wall: (a) outside continuous signal of substructure and (b) weak internal substructure signal with significant damage signal.



a (a) scan_1_outside

b (b) scan_2_inside

Fig. 6 The survey was carried on a damaged wall inside.



Iftimie, et.al., 2021»; «N. Iftimie, et.al., 2019». Both equipment utilize specific software to collect and interpret the obtained results.

3. Results

In figure 5 (a,b) it was show of the top of the image coincide with the top of the substructure and represents a cross section of the floor. In Figure 6 (a) the survey was done cross section damaged wall inside where the lack of bricks stands out in the form of cavity as well as continuous anomaly of bricks stands. In Figure 6 (b,c) the survey was carried longitudinal and cross section on the same wall as mentioned above. Also, the particular image shows a significant void signal at is typically appears in GPR radargram. The void signal is distinctive because of a ringing or echo present within the recorded data.

4. Conclusions

The technical solutions for the structural interventions were determined based on the results collected with two different equipments, visual inspection findings and the technical-financial analysis.

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Part three – Monitoring of Cultural Heritage

The microclimates unbalance of subterrain historic spaces in Italy

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Abstract

One of the primary challenges in conserving a historic site or building in use is determining the optimal threshold for safe and comfortable usage, as well as quantifying and qualifying the risks associated with this usage.To establish a standardised monitoring procedure that effectively collects the necessary information and data, it is crucial to have robust data management procedures focused on capturing essential information for maintenance planning. Additionally, gathering information to support information exchange among key stakeholders involved in the conservation of historical buildings and surfaces, particularly regarding microclimate evaluation and management, is imperative.

To achieve these goals, the paper presents microclimatic curves obtained from monitoring buildings in Milan and Sardinia (Cagliari), two regions with distinct geographical and climatic characteristics. The analysis of these curves allows researchers to identify similarities between different locations, similarities within the same location, and the range of days where exterior climate conditions are more stable. This stability enables frequent exchange between the interior and exterior with minimal risk to the conservation of historical materials.

These findings are particularly important when a new usage requires the placement, substitution, resetting, or implementation of HVAC systems, including the use of dehumidifiers, to monitor and reduce rising damp [1-2].

Keywords: cultural heritage, building conservation, microclimate monitoring, non-destructive techniques, historical building, preservation risk, ancient masonry, subterranean historic architecture, archaeological areas.

Introduction

The preservation of artifacts in historic buildings and archaeological sites is significantly affected by climatic conditions and the microclimate generated within these environments. This study aims to assess strategies for controlling and monitoring microclimate parameters to mitigate the risks associated with microclimatic variations. Recent research on underground spaces has revealed that variations in microclimate can occur due to external influences and the use of the space above the underground rooms, such as the presence of gardens, soil characteristics, water ducts beneath road pavements, and more [3-9]. Through monitoring numerous underground sites over the past decade, recurring degradation phenomena have been identified.Considering the potential for reuse, insights gained from microclimate monitoring are crucial for making informed decisions regarding conservation and utilization. Specifically, when repurposing hypogeal spaces, changes in thermo-hygrometric parameters may arise due to the installation of new equipment or the presence of individuals who may occupy the space for extended periods, such as janitors and staff, as well as temporary visitors. Understanding these dynamics aids in ensuring the preservation and appropriate utilization of such spaces.

Environmental monitoring plays a critical role in determining the thermohygrometric conditions of the microclimate, thereby ensuring the stabilization of the property It serves to assess the following aspects:

- Congruence with new use: Monitoring helps determine whether the existing conditions align with the intended new use and identifies potential risks;

- Timing and duration of public access: Monitoring allows for the preservation of the property without compromising its condition [10-13], by the identification of temporal "windows" during which exchanges between the interior and exterior, moisture input, and temperature fluctuations are less.

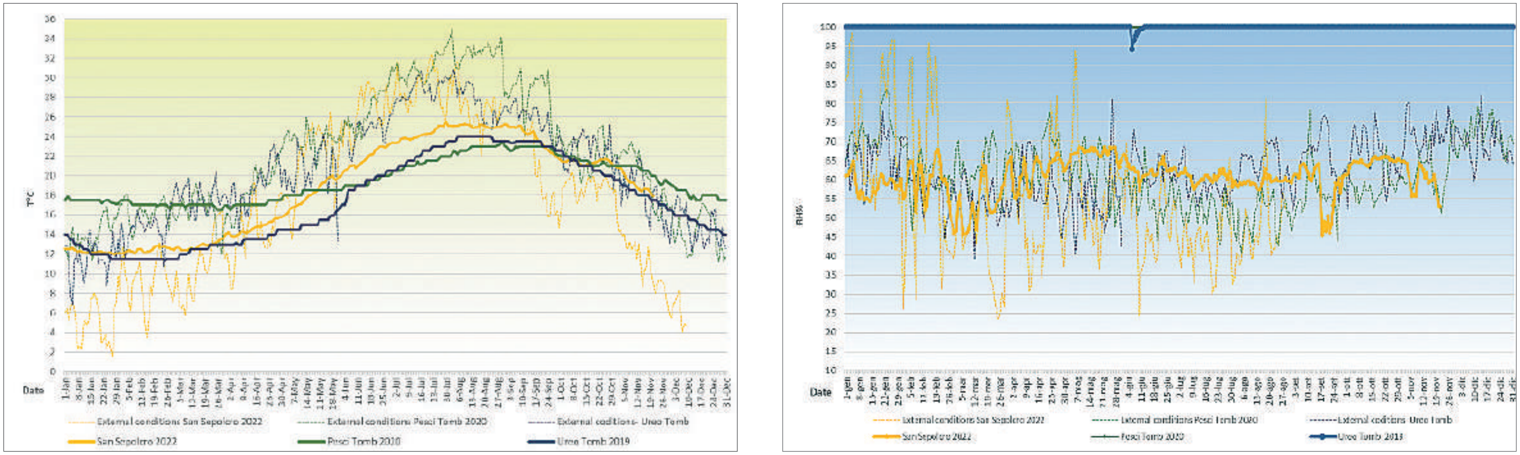
At present, scientific literature and regulations focus only partially on the issue of monitoring, some references are as bibliography of the present paper [4,13, UNI 10829/99, UNI 10969/02, and EN 16682/17.].

Fig. 1 Image of the case studies.

San Sepolcro crypt, Milan

Pesci and Spiga tomb, Santa Verdrace, Cagliari

Tomb of Ureo, Tuvixeddu, Cagliari



a b

Fig. 2 a) The annual graph of the daily average tempratures of the case studies; b) The annual graph of the daily average RH% of the case studies.

Introduction of the case studies and methods

The studies showcase a variety of historical properties, situated in different climatic conditions such as Milan and Cagliari (Fig. 1). The materials utilised in these properties encompass a diverse range, including frescoes, plaster, mortar, and stone. The case studies also shed light on the implementation of various monitoring systems, encompassing properties equipped with dehumidifier systems as well as those without dedicated climate control systems. San Sepolcro Crypt in Milan is a historically significant architectural site constructed in the 11th century during the Romanesque period. A comprehensive three-year monitoring study was conducted on the crypt, starting in 2019. The monitoring project aimed to evaluate the effectiveness of the dehumidifiers, ensuring their impact on the environment was controlled and prevent any damage due to microclimate variations.

The Tombs of Pesci and Spighe and Ureo, in Cagliari, are captivating historical monuments with deep cultural significance for its decoration dating back the Roman empire, monitoring started in 2017 and 2019.

The project for the reopening of some chamber tombs must include the mitigation of the imbalances that occur at the entrance, since it has been verified through monitoring that the frequent opening of the Tombs, even with the presence of a few people, is the factor that has the greatest impact on the variations in the internal microclimate. The techniques used (psychrometry, environmental probes, thermography), which are strictly nondestructive, have no impact on the property and its use, can have prolonged application over time and ensure what is the maximum duration that can be expected for the site to be open without significantly changing the indoor microclimate.

Results and Discussion

The comprehensive study of multiple cases, characterized by variations in geometry, construction age, materials, geographical location, and other factors, demonstrates the effectiveness and utility of monitoring at different stages of the conservation and reuse process. This enables a thorough control of potential impacts on the preserved asset while

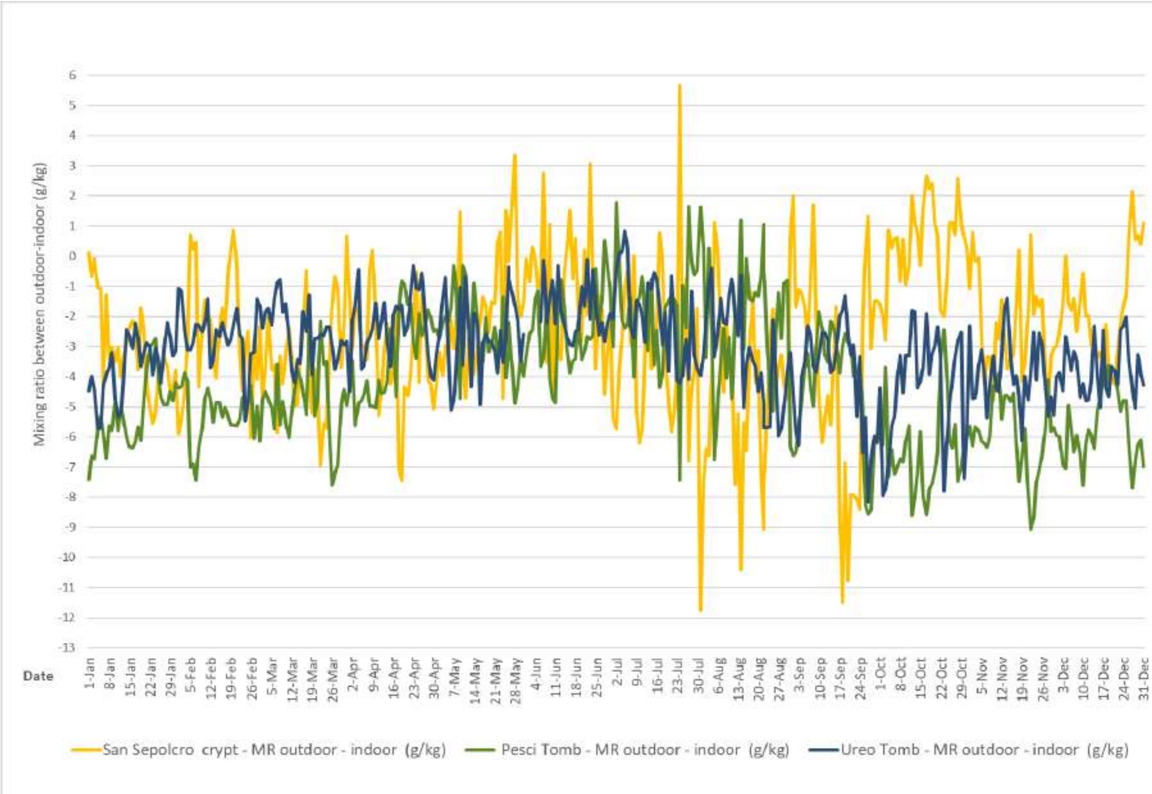


Fig. 3 The annual graph of the daily mixing ration exchange between the indoor and outdoor environments.

minimizing costs. The monitoring approach takes diverse forms based on preliminary surveys and may conclude once stabilization of microclimate parameters is achieved. Risk mitigation factors and facility validation operations are equally subject to monitoring, facilitating the assessment of effects and timely intervention if necessary.

Comparisons among different tomb types have revealed a consistent relative humidity (RH) value ranging between 90% and 100% for all the analyzed environments (Fig. 2). The comparison of the air-exchange rate's mixing ratio (MR) among the case studies reveals minimal values for the tombs, indicating limited air movement and exchange within these enclosed spaces (Fig. 3). In contrast, the San Sepolcro crypt exhibits greater variability in MR, particularly during the summer and autumn seasons. This variability suggests fluctuations in the ventilation and air circulation within the crypt during these periods.

As a conclusion, monitoring acts as a safeguard during the implementation of changes, which often occur with unplanned timing and interruptions. The monitoring strategy carefully balances the acquisition of pertinent information for assessing intervention effects and the sustainability of evidence, employing various techniques and instrumentation specific to the issues under investigation. Commencing monitoring before the design phase is crucial. Project initiation often experiences delays due to necessary agreements and negotiations, resulting in unforeseen time extensions. However, once the construction site is operational, all participants strive to minimize intervention duration and expedite the asset's return to the market. Initiating monitoring with even basic tools during the early stages of inspections allows for the accumulation of valuable months of data, facilitating informed decision-making in both the design and intervention phases.

The first site survey, supported by NDT-type instrumentation, is used to assess the critical points where instrumentation for continuous monitoring will be placed, if necessary. Therefore, the first installation of a few environmental probes can be directed by the geometry of the property, the presence of openings or obstacles to the movement of air masses inside and outside and degradation, of the presence of thermal imbalance mitigation systems, also "historical" or recently installed such as curtains, curtains, carpets or partial wall coverings, footings, etc. However, it is possible, after the first few months, to evaluate changes to be made to the data control and measurement strategy or implementation with other diagnostic techniques. In all reported experiences, the synergy between the technicians and other research institutions on the one hand and between the technicians and all stakeholders in the building/site (managers, custodians, owners, visitors, etc.) on the other hand has been very useful. The former has been useful in comparing externally recorded data and in assessing and identifying some causes of degradation through the implementation of other, more specific surveys. The creation of a network among the various research agencies and institutes, which already existed for some of the case studies although based more on a custom of work than on a normal and planned routine, is a guarantee of a more in-depth research and evaluation of risk factors starting from a common basic monitoring and extensive analysis. The latter, on the other hand, have been invaluable as janitors of assets. The presence of supervisory personnel, whether the owner or the restorer, has been of valuable help in identifying incipient deterioration and activating a preventive diagnostic campaign and for monitoring microclimatic conditions. Increasing awareness of the valuable role they play through common and simple monitoring practices and increasing sensitivity to the surveillance of such assets can initiate an invisible network of active "monitoring" that complements instrumental monitoring. Awareness about the value of the asset, the importance of conservation and the influence that one's own behavior can have on conservation, are tools that can be transferred by technicians even to those who are not experts in the field, but who use such assets.

Monitoring, in its meanings of passive through instrumentation and active through the control of people, thus has value as a synergistic and constant control, capable of preserving the assets by allowing timely intervention and safeguarding the permanence of the asset in case of obvious changes that may compromise its permanence.

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Aerial thermography applications for energy conservation and retrofit of urban heritage

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Abstract

Cities are the main responsible for energy consumption and greenhouse gas emissions in Europe, with the European Union playing a key role in policy-making to address this issue by enhancing the current energy performance class. In this process it is to be acknowledged that restrictions on cultural heritage can obstruct the renovation process by preventing transformations, thus requiring policymakers to find a trade-off which balances conservation and energy retrofit targets.

Infrared thermography can support the assessment process on multiple scales. By crossing estimated data on indoor temperatures and thermographic images it is possible to define the thermal dispersion of the building envelope, then correlating it to the energy performance class for planning interventions.

A real application on a district in Turin, Italy, is presented. It aimed at creating a hybrid Urban Building Energy Model based on aerial thermographic images and statistical data gathered through the Energy Performance Certificates and the national population census. The current state was defined before comparing two alternative renovation scenarios which considered alternative energy performance parameters and energy supply options. Specific insights can be produced on protected assets of the district area, thus enabling conclusions targeting an optimal trade-off between conservation and renovation.

Keywords: aerial thermography, remote sensing, energy performance, EPBD, energy renovation, urban energy modeling.

Introduction

Energy demand and emissions are strongly associated with cities, with these likely to further increase due to growing urbanization. At European level, the fit for 55 package targets a 80-95% reduction of GHG emissions by 2050 through 13 proposals, among which there is the revision of the Renewable Energy Directive, Energy Efficiency Directive and Energy Performance of Buildings Directive EPBD [COM/2021/802]. Especially the last two put the accent on the need for extensive energy classification, giving new light to this subject, due to the new minimum energy performance requirements that are expressed in terms of minimum energy class. In particular, energy performance class D must be reached for all buildings by 2035, while eliminating the building sector dependency on fossil fuels and relying on renewable energy sources.

The discussion generated from European policies highlighted the need for tools supporting energy assessments and planning. Geographic Information System (GIS) is able to overlap several layers for the understanding of complex phenomena. In the energy sector, it is used to create Urban Building Energy Models. UBEM's main weakness is the use of archetypes, with bottom-up physics approach being too expensive due to the extensive data gathering needed. Aerial thermography is a non-destructive, non-invasive technique that have great potential to solve this problem by providing data on a wide portion of the building stock, including dense urban areas that are recognized as cultural heritage.

In the context of energy assessment and planning, architectural heritage is often seen as an obstacle due to the constraints imposed by preservation authorities, that may occur both for monitoring campaigns and retrofit intervention. In particular, the need to preserve the current aspect often results in the impossibility to meet the EU objective and reduce energy demand through external envelope insulation, thus requiring dedicated design of other plant-based energy strategies based on detailed energy assessment of each building.

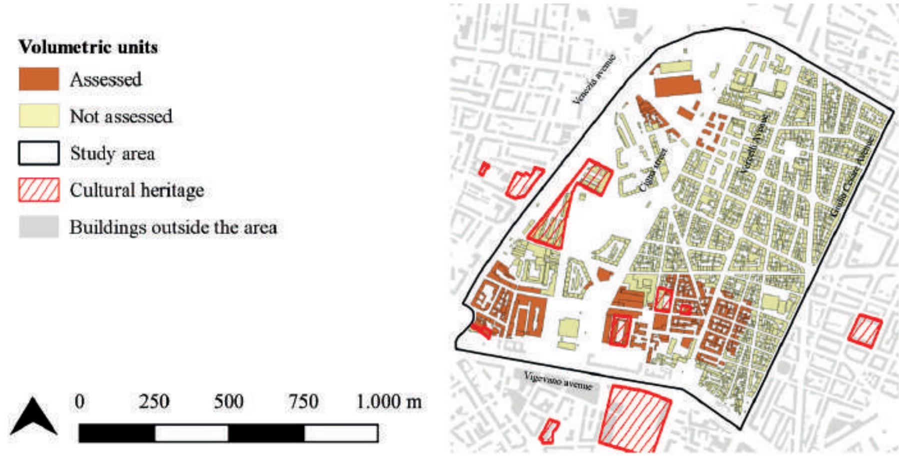

Fig. 1 Definition of the study area.

The study area

The analysed sample is located in the *Barriera di Milano* district, in Turin. This area has been one of the major expansion areas during the economic boom of the post-war period. In particular, multiple factories were located in the nearby, resulting in a pressing housing and services demand. Cheap housing was realised in the district, resulting in a building stock which nowadays proves to be crumbling or in the need for extensive renovations. Moreover, the dismission of historic factories – moved outside the cities or to other countries – in the Nineties left a considerable heritage in terms of volumes and value. The 1995 Turin masterplan fostered the regeneration of dismissed shopfloors and the area is now characterised also by malls and museums hosted in former production plants. The quality and results of such renovations, however, are still to be evaluated.

Nevertheless, minor heritage is still present and preserved by the Authority for Cultural Heritage, as shown in Fig. 1. It is the case of a wing of the former INCET factory – closed in 1968 – and of two schools realised between the end of XIX and the beginning of XX century.

Nevertheless, the historical urban structure has been kept, with a strong functional heterogeneity. The inner part is dense and designated to residences, while the main shopping areas and services are located on the boundaries of the study area. Such boundaries are now represented by the mobility infrastructures which used to serve the factories. In particular, it is the case of the former railway, a part of which is now the "backbone" of the interventions deriving from the 1995 plan.

Dataset acquisition

For this study, remotely sensed pictures were the key input. The evaluation of the thermal energy demand was carried out by observing values registered by a FLIR A8581 MWIR HD thermographic camera on 9/1/2022, which registers the bands with wavelength comprised between 3 and 5 μm and returns the surface temperature with a ±1°C accuracy. The pictures (example in Fig. 2) have a nadiral perspective and they were orthorectified, so the roofs only are visible. Moreover, the acquisition was performed during the day, with the results flawed by solar radiation and shading effect.

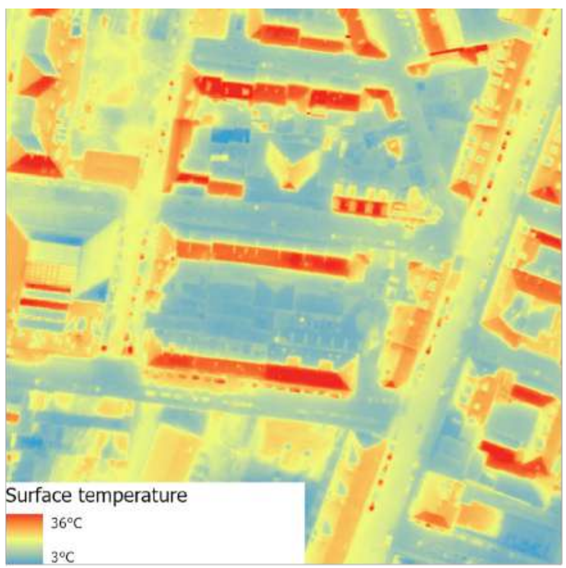

Fig. 2 Example of the acquired thermographic images.

To make them usable, thermographic pictures were georeferenced. The whole process was carried out in ArcGIS Pro by ESRI, in two phases: (i) scaling and rotating the picture for a first fit; (ii) definition of Ground Control Points for refining the georeferencing. The five images – covering approximately 0.35 km^2 – are located with a forward error equal to 0.941, equal to an inverse error of 1.412.

A LiDAR sensor was coupled to the camera during the survey for the TerraItaly™ Metro HD project, acquiring on average 8 points/m^2. Thanks to it, it was possible to realise a Digital Surface Model with a 0.5 m cell size, making it possible to compute geometries with a high accuracy. The DSM was one of the principal inputs for assessing the photovoltaic potential of the area.

The calculated data were referred to the volumetric units, assumed to be the minimum unit of analysis. The vector file containing the units is part of the technical map of the City of Turin, available on the Geoportal. The same source publishes the vector file of all protected buildings.

Determination of energy performance

Based the outer surface temperature obtained through thermography, it was possible to correlate the observed thermal dispersion to the actual energy performance of all buildings in the area. This was done by gathering the available Energy Performance Certificates, reporting calculated data on the energy consumption for space heating and cooling, and then extending the so-determined energy performance to buildings with similar thermal dispersion.

The most energy-intensive units are the biggest ones, especially former industrial buildings. On the other hand, reconverted buildings in the Western part of the study area are among the best performing. The historical buildings considered show low performing values, being classified in E or lower classes. In particular, two units pertaining to the primary school are classified in the worst class, G. As for the former industrial building, only one unit is falling in class G, but the huge footprint makes it the most consuming building among the three protected.

As for the total energy demand, electricity consumption are negligible due to the inclusion of residential needs only, equal to 9%. The average building can be classified as class E, based on a consumption of 155 kWh/m^2.

Determination of photovoltaic potential

Photovoltaic technologies are the most diffused in cities, thanks to the possibility to install modules integrated in roofs. Despite the mentioned problem of the potential impossibility to install photovoltaic panels on some roofs of architectural heritage, it is possible to identify available roofs and foresee collaboration forms, towards Renewable Energy Communities. Therefore, the photovoltaic potential of the available roofs in the studied area was calculated though the Suri equation (1):

$$PV_{potential} = PR * \eta * surface * Solar\ energy\ [kWh/year] \quad (1)$$

where the Performance Ratio PR – assumed to be 75% – estimates the efficiency of the system, including potential leaks; the conversion efficiency η (set to 18.4% for polycrystalline cells, according to Green et al.) returns the share of solar energy converted into electricity by different technologies of photovoltaic modules; the surface is assumed to be 40% of the footprint of each unit, with this share correcting the inclination and presence of obstacles. Concerning the detailed calculation of solar energy, it was assessed through the "Area solar radiation" tool in ArcGIS Pro, whose inputs were set in order to reduce the elaboration time while keeping the accuracy.

Two crucial parameters are the two pertaining the radiation – diffuse ratio and transmissivity. The former is calculated through an online tool by the European Commission – PVGIS – while the latter requires further calculations on the data extracted from the same source.

With these parameters, the process takes approximately one hour for 0.7 km^2 (two hours to process the whole area). Each building was assigned a production value by converting the raster output of the "Area solar radiation" tool to points and spatially join them to the volumetric units dataset – using the values of the closest point to the centroid of the unit.

From this it derives a yearly producibility of 8.8 GWh, with differences deriving mainly from the dimensioning of the systems – and therefore from the roof areas – with all buildings producing more than 120 MWh/year having panels for at least 480 m^2.

Nearly half of the volumetric units can self-produce their electricity need, with 15% of the total potentially producing twice the demand. 83.2% of the demand can be produced in the district, with a resulting need to produce collaboration forms which maximise benefits for the community.

Renovation scenarios

To test the method described above, two alternative renovation scenarios were elaborated by changing some of the relevant input parameters, such as energy performance class and energy supply option.

First, savings were assessed in terms of primary energy. In Fig. 3 all the different configurations are compared. It emerges that natural gas boilers (G) – which are currently used – cause the highest consumptions, while

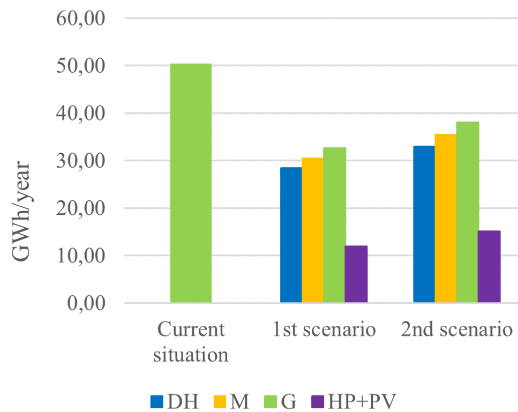

Fig. 3 Primary energy consumption.

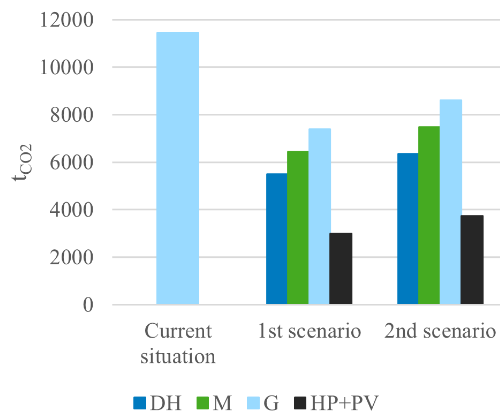

Fig. 4 CO_2 emissions.

the installation of heating pumps – with the demand partially covered by photovoltaic panels – (HP+PV) would half the energy need. Nevertheless, keeping this supply option it would be possible to cut the CO_2 emissions (Fig. 4) by 2829 tonnes in the second scenario. District heating (DH), whose implementation in the district is likely in the near future, reduces consumptions by a further 15% compared to natural gas boilers. The mixed scenario (M), with thermal consumptions provided by gas boilers and district heating for 50% each, is an average between the two.

The second scenario can be seen as a first step towards the implementation of the optimum one. The additional retrofit would result in energy savings comprised between 14% and 21% without the need to change the energy supply option, with additional benefits moving from natural gas boilers to district heating too – 25%. As for carbon emissions, savings are increased by 10% when transitioning to district heating from gas boilers, 6% in the case of stopping with a mixed scenario.

Conclusions

This research aims to create a simple but reliable method to assess energy consumption and production from RESs, with the possibility to use it to compare alternative renovation scenarios considering the boundaries of architectural heritage and their identified technical constraints. It emerged a need for extensive and reliable data as input, but also the possibility to quickly evaluate savings in terms of primary energy and prevented emissions.

The used dataset resulted in some limitations. In particular, the nadiral perspective of thermographic pictures caused the impossibility to assess the thermal dispersion of the facades, with roofs being also affected by incident solar radiation flawing the results. Moreover, the adopted temporal resolution for the two example retrofit scenarios – yearly – is suitable for a suitability analysis, while it requires additional calculations for defining precisely the potential benefits.

Still, the main aspect to be tackled, considering limitations emerging from the need to preserve the architectural heritage and the different characteristics of the urban structure – making some interventions more suitable than others in the medium term – is the realization of Energy Communities, which empower the community and enact a virtuous cycle of economic and environmental benefits. The two scenarios – properly deepened in terms of requirements – can be used for setting a roadmap towards the implementation of Energy Communities, with this tool being a support to respect the dimensioning requirements.

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Precettoria of Sant'Antonio di Ranverso, an integrated approach for the study and monitoring of the Jaquerian painting cycles. The process for the definition, implementation and verification of conservation strategies

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Abstract
The Precettoria of Sant'Antonio di Ranverso, property of Fondazione Ordine Mauriziano, is a Gothic church in which is present an extraordinary cycle of frescoes by Giacomo Jaquerio (first decade of the 15th century), the greatest exponent of late Gothic painting in Piedmont.
Since 2021, the CCR has been engaged in the study of the wall paintings aiming at understanding the causes of the deterioration of the pictorial surfaces to define conservation strategies. The walls, in fact, are mainly affected by capillary rising dampness and infiltration of meteoric water.
Thanks to an integrated approach based on different investigation techniques carried out on the painted surfaces and on the building, it was possible to obtain a rich and articulate diagnosis of the conservation status.
Before the restoration, the necessary corrective actions were also evaluated, including roofing overhaul, cleaning of downpipes, renovation, and adaptation of the stormwater drainage network, and their effectiveness was evaluated through repeated monitoring and surveys.
The preliminary study of conservation events, the autoptic analysis, and the monitoring through repeated photographic campaigns were carried out according to a programmed plan. In parallel, the execution of a three-dimensional virtual model of the building allowed a better contextualisation of the data. An initial multispectral campaign and subsequent scientific analyses allowed to investigate the nature of original, non-original, and new formation materials. In the building was carried out an environmental monitoring of temperature and relative air humidity and the surfaces were subjected to periodic humidity measurements. A campaign of thermographic analyses was conducted by the Non-destructive Diagnostic Laboratory of Politecnico di Torino to investigate more accurately the presence of water in the internal and external walls and floors. Finally, endoscopic investigations clarified the nature and conformation of the layers underneath the floor level.

Keywords: cultural heritage, mural paintings, capillary rising dampness, moisture, salts efflorescence, infrared thermography, environmental monitoring.

Introduction

The Precettoria of Sant'Antonio di Ranverso, property of Fondazione Ordine Mauriziano, is an extraordinary Gothic church with frescoes by Giacomo Jaquerio. Starting in the mid-19th century, the gradual rediscovery of the mural paintings contributed to the study of the Piedmontese school and the beginning of the critical fortune of the Ranverso paintings that were published and became internationally known (Cavalcaselle and Crowe, 1887). From the end of the 19th century until 1921, a large *descialbo* site directed by Alfredo d'Andrade and Cesare Bertea (Curto, 1981) brought the entire decorative apparatus to light, with inevitable losses and tampering.

Since 2021, the Centro Conservazione e Restauro "La Venaria Reale" in collaboration with the LabDIA of Politecnico di Torino, has been engaged in the study of the paintings aiming to understand the causes of the deterioration of the pictorial surfaces to define conservation strategies.

The research focuses on the north wall of the presbytery with the Virgin and Child with saints, kings, and prophets of the Old Testament painted by Jacquerio in the first decade of 1400 (Fig. 1). The state of conservation of this wall was considered representative of the main types of degradation phenomena found on all the decorated surfaces of the Precettoria.

To conduct an exhaustive analysis of conservation status and its causes, a preliminary in-depth study on the environmental context, the materials and construction techniques, and the conservative events was necessary.

Technique of execution and state of conservation

In the church coexist various decorative phases and the paintings with Stories from the Life of the Virgin are superimposed on the late 14th century paintings with large red veils, still visible in the lower parts. The paintings were realized with the fresco technique. The colour was mostly applied on freshly lime plaster through successive glazes of colour, but we also found colours such as blue and green applied on the dry plaster, probably with an organic medium. On the other hand, the highlights and lighter colours were created using pigments mixed with lime, and small fragments of gold leaf were found in the haloes of the Virgin and Child.

Fig. 1 North wall of the presbytery.

The north wall, observed from external, is made in parallel courses of bricks and there is no plastering. During the preliminary inspection, we noted that the main conservative problems were caused by the presence of water in the masonry affected by capillary rising dampness and infiltration of meteoric water that was not well conveyed and defects in the groundwater drainage system.

In this context, the condition of the decorative palimpsest today makes the conservation situation more delicate, with problems of constitutive fragility and complex responses to degradation events. Detachment and falling plaster phenomena are evident, and there is a massive presence of salts with conspicuous efflorescences, of varying conformation, on all surfaces up to great heights, mainly located in correspondence with the external downpipes in poor condition.

The floor consists of quadrangular terracotta tiles with evidence of moisture stains, crystallisation of salts and, in some cases, biological colonisation.

The situation described is common to the entire building, with different declinations of the degradation manifestations depending on the position and the type of alteration prevailing.

Preliminary study and investigations

Thanks to an integrated approach based on the study of different investigation techniques carried out on the painted surfaces and on the building, it was possible to obtain an articulated diagnosis of the conservation status.

A first photogrammetric survey was intended to obtain a dense cloud of the whole internal and external architectural complex to allow 3D navigation and spatially locate the studied area. These surveys have granted 3D spatial models used for monitoring the paintings from a morphological point of view and generating high-quality orthophotography images. With the cooperation of the restorers, specific areas for macro-photogrammetric surveys and micro-photography were chosen to read better the deterioration of the pictorial surfaces and study the adopted pictorial techniques.

To characterise the environment from a thermo-hygrometric point of view, dataloggers Testo 175H1 were used, to acquire temperature and relative air humidity values every 15 minutes. The acquisition campaign started in January 2022 and is still ongoing.

A total of four dataloggers were placed: two in the apse, at two different heights (2 and 5 meters above ground level); one on the internal gate of the presbytery and another one inside the presbytery itself. The sensors were placed in different positions to assess the homogeneity of the rooms and determine a possible stratification in height. The microclimatic survey also supported thermographic investigations.

A comparison of the data recorded at the different points shows a general homogeneity of readings. Even concerning the vertical, no significant air stratification is observed. The values follow the seasonal cycle, but good building inertia concerning external events is observed.

Visible light images before, during and after the study were collected and compared with the same images acquired in UV light and with infrared reflectography.

Besides imaging and multispectral documentation, scientific analyses were carried out to characterize new formation and degradation products on the wall surfaces.

Efflorescences and subflorescences were analysed to relate the composition to the nowadays state of conservation of the building. Microsamples scraped from the surfaces were analysed by FTIR spectroscopy.

The analysis showed the use of carbonate mortars rich in materials based on magnesium and gypsum. The presence of magnesium with gypsum based materials and a high moisture content affected the formation of magnesium sulphate based efflorescences and sub-efflorescences (Fig. 2). This compound, highly hygroscopic and soluble, easily changes physical state with an increase in volume, leading to increase tension in the walls and a quick disintegration. Nitrates based efflorescences were also evidenced; nitrates are commonly found in the country lands and in the places used for burial. As well as magnesium sulphate salts, nitrates are very soluble and crystallizing can induce fractures and falls of the paint film.

The painting was also studied by means of cross sections to observe and characterize the stratigraphical sequence of

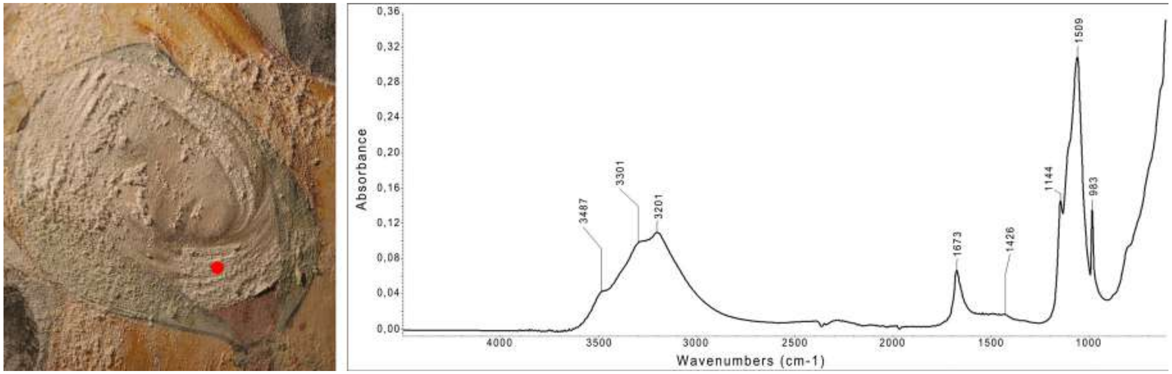

Fig. 2 Efflorescе composition: magnesium sulphate and oxalates.

Fig. 3 Before and after removal of salt efflorescence.

the painting layers. A focus on blue and green fields has been done and azurite and malachite were identified. Traditionally, these two pigments were used with a binder. Due to the state of conservation and probably the small amount of organic components, the binding medium is still unknown, but more analyses are in progress.

First corrective actions

Thanks to the preliminary study, it was possible to carry out a combination of immediate corrective activities to mitigate the causes of degradation, including roofing overhaul, cleaning of downpipes, renovation and adaptation of the underground stormwater drainage system, and their effectiveness was evaluated through repeated monitoring and surveys internally and externally.

On the painted surfaces, preliminary securing included the removal of inconsistent surface deposits and salt efflorescences (Fig. 3) to minimise the retention of moisture on the surfaces, and mechanical stress caused by continuous cycles of solubilisation and crystallisation of salts and localised consolidation at the detachments of preparatory and pictorial layers. Finally, localised consolidations of the preparatory and pictorial layers were carried out.

Survey after the first corrective actions

To assess the effectiveness of the first corrective actions, periodic monitoring was carried out through autoptic analysis of the surfaces supported by repeated photographic campaigns on both external and internal walls.

In parallel with the environmental monitoring and to further integrate the diagnostic picture, the non-destructive investigation campaigns conducted by LabDIA were started, as foreseen in the preliminary methodological protocol.

Thermographic inspections were performed to map the moisture front observed on the internal and external façades of the north wall of the presbytery. The repetition of the acquisitions over time, also following the execution of significant rainwater conveyance works, made it possible to transform the surveys from occasional events to monitoring.

The three IR campaigns out of the five planned were carried out in semi-passive mode. The high relative air humidity measured during the thermographic acquisitions (always over 70%) suggested creating natural ventilation of the internal surfaces to induce, in case of moisture, the evaporative phenomenon to be seen in infrared.

The data comparison in the year following the renovation work shows an improving situation despite the heavy rain that lasted for about a month before the last survey campaign. A reduction in the height of the equilibrium line and, in general, a decrease in signal intensity over the entire surface was observed on the inner wall (Fig. 4). On the other hand, it was not possible to carry out assessments from the outside due to the still present effect of rain on the bricks. However, to objectively evaluate the results and determine if this phenomenon is gradually fading in view of the restoration work, it is necessary to keep monitoring the surfaces.

Remote visual inspections conducted in the apsidal area confirmed the presence of damp soil, as assumed by thermographic acquisitions on the floor (Fig. 5). The information regarding the absence of extensive cavities (e.g., a crypt), at least up to a depth of 90 cm, also provided an additional element to the building's knowledge.

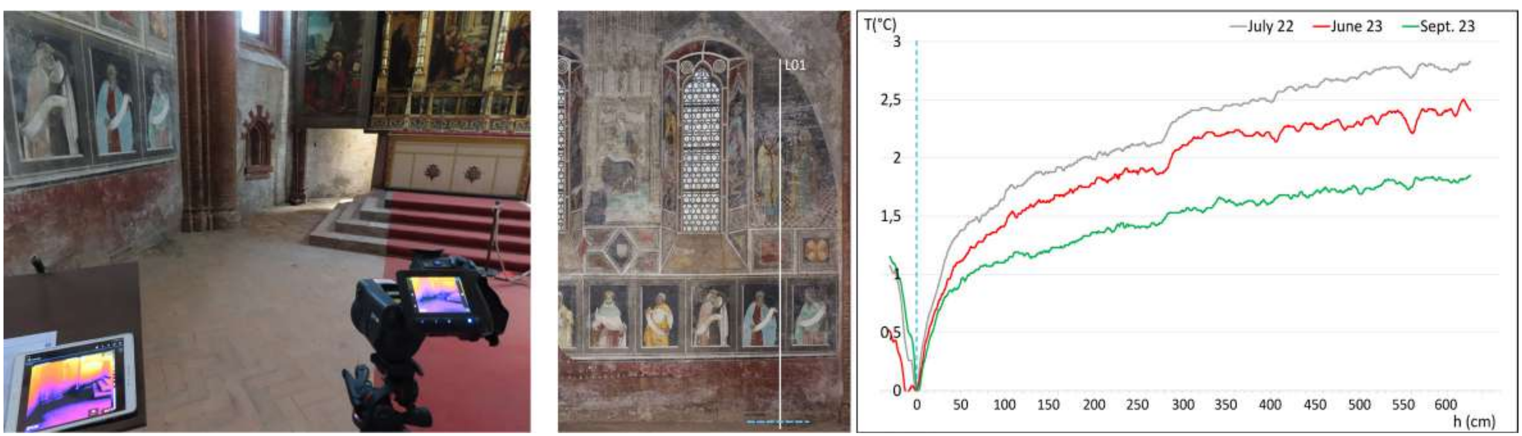

Fig. 4 North wall. On the left: IRT, June 2023 (the IR image on the tablet screen refers to July 22). On the right: graph of wall temperatures plotted along the L01 axis in the July 2022, June and September 2023 surveys.

Conclusion

This complex conservation scenario required a clear knowledge of the materials, but above all of the mechanisms triggering the degradation phenomena within an extremely articulated system. The cognitive steps were therefore conducted by means of a holistic approach and various investigation techniques that allowed the definition of methodologies to implement the necessary corrective measures to mitigate the effects of degradation. The effectiveness of the corrective measures was subsequently evaluated through an integrated monitoring system that is still in progress, which will be able to indicate the appropriate timeframe for future restoration and will be able to support providing the methodological guidelines for the intervention.

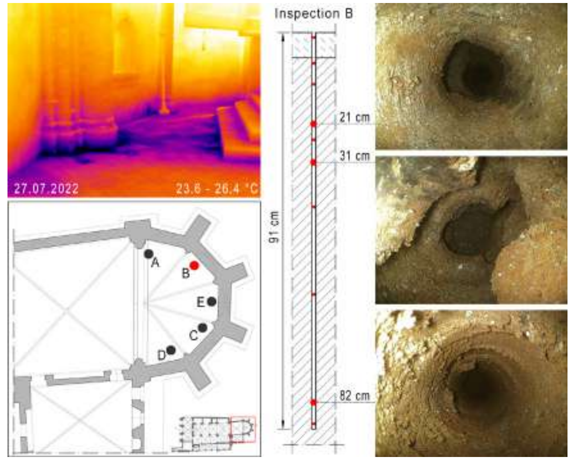

Fig. 5 Apsidal area: IRT and RVI, Selection of endoscopic images acquired at different depths in borehole B. The plan extract is from L. Di Pasquale, C. Gattiglio op. cit.

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Some data about traditional Venetian building materials characteristics

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Abstract

In Venice urban context, building materials are placed in contact with water on a permeable soil, with high quantity of salt aerosol, brushed by salt water and exposed to air with high level of relative humidity throughout the entire year. As a consequence, water can penetrate porous material by different processes such as vapor condensation, rain washout, drying-wetting cycle, capillary rise and operating humidity. These factors generate aesthetic, hygienic, thermal and mechanical damages. Materials and structures are subjected to deposition, surface alteration and fragmentation, internal erosion and dissolution. These damages can be avoided through designing and planning proper interventions, at the basis of which a complete knowledge about materials characteristics and behaviors is fundamental. Almost all Venice buildings have a masonry structure with clay bricks and lime mortar, and in some cases Istrian limestone as a structural part or decoration element. As a first step in this analysis, clay brick and lime mortar were considered.

Many studies starting from the two edition of the conference "Il mattone di Venezia" in 1979 and 1982 supplied useful information but often unlinked among them. In this context the aim of this study is to collect and present chemical and physical data from previous studies of the past decades, related to traditional buildings materials in Venice lagoon. Usually in fact, characterization is developed in each specific research only from a specific point of view and it is seldom complete for a single material. On the other hand, this information are of basic importance for the design and realization of sounded restoration and conservation activities.

Keywords: construction materials, historical building, masonry, mortar, Venetian lagoon.

1. Introduction

In Venice the construction materials are placed on a permeable soil, with high quantity of salt aerosol, brushed by salt water and exposed to high level of relative humidity (about 70%) during all year. The first Venetian residences were made of wood, but after the fires in 11th-12th centuries and the needs to require more durability for peculiar environmental conditions (high relative humidity, salt water, floods), gradually passed to made masonry structure of clay fired bricks joint with lime mortar, with visible brick finish or covered with plaster [1], [2]. The walls with a three-wythes brick thickness (40 cm) at the base and two-wythes brick thickness (25-30 cm) on the upper floors are common, to lighten the weight on the foundation. At the base of walls, the Istria stone had the purpose of avoiding the wetting of the masonry by the lagoon water. But the progressive rise of the sea level does not make such a solution satisfactory anymore.

The extrinsic (climate, external conditions) and intrinsic parameters (characteristic of materials) influence the penetration of water in the structures by many processes such as vapor condensation, cycle of drying-wetting, capillary rise, accidental leakage of conducts and operating humidity. These factors generate aesthetical, hygienical, thermal and mechanical damages [3], such as surface alteration from meteoric rain (dissolution of calcite) and wave motion, crystallization, exfoliation and scaling. This process begins in the mortar joints and then also in the internal layers, with erosion, loss of material and disintegration of the entire masonry. Therefore, the restoration problem and the conservation are fundamental to preserve the heritage architecture of this city.

The objective of this study is to provide quantitative elements on the original Venetian masonry, thanks to 35 years of analyses in the field [4]–[11], identifying as many features as possible: chemical, physical, mineralogical and mechanical parameters and technological characterization. Usually in fact, only one group of parameters presented in a specific disciplinary research other parameters being missing for a specific material. Data derived from samples collected in 45 historical buildings, erected between 13th and 18th century (Fig. 1). First level of knowledge consists of macroscopic analysis, identifying technological components and state of conservation.

Fig. 1 Location of the data collected about Venice materials (red, chemical + physical characterization; green, chemical characterization; purple, physical characterization).

2. Materials

2.1 Brick

In the Middle Ages, both kilns located in the Venice lagoon with clay at the lagoon edges, and mainland kilns (Altino and Padua) with clay from the Brenta river between Padua and Venice were used for the brickwork [12]. The latter had reduced costs, deriving from the easier supply of materials. Sometimes recycled bricks from the nearby area were used, such as Roman bricks and trachyte to stabilize the buildings.

The bricks used in masonry are distinguished by type of clay, manufacturing (lightweight and porous),

Tab. 1 Type of bricks widespread in Venetian ages [1], [13].

Age	Typology	Length [cm]	Width [cm]	Thickness [cm]
10th-12th century	Medieval	45-47	23	7-8
12th-14th century	Byzantine (“Altinella”)	15.5-17.5	8	4-4.5
14th-16th century	Gothic	26-30	12-15	6-7.5
16th-19th century	Renaissance	26	13	6
Since 19th century	Modern UNI	25	12	5.5

color of the mixture, firing, size, shape and adhesion to mortar. To improve the mechanical strength and make the bricks suitable for underwater foundations, vitreous surfaces are made, developed them salt-water resistant. The information about their method of installation, mortar type, surface finish (if present) and mortar joint height, provide for tracing back the historical period of construction.

2.2 Mortar

In Venice, the widespread mortar before the 19th century was a mixture of lime and sand of lagoon origin[14], [15]. The plaster until the 15th century was the same material used as a binder in masonry, with aged lime putty and sand (from the dune or lagoon), to obtain a thin finish that was then frescoed with polychrome pigments or faint lime. Since the 16th century, another mixture such as Cocciopesto (minced clay-brick) or stony aggregates were added to the finish in addition sand mortar. These mortars, until the 19th century, are organized in overlapping layers with different combinations, and the last layer has the color of the aggregate material. The plaster surfaces, both Medieval and modern times, were wet-treated with natural-derived protectants (oil, wax, soap, lime milk) and iron-finished to guarantee protection and a shiny appearance reminiscent of polished stone.

The mortar used since the 15th century have been slightly hydraulic, called “calce Negra” or “Padovana” in relation to their appearance (gray) and origin (Euganean hills). During the 20th century, hydraulic binder was widely used, cement in particular, both for masonry and for plaster; since the post 2nd World War period, industrial admixtures have been included in the premixed mixture or as dry-added protective surfaces.

2.3 Stone

In Venice, marble and stones had been used in the centuries both as construction material and for decoration [16], [17], such as Istrian stone, Verona red stone, Greek and Carrara marbles (saccharoidal marbles), white marble by Vicenza and Arenaria (used mainly for foundation).

Istrian stone [18]–[20] is a reef limestone of sedimentary nature formed in the Cretaceous, characterized by gray-green shades. The widespread use in Venice since the middle of 13th century, is related to its origin (Croatia), which facilitated its transport by ship. Thanks to its low porosity and high resistance to the marine environment that makes it a good waterproofing material, it has been used for the cladding of buildings, foundations or along canals at the base of the building to limit the phenomena of rising damp as a load-bearing element in structures, due to its high compressive strength.

The Verona marbles (color shades from yellow by hematite, to red brown by limonite), and those derived from Greek or Carrara mines, are usually used as decoration (i.e. statues, columns, capitals), because they have a limited durability in areas exposed to atmospheric agents, derived from structure heterogeneity.

3. Materials characterization and conclusions

The dataset consists of 88 observations for different materials and investigation topics. Many data derived from chemical/mineralogical characterization, especially for bricks (57%), probably related to the ease of drilling and finding the material on masonry. This classification includes the material composition in basic and acid oxide. Among the physical-mechanical characteristics analyzed (Tab. 2), studies focus on compositional structure such as porosity [%], density [kg/m^3] and pore radius [μm], parameters that are closely related to each other. On the other hand, there is a lack of investigations on hygrometric variables (Fig. 2). Again, data on brick samples are more numerous and complete (95%).

In the case of mortar and stones, there is a reduced analysis, especially in the physical domain, with only density and absorption data, respectively. Mortar has been more investigated in the chemical sphere, due to the simpler processing of the powder in the tools.

In this research, the collection of data related to the characterization of building materials, made it possible to recognize missing data in the various study areas or in the different elements analyzed. The prospect to enlarge the database, from existing studies and implementing them where it possible, would increase knowledge of Venetian materials used in historic construction. The future goal is to increase a technical knowledge of the built heritage and develop a targeted conservation strategy, relating it to environmental conditions, creating an open-access and georeferenced dataset useful for the restoration sector. This approach can also be used in other regions, contributing to comprehensive cataloging of cultural heritage.

Tab. 2 Physical and mechanical characteristics of Venice materials (φ [%] = porosity, ρ [kg m^{-3}] = density, π [kg m^{-2} s$^{-0.5}$] = permeability constant, CA [%] = absorbed water capacity, θ [-] = saturation coefficient, Ø [μm] = pore radius, σ_{10} [N mm^{-2}] = compression strength.

Materials	ϕ	ρ	π	CA	θ	Ø	σ_{10}
Brick	28±11	1608±246	0.21±0.02	31±5	0.87±0.03	0.49±0.55	17±12
Lime mortar	-	1750	-	-	-	-	-
Stone	-	-	-	20.5	-	-	-

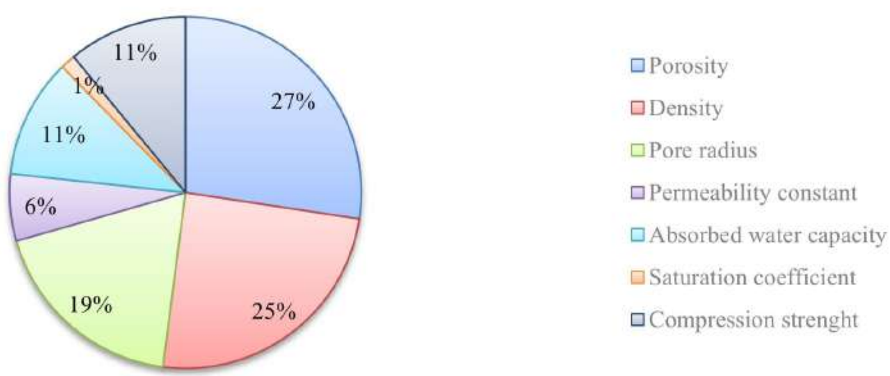

Fig. 2 Numbers of data collected about bricks physical/mechanical properties.

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Non-destructive monitoring as a methodological approach for the conservation of cultural heritage: 10 years of studies on the Chapel of Sant’Eldrado

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Abstract

Due to its artistic unicity, the Chapel of Sant'Eldrado in the complex of the Abbey of Novalesa (province of Turin) has always been the object of special care by the Institution for the protection of the cultural heritage. Its interior is entirely frescoed with an important iconographic cycle dating back to the late 11^{th} century. Despite continuous interventions to preserve the artwork, repeated alteration phenomena are compromising the legibility of some areas of the pictorial register, particularly on the south wall.

In this context, non-destructive investigation techniques impose their role as a knowledge and diagnostic tool that cannot be ignored concerning the need to protect and conserve the monument.

Infrared thermography initially used to respond to punctual requests from the property, has become an essential tool for monitoring the chapel over time.

Given the specificity of the distribution of alterations on the interior surfaces, the importance of assessing the building not only as a container but as an object-environment system was clear from the outset.

Since 2012, infrared surveys, conducted with rather unconventional protocols for the time, have been correlated with historical research on the maintenance and restoration of the property, remote visual inspections, meteorological and microclimatic analyses, observations on the geology of the site, and technical-scientific evidence on the finishing layers.

The monitoring allowed us to rule out one of the most accredited hypotheses for the origin of the alterations. Although the effective causes of the decay have not yet been identified, the surveys suggested interventions on the Asset aimed at limiting its effects. A first work carried out a few years ago has been validated by evaluating its effectiveness as thermal response and direct surface analysis. A second experimental operation of reversible nature to control deterioration is currently underway; its effects will be assessed over the next year.

Keywords: building monitoring, cultural heritage, infrared thermography, environmental monitoring.

Introduction

The Chapel of Sant'Eldrado is one of the four medieval chapels of the Abbey of Novalesa, a Benedictine monastery in Piedmont (Italy) built in the direction of France at the end of the Cenischia Valley, along the ancient Via Francigena, which was an important pilgrimage route. The Chapel was built in the early 11th century (except for the 17th century portico in front) on the site of a ninth century chapel. It is especially notable for its impressive cycle of frescos, realised between 1096 and 1097, which unfortunately has been partly damaged by decay.

NDT and micro-climatic monitoring have been applied to verify the deterioration process, which is particularly affecting the southern wall of the building. The research, commissioned in 2012 to the Non-destructive Diagnostic Laboratory (Politecnico di Torino) by the Turin Provincial Administration[1], was implemented under the supervision of SABAP-TO[2] officers.

The previous state and the action taken

The initial step of the Research involved analysing archive documents to find out the state of preservation of the building and any maintenance and restoration work carried out over time.

The first information found is dated 1883[3] and reports the excellent state of preservation of the Chapel's paintings. It was not until 1976[4] that complaints were made about the severe condition of decay of the frescoes due mainly to infiltration from the roof and capillarity from the soil. Furthermore, two interventions could likely have contributed to the constantly worsening status of preservation: the removal of plaster that covered the external walls (1967) (Fig. 1) and the reopening of the single-lancet window on the southern side of the Chapel (2004), closed in the late 11th century before frescoing the surfaces.

Over the years, the Chapel was subjected to continuous maintenance works and several interventions aimed at improving its preservation status. In detail, a crawlspace was constructed around the perimeter (1978), the roof was reno-

Fig. 1 The apse before and after the removal of plaster [photos dated 1957 and 1968, Archive SABAP-TO].

vated (1984), new stucco was applied on the joints of the external walls where water infiltrations were observed following the removal of the plaster (1985), the gypsum plaster patches were removed (1999), and several cleaning and restoration cycles were performed on the painted surfaces (up to now).

Despite all this work and continuous monitoring by the Institutions, the interior pictorial surfaces, especially on the south wall, are still affected by decay. Hence the need to conduct further scientific investigations to assess the building and environmental system.

The monitoring activities

The Chapel has been the focus of thermographic surveys since 2012, which are still ongoing.

In the meantime, monitoring the site's indoor and outdoor microclimate conditions also started. Two data loggers were installed inside the building to monitor air temperature and relative humidity parameters. However, for an objective assessment of the influence of weather phenomena on the construction, continuous thermo-hygrometric measurements were required, along with wind monitoring. Hence, one year after the beginning of Project activities, in collaboration with the Regional Agency for the Protection of the Environment of Piedmont (Arpa), a meteorological station was installed to obtain data about the Novalesa Abbey's area.

The thermographic survey was designed to assess the distribution of internal surface temperatures and monitor the observed phenomena evolution over time. The investigations are carried out by exploiting the thermal

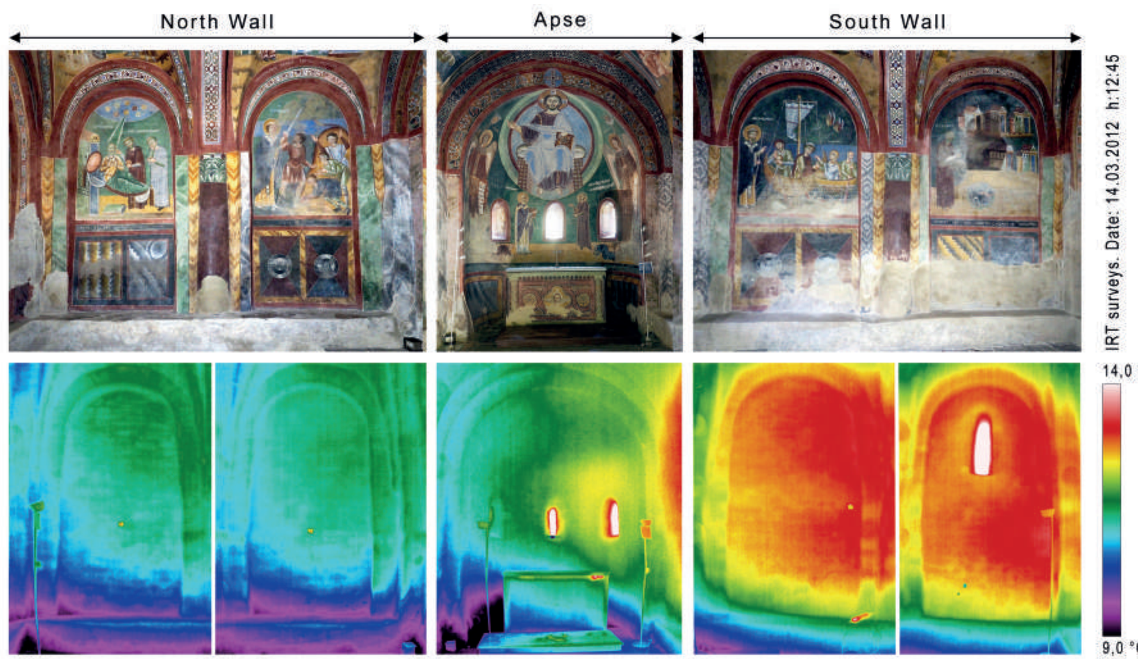

Fig. 2 Chapel interior walls: visible and infrared images.

gradient between the interior and exterior of the Chapel. Protocols include seasonal qualitative surveys and continuous acquisitions lasting 48 to 96 hours[5]. A series of checks on specific issues identified by the data analysis were also performed.

Acquisitions are recorded in passive conditions. It was decided not to use artificial thermal stimulation and ventilation to avoid further damage to the frescoed surfaces.

Inside the Chapel, chromatic alterations coherent with rising damp fronts are visible on the north and south walls: two distinct heights of the equilibrium line can be identified, with different stages of decay. The thermographic surveys show a different thermal behavior between the north and south wall interior surfaces. Despite the section of the wall, made of stone, being approximately 70 cm, the acquired IR signal showed the important influence of the wall orientation on the thermal trend of the interior surfaces (Fig. 2).

The south exposed wall has a variable surface temperature highly linked to external conditions (sunshine or cloudiness). Considering the results of the analysis (Fig. 3), which reveal the periodic trend of the thermal stress, it was observed that, in general, the temperature of the inner wall has a shift of about 12 hours, compared to outside air temperature, and the surface has a daily fluctuation of almost 1.5°C. However, it must be underlined that the thermographic data acquired in nearly all the survey campaigns do not provide objective signals related to the presence of a capillary rising damp front from the ground. The IR signal processing shows only a limited number of thermographic sequences in which alterations occur that may be linked to the presence of moisture (infiltration from the external wall or capillary action?).

The wall facing north shows a stable temperature over time in all the survey campaigns (maximum fluctuation observed in the day/night cycle is 0.5°C) and has a linear thermal gradient on the vertical compatible with the presence of moisture. It is assumed to be rising damp, whose evaporative front, not very extensive in height, is stable over time (this justifies the surface colour alteration and the simultaneous absence of efflorescence).

Following thermographic cycles and targeted measurements of the contact temperature, it was also possible to check the conditions of condensation formation on the internal walls. In all the eight survey campaigns conducted for this purpose, the measured dew-point curve was always lower than the wall temperature. The results thus would exclude condensation moisture forming on painted surfaces.

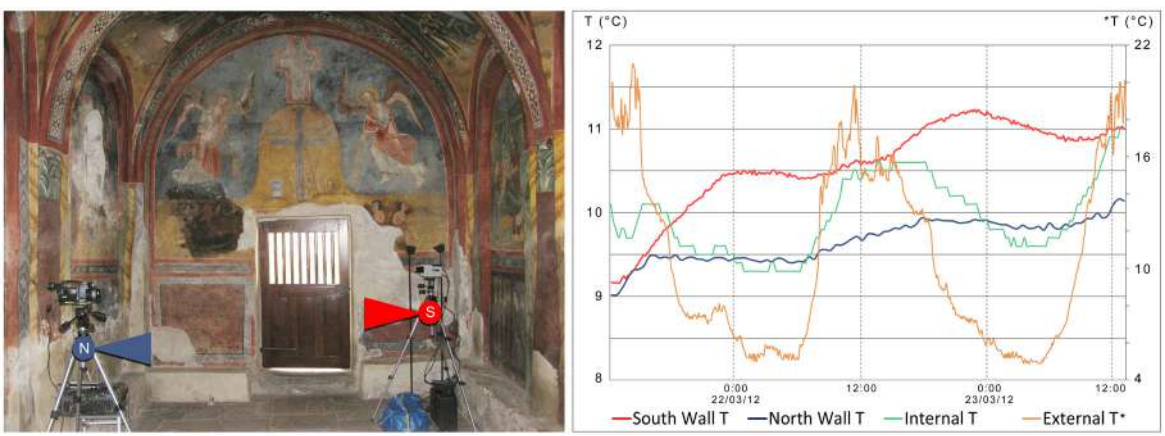

Fig. 3 IRT acquisitions; graph of wall temperatures by IRT versus indoor and outdoor temperatures.

Basic corrective actions were taken after the first phase of thermographic monitoring. The lighting system was changed from halogen lamps, which caused localized temperature increases of the walls, to LED lamps, and the number of group visitors was reduced, as they were too numerous and concentrated over a short-period, causing sudden temperature increases.

Moreover, the single-light window facing the inner side of the Chapel was closed, and the resulting wall section (about 40 cm) was filled with stone. The impact of the intervention was monitored by IRT (2014): the increase in the inertia of the wall section after the filling severely limited the thermal bridge that was present, and that altered the temperature conditions in its surroundings, creating a thermal situation that was more homogeneous and similar in the trend of the wall as a whole.

Concerning the environmental data analysis, a comparison between the data acquired inside and outside the Chapel shows a significant influence of meteorological conditions on the internal parameters of temperature and relative humidity, since the environment is only partially confined. Particular attention was given to assessing the relative humidity parameter within the building: the annual average value is around 60%, and, on the whole period, more than 1/3 of the RH values measured exceed 70%.

The 10-year parameters acquired by the weather station were processed to verify the possible presence of precipitation that hits the south wall and could lead to the formation of internal moisture pockets because of meteoric water absorption from bedding joints. The winds come mainly (56%) from the NW sector (Moncenisio Pass), as well as wet winds (68%). The percentage of humid winds blowing towards the south face of the Chapel is minimal and stands at 6% of the total values, making it unlikely that moisture is primarily due to rain (Fig. 4).

In addition to the IRT, remote visual inspections were carried out on the cavity built around the Chapel in the late 1970s. The surveys didn't reveal moisture fronts and let us know that the hollow space isn't all around the building but ends on the south side near the connection between the apse and the aula because of the presence of rock.

Conclusion and developments

From a situation where the presence of humidity in the masonry is evident despite the many interventions made over time to reduce the phenomenon, the results obtained from the IRT and the analysis of the environ-

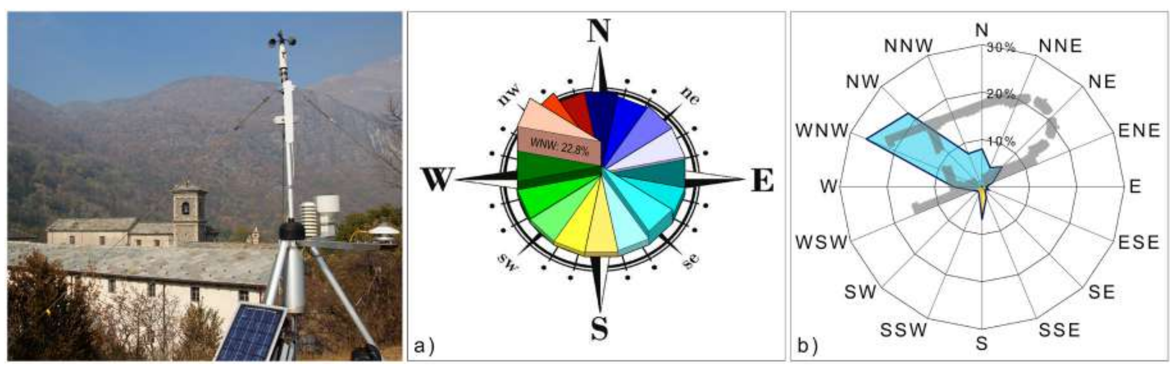

Fig. 4 Arpa meteorological station. Period 2013-2022: a) wind rose plot b) wind rose plot with rainfall > 4 mm/h.

mental data have shown, for the south wall, that the contribution of moisture due to driving rain is negligible, while the effects of direct thermal radiation on the distribution of the internal temperature of the frescoed surface are significant. Severe degradation could thus be caused by the continuous heating and cooling cycles to which the stone wall is subjected, as it is not shielded by vegetation or sacrificial surfaces.

As a result of these considerations, the Authority in charge of protecting the property arranged to construct an artificial structure to screen the south wall (the Chapel stands on a rocky base, which cannot be planted). Also in this case, thermographic and environmental surveys were carried out to analyse the temperature distribution on a sample portion of the frescoed wall facing south to verify the effectiveness of the shielding intervention adopted outside (2018). Unfortunately, only one assessment was done due to the accidental removal of the shielding. The initial results revealed an interesting "thermal gain". However, surfaces should be monitored for a more extended period before reaching conclusions about the effectiveness of the intervention. New surveys will be part of a three-year pilot project extended to other assets within the abbey complex focusing on scheduled maintenance and preventive conservation[6].

Acknowledgements

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Notes

[1] Current Metropolitan City of Turin, owner of the Abbey.

[2] Superintendence Archaeology Fine Arts and Landscape for the Metropolitan City of Turin (Dr. V. Moratti).

[3] Alfredo d'Andrade, Novalesa – Abbazia, cappella di S. Eldrado, finestre, 16 agosto 1883, matita su carta quadrettata, GAM, fondo d'Andrade fl/8253 (91 LT).

[4] SABAP-TO, incarto relativo all'Abbazia di Novalesa, pratica n. 3399 del 21 luglio 1976.

[5] The surveys were performed in parallel on the south and north walls using Flir SC3000 and Flir SC660 thermal imaging cameras, respectively.

[6] The Research is part of the PRIMA project, funded by the Compagnia di San Paolo Foundation, with technical economic support from the Metropolitan City of Turin. Partners: Koinè Conservazione Beni Culturali s.c.r.l. and Non-destructive Diagnostic Laboratory (Politecnico di Torino).

Digital Twin Environment for data integration of ICT technological services in Cultural Heritage field

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Abstract
In the last years, the Digital Twin concept is growing due to different technologies proliferation such as easy photogrammetric 3D reconstructions, virtual and augmented reality, as well as also building information models for cultural heritage (HBIM) and, in general, all technologies that allow to digitally replicate heritage assets. The paper shows the capabilities of It@cha (Italian Technologies for advanced applications on Cultural Heritage) virtual lab, started in 2013 by ENEA for the project fully embedded in the HPC ENEA infrastructure named CRESCO (Computational RESsearch Centre on COmplex systems CRESCO) by some case studies. It@cha, according to FAIR principles (for the integrated use of tools), focused at highlighting its interoperability, scalability, and versatility, with remote web access, supports the value chain of cultural heritage for research, protection, conservation, valorization and dissemination. The hardware and software facilities available in the platform allow to obtain detailed numerical models from 3D reconstructions by cloud point technologies to finite element models for structural analysis. Moreover the paper shows the new developments within the D-TECH (Digital-Twin Environment for Cultural Heritage) project, currently in progress, financed by Lazio region and MIUR, which aims to create an advanced multimedia platform dedicated to cultural heritage managers, that will offer web services for sharing and visualizing digital copies of movable and immovable cultural heritage assets even if they should be damaged by events of a different nature, or no longer accessible.

Keywords: digital twin, 3D models, data integration, digital technologies, HPC infrastructure.

Introduction

CRESCO is the High-Performance Computing (HPC) infrastructure developed by ENEA. It is a complex infrastructure based on a cluster of 434 nodes (servers) each with top level hardware resources that brings to 20832 cores. All these resources are available through a remote system based on the SSH protocol. The infrastructure has a unique authentication system and with both the General Parallel File System (GPFS, brand name IBM Spectrum Scale) and Andrew File System (AFS) allows users to have a personal and a shared environment to work with.

On top of that hardware resources, some Virtual Labs are being developed: they are a set of software tools that use CRESCO resources with an open concept of laboratory, achieved through a general-purpose web interface developed by ENEA, which permits an integrated access to all above mentioned activities. This web interface is developed within the technology named FARO2 (Fast Access to Remote Objects), based on JavaFX (also HTML5, css3 and javascript) that uses a 3D Remote protocol over a ssh tunnel to access any of the computational resources of ENEAGRID [1]. FARO2 is characterized by a friendly interface, which can be customized according to the specific virtual laboratory needs.

IT@CHA Virtual Lab

The IT@CHA (Italian Technologies for advanced applications on Cultural Heritage) Virtual Lab is an advanced application laboratory developed for Cultural Heritage field, with remote web access, able to share HPC structural and graphics resources through a high-performance network, by commercial and open-source professional software for computer vision workflows (Fig. 1).

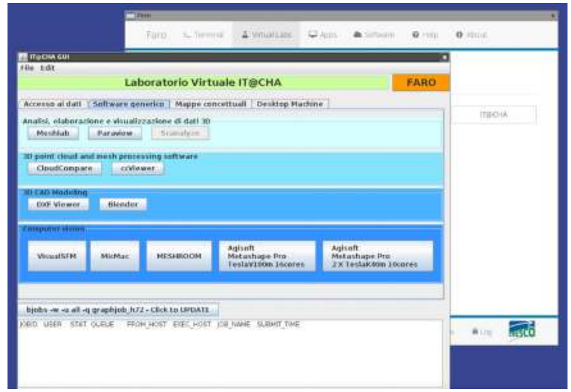

Fig. 1 IT@CHA Virtual Lab.

The virtual lab works on the entire numerical modeling chain (from digital twins to FE analysis), according to FAIR principles (for integrated use of tools) [2], with the goal of highlighting interoperability, scalability and versatility. The platform offers hardware and software capabilities to define 3D models, as well as areas to share images, documents, experimental data and store large volumes of data computing capacity, virtually unlimited, on geographically distributed file systems such as AFS, GPFS or on ownCloud. Moreover, an innovative system such as E3S (Enea Sharing Staging Storage) allows experimental and/or computational results to be uploaded to a single area to make them available to researchers.

Therefore, users can develop numerical models and manage 3D data to support the monitoring and planning diagnostic interventions too.

Thanks to IT@CHA is possible to work remotely with many tools such as Metashape, Meshlab, Blender, Nastran, Patran, Ansys, Abaqus, etc. within the same environment, ensuring interoperability and integration on the Cultural Heritage data.

New implementations and functionalities have been developed in recent years, such as a modern dedicated NoSQL database to store metadata of digital objects, making them available for further work and research and to easily integrate with advanced visualization services such as 3D HOP for visualization of 3D objects or IIPImage server for high Gigapixel resolution images.

These new capabilities are hosted on a dedicated virtual machine (heritagescience.portici.enea.it) managed in a VMWare cluster to ensure redundancy and backup.

Non invasive investigation by photogrammetry

Three-dimensional photogrammetric reconstruction is commonly used in every field of cultural heritage because it provides an easy to use and a fast way to obtain metrical information in terms of shape, size and position of the detected object, which are fundamental for the study of monumental complexes as well as of small size objects. For this reason, photogrammetry is used as a non-destructive technology for interdisciplinary usages and also for an integrative approach [3] to other diagnostic tests for protection and conservation of cultural heritage [4]. It is a low-cost, contactless and non-destructive survey technique producing 3D models, starting from 2D images, by Structure from Motion (SfM) method. Furthermore, from the point of view of the "technological transfer", it can be easily used to produce digital archiving of artworks or archaeological elements such as also multimedia videos for the valorization by means of "virtual reality".

As one of the most important problems in the use of 3D photogrammetric reconstruction is the considerable demand in terms of hardware and software resources for images processing and data storage, thanks to the HPC (High Performance Computing) resources provided by the CRESCO infrastructure (Research Computational Centre on Complex Systems), it is possible analyzing and processing many high-resolution images by remote access to IT@CHA Virtual Lab.

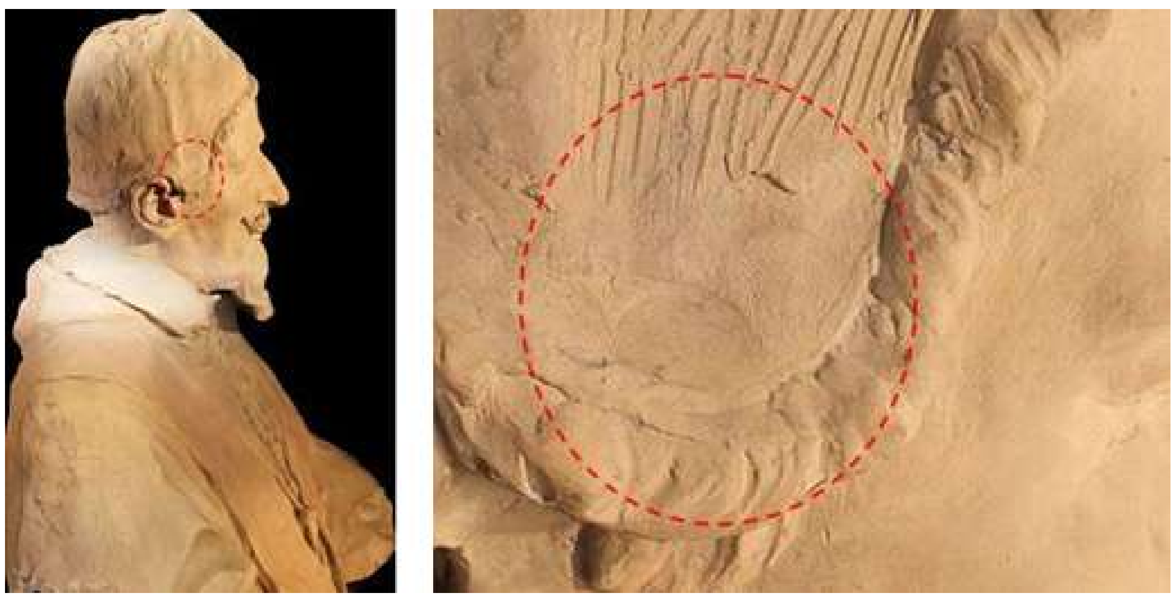

Fig. 2 Ortophoto of the rightside (left) – Bernini's finger prints right.

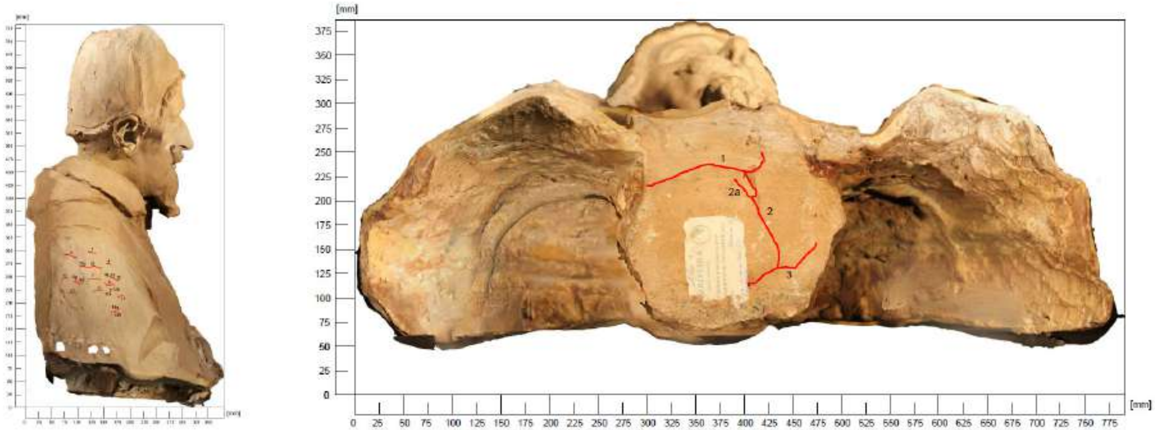

Fig. 3 Survey of cracks map on the right shoulder (left) and at the hidden basis (right).

Two different examples of 3D reconstructions obtained with different aims by the computational facilities of the IT@CHA laboratory will be shown.

Improving the visibility of less-known artworks, for different types of audience and enriching the Web site documentation of the Corsini Gallery in Rome, the 3D photogrammetric reconstruction of the portrait bust of Alessandro VII Chigi, a terracotta sketch attributed to Gian Lorenzo Bernini, was performed. Firstly, the 3D model revealed the presence of the fingerprints left by Gian Lorenzo Bernini during the realization of the work on the “papalina” of the bust, as evidenced by the two orthophotos of the right side of the bust (Fig. 2), secondly, it was possible to put in evidence some cracks on the shoulder and at the basis of the statue to be monitored over time (Fig. 3) [5].

The 3D photogrammetric reconstruction of the Tower Bridge of Spoleto was performed from about 800 HD images produced by a drone. The bridge is a very huge structure (200 meters long and 76 meters the highest part) consisting of 9 piers and 10 arches. Thanks to further high-density mesh model it was possible to create a textured model, which represents the 3D digital reconstruction of the bridge. Starting from this model, two orthophotos, one for each side of the bridge (Fig. 4), were exported in order to create a map of the damage. The most important cracks have been taxonomical defined, allowing to periodically check and verify the evolution of the damage extension during the time (Fig. 5).

The 3D photogrammetric reconstruction gave additional information about the structure as dimensions of each pier resulted different in section and height, the foot of the piers also showed an enlargement. Based on the geometric survey obtained by photogrammetric scanning it was possible to define a CAD model to calibrate the FE analysis updating the foundations and the measures of the photogrammetric reconstruction.

D-tech project and future developments

Starting from the experience of IT@CHA Virtual Lab and the collaboration within the Culture Technology District of the Lazio Region (https://dtclazio.it/), the

Fig. 4 Dense clouds texture of north (left) and south (right) sides of the bridge.

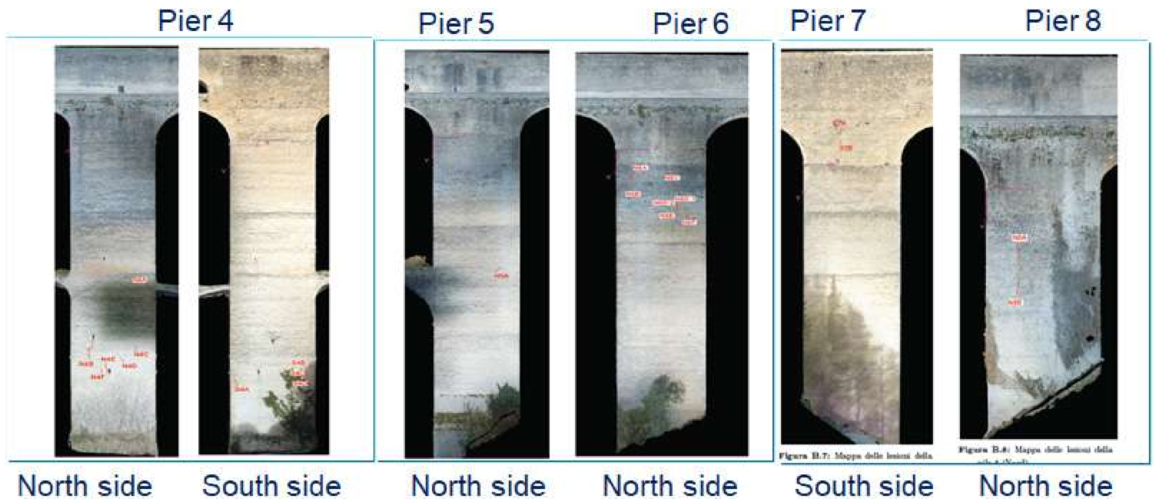

Fig. 5 Taxonomy of the cracks piers 4-8.

ENEA environment of Digital Twin and 'FE analysis for Cultural Heritage has also been implemented through the ongoing D-TECH (Digital Twins for Cultural Heritage) project, with the aim of building a distributed infrastructure that offers web services for sharing and visualizing digital copies for cultural heritage assets. It is based on the Data Mesh paradigm to leave the control of the data such as possible in the hands of heritage managers.

Conclusion

The "digital transformation" aims to optimize working logics, redesign the modes of interaction between users involved, develop and implement new models of value within the ecosystems that are enabled by digital web platforms. The sharing of IT services and network resources, using the CRESCO infrastructure, activating virtuous multidisciplinary collaboration in the management, safeguard and knowledge of cultural heritage assets. Moreover, it is absolutely in line with green deal policies, supports digital transition and technology transfer.

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Part four – Environmental Control and Protection

The moisture issue affecting the historical buildings in the Alps region

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Abstract
This paper deals with the climate-related risks associated with the conservation of historical buildings in the Alps region. The aim of the paper is to build the microclimatic curve of the T°C (temperature) and RH% (Relative Humidity) daily average in different locations (at a similar altitude in the same valleys), compare them against each other and also to the microclimatic curves obtained in the Po valley [3]. The case studies in Valtellina and Val Poschiavo Valley were identified to monitor and analyse the thermo-hydrometrical variation of air T°C and RH%, followed by a thorough assessment and documentation of the buildings (state of conservation, materials and building techniques, presence of rising damp and intervention for its reduction). The analysis is composed of visual inspections, microclimate monitoring using psychrometry and monitoring probes, Infra-Red (IR) Thermography. The result of the study explores the correlation with factors pertaining to building materials and construction techniques, the climatic and microclimatic characteristics. Curves describing the daily mean values of T°C and RH% for a period of one year have been defined by the authors for each of the historical buildings.

Keywords: cultural heritage, building conservation, microclimate monitoring, non-destructive techniques, historical building, preservation risk, ancient masonry.

Introduction of the case studies

The study presents four case studies located in the Alps region focus on evaluating and comparing the microclimatic conditions, including T°C and RH%. Additionally, this research explores the comforting aspects related to the location, building type, structure, elements, orientation, use, and altitude of each site. By investigating the microclimatic data, we aim to gain a deeper understanding of the indoor environmental behavior provided by these structures and identify the influence of various factors on the microclimate. The comparative analysis of temperature and relative humidity profiles across the sites allows for a comprehensive assessment of their thermal performance and humidity control strategies. By combining empirical data with the analysis, this study contributes to the understanding of how these can achieve the best comfort and preservation conditions [1, 2; 4-13]. As additional reference, we quote the standards in use for the measures: UNI 10829/99, UNI EN 16714-1/16.

San Romerio church, Brusio

San Romerio Church is located atop a mountainous ridge above the Poschiavo lake at 1.800 msl. The church features a compact, small and simple building structure, it has a unique nave, a crypt at the underground level, few small windows, and the belltower in its northern side. The church was restored in the 17th century and later in 1951-53. It is primarily constructed using local stone materials, plastered walls and some fresco remains in the northern interior wall. The church is oriented to face the south and its strategical locations expose the building to thermohydrometric conditions possibly critical, posing it to serious conservation issues.

Visconti-Venosta Palace, Tirano

The palace is in the historical heart of Tirano at an altitude of 440 m, in a dense low/ medium-rise urban form. From the analysis of stylistic features, the building dates to the 15th century and it went through different construction stages in the 18th century. The building is constructed with continuous masonry (stone), consisting of three full floors with vaulted ceilings on the ground floor, basement, and attic. The building has not been in used since 1985, showing noticeable absence of significant restoration processes.

Semadeni Palace, Poschiavo

Semadeni palace is part of a historical complex in

Site/building characteristics	San Romerio Church	Visconti-Venosta Palace	Semadeni Palace	Besta Palace
Building Materials	continuous masonry (stone)	continuous masonry (stone)	continuous masonry (stone)	continuous masonry (stone)
Construction date	17th century	15-18th century	19th century	15th century
Building use	Occasionally used during summer-autumn	Not in use	Not in use	In use by visitors
Elevation level	1800 m	440 m	1014 m	900 m

Tab. 1 Summary of the characteristics of the case studies.

Fig. 1 Image of the case studies: San Romerio church, Tirano (Brusio, Switzerland); Visconti Venosta palace, Tirano, Italy; Semadeni palace, Poschiavo, Switzerland; Besta palace, Teglio, Italy (left to right).

Poschiavo (at an altitude of 1014 m), built in the second half of the 19th century. It is included in the Inventory of Swiss Settlements to be Protected of National Importance (ISOS) and is on the List of Historic Gardens of Switzerland (ICOMOS). The building is constructed with continuous masonry (stone), consisting of a semi-basement, of three floors, and an attic. It is an almost metropolitan urbanization complex in its basic concept, with an orientation that maximizes natural light and heat gain, taking advantage of the sun path along its façade.

Besta Palace, Teglio

The palace is a significant historical site that was constructed during the 15th century and later transformed into the most important Renaissance court in Valtellina. It is in Teglio (So), at an elevation of 900 m. The building is constructed with continuous masonry (stone), consisting of three floors, with a central cloistered courtyard. The courtyard elevations and the upper floors are frescoed. Since1927 the palace opened to the public as a museum, and it has been subject to several restoration processes.

Methodology

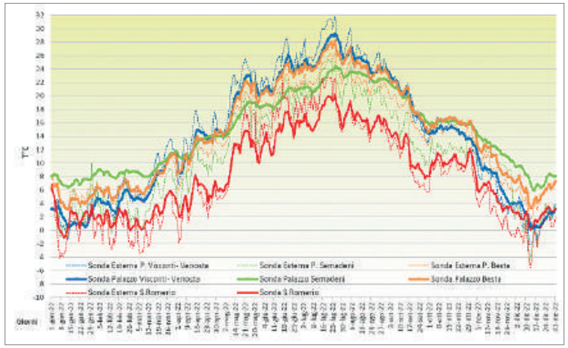
The scenario of changing climate and its consequences on the built heritage constitutes a challenge for the current standard methods for humidity measurements [13], both in the masonry and in the air. Most recurrent methods of measurement exploit the cross-referencing of data from different non-destructive (ND) techniques, with the aim to adopt an extensive qualitative approach for the preliminary tests and to ensure the least destructive application of the quantitative tests on sampling areas/spots such that it results in more significant collection of data and less disfiguring/destroying of the historical materials [13].

Owing to the advancement in microclimate monitoring techniques and procedures, fast scan working techniques have a considerable advantage over those techniques that give punctual data back while also requiring a long time for the processing phase. Gathering the documentation about the building, damage location, its evolution over time, the use across years to devise an effective diagnostic plan, remains mandatory, as it is for all other diagnostic techniques. The main analysis focusses on the four case studies (San Romerio church, Visconti-Venosta Palace, Semadeni Palace and

Besta Palace) analysed in the same year (2022). The annual daily average graph of T°C and RH% of these case studies has been compared with all the other cases. Despite of the differences in location, size of the buildings, orientation there are many similar characters, especially during the late spring- summer. On the other hand, the main differences are registered in late autumn, winter and early spring as further presented in the next paragraphs. Statistical analysis was used for comprehending the T°C and RH dynamics in historical buildings: it enabled the identification of trends, variables, and correlations, shedding light on the factors influencing indoor microclimates. Probability density function (PDF) analysis was used to analyse the indoor climate data due to its ability to provide valuable insights into the statistical distribution of variables parameters such as T°C, RH%. By calculating the PDF, it was able understand the frequency and likelihood of different values occurring within a given range. This information is crucial for assessing the variability and stability of indoor microclimates, as well as identifying potential risks and hazards. PDF analysis allows to determine the most probable values and the spread of data around those values. It helps in understanding the central tendencies, such as mean, median, and mode, which are important for establishing reference values and setting appropriate environmental conditions and therefore quantitatively comparing the case studies. Furthermore, statistical analysis facilitates the identification of correlations between T°C and RH%. The correlation coefficient for T°C and RH was calculated to assess the similarities between buildings/ indoor microclimate case studies. The correlation coefficient measures the strength and direction of the linear relationship between two variables. It quantifies the degree to which changes in one variable correspond to changes in another.

Results and discussions

The microclimate was monitored using data loggers. Fig. 2 (a,b) represent the annual daily average of T°C and RH%. The indoor temperature data represents the conditions within a controlled environment. The absence of heating systems or other climate control system in all the case studies reveals a significant dependency on the outdoor environment for indoor temperature regulation. As expected, San Romerio church exhibits consistently lower indoor temperatures throughout the year, ranging from -1°C to 21°C. This finding confirms the lapse rate phenomenon observed in the alpine region, wherein temperature decreases with increasing altitude. The indoor environment of San Romerio experiences temperatures between 4°C to 8°C lower compared to the other buildings, further validating the impact of altitude on temperature differentials within the alpine setting. Visconti-Venosta and Besta palaces exhibit similar temperature patterns throughout the year, with the highest values occurring during the summer season, ranging from 20°C to 29°C. This can be attributed to factors such as limited window openings in Visconti-Venosta palace or the influx of visitors in Besta palace. Additionally, the presence of urban form in these case studies may contribute to the observed temperature trends. In contrast, Semadeni palace demonstrates greater temperature stability during the cold seasons. This stability can be attributed to the construction of the building and its non-utilization, which effectively regulate the internal temperature by reducing heat exchange with the external environment. The annual indoor RH% graphs unveil discernible and distinct patterns. In the cases of San Romerio, Visconti-Venosta Palace, and Besta Palace, RH exhibits seasonal fluctuations that closely align with the outdoor humidity trends. San Romerio and Visconti-Venosta Palace consistently demonstrate elevated RH% values ranging from 40% to 90% during



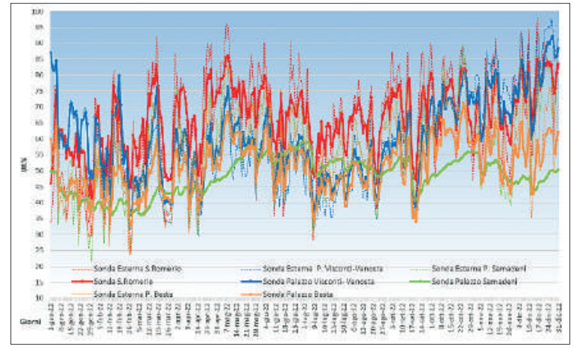


Fig. 2 a) The annual graph of the daily average tempratures for the case studies; b) The annual graph of the daily average RH% for the case studies.

the spring, autumn, and winter seasons. However, there exists a discrepancy of approximately 10% between the indoor and outdoor environments throughout the year, underscoring a notable exchange rate between these two domains. Notably, San Romerio Church records the highest RH% values during the summer season, ranging from 50% to 87%. Of particular significance is Semadeni Palace, as it stands out from the other locations due to its relatively stable RH% levels throughout the year. This stability is likely attributed to the non-utilization of the building, which effectively regulates the exchange of heat and humidity with the external environment. Besta Palace exhibits higher RH% levels during the cold seasons, primarily resulting from moisture infiltration, while lower RH% levels are observed during the warm seasons due to enhanced ventilation and the influx of visitors. These observed patterns shed light on the influence of outdoor climate, building materials, and ventilation on the dynamics of indoor RH% in the absence of central heating.

Conclusions

Looking at the annual graph of T°C, the strong correlation between temperature and altitude in the alpine region can be attributed to several factors. Firstly, the lapse rate phenomenon, which describes the decrease in temperature with increasing altitude, is prevalent in mountainous areas. Secondly, the alpine region often experiences similar weather systems and atmospheric conditions across different altitudes. This coherence in weather patterns, such as temperature inversions or temperature fluctuations due to regional wind patterns, valley orientation or exposure to solar radiation can help maintain the strong correlation between temperature and altitude.

These findings contribute to our understanding of the complex interplay between altitude and temperature in alpine environments and have implications for climate studies, ecological research, and regional planning in these unique and dynamic landscapes.

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Analysing objects to produce more sustainable conservation environments

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Abstract
Preventive conservation mainly determines conditions from an artifacts material type. Within most material groups there are a wide range of documented different responses to RH and pollution conditions. If sufficient knowledge exists, which is just becoming available for some cultural heritage materials, and suitable analytical methods have been developed, then analysing the artefact can be used to determine the required environment. Some glass compositions are unstable and different RH conditions have been recommended for stable and unstable glasses. Measurements have shown approximately, a three times larger carbon footprint to generate the tighter RH environment for unstable glasses, compared to that for stable glasses. Sampling from art glass is extremely difficult.

Keywords: glass, IRRAS, ATR-FTIR, NIR, OCT, ion chromatography, non-invasive techniques.

It has been recognized for some time that certain glass compositions make those objects much more environmentally sensitive (Brill 1975, Bimson 1968). Recent research (Koob et al 2018) has recommended very strict RH conditions (40-42% RH) for such unstable glasses. Maintaining this tight RH range for unstable glass is energy or carbon intensive, but only a small portion of glass objects require it. A wider band (40-50% RH) is recommended for other glass objects. Several methods can be used to analyse glass objects and determine those pieces with composition or behaviour that predicts such instability. Conservation examination by eye or using low magnification microscopy can determine the early stages of degradation of some glasses. However, visual detection of the gel layer depends on differences in refractive index, which are not always present. Efflorescences can be confused with either dust deposition or remnants of casting (Thickett and Pretzel 2010). This can lead to instances of deterioration going unnoticed (Thickett and Ling 2021, Lombardo 2022). Additionally, the authors have undertaken several analyses for new displays highlighting unstable glasses, thought to be stable via conservation examination. Instrumental analysis can be advantageous, either the glass composition or the early stages of deterioration can be determined in some way. The value of glass objects means non-invasive methods are highly preferred. Sampling will be visible in most objects. The thickness of alteration layer that will sensitize a glass to low RH conditions (cause it to crack when RH is low) is unknown. It is also likely that the degree of alteration in the layer and residual stress will also affect this. For glasses (15% K, 48 Si, 15 Ca, 4 P, 3 Na, 3 Mg, 1.5Al, 1 Mn, 1 Fe) corroded in sodium carbonate solution at 30°C, cracking was observed when alteration layers thicker than 2-3 µm were present.

X-Ray fluorescence can analyse the elements of interest, however the production of alteration layers may affect results, which are very surface sensitive. A range of other non-invasive techniques: absorption- reflection Fourier Transform infra-red spectroscopy (FTIR); attenuated total reflection (ATR FTIR); near infra-red spectroscopy (NIR); confocal Raman micro-spectroscopy; surface ion analysis and optical coherence tomography (OCT) have been assessed for this purpose. Each has been applied to two sets of objects: 19th century cover glasses from daguerreotypes and Limoges enamels.

Methods and materials

Two sets of objects were used to compare different analytical methods. A set of Limoges enamel plaques, part of the Wernher Collection and displayed at Rangers House, London, and a set of cover glasses from six daguerreotype packets of Charles Darwin's family from 1842 and one replacement from 1996. Both sets of objects present some level of degradation. In the case of the Limoges enamel plaques, previous analysis has shown degradation of some colours with alteration layers of some depth (Thickett et al 2017), while the cover glasses present very thin alteration layers (Thickett et al 2022).

Infrared spectroscopy, infrared reflection-absorption (IRRAS) microscopy and reflectance spectroscopy have all been used to characterise the alteration layer thickness. As the alteration layer forms, Si-O-Si bonds break to Si-OH and Si-O-Na bonds, which can be observed at characteristic wavenumbers (around 1100 cm^{-1} and 970 cm^{-1}) in infrared spectra (MacDonald et al 2000). In this work, a Nicolet Inspect IR microscope was used for external reflection FTIR running off a Nicolet Avatar 360 bench. This fixed-focus instrument collected a spectrum from a 100 µm-diameter circle at 1 cm^{-1} resolution. Previous work has shown the beam capable of penetrating 1.78 but not 2.04 mm of enamel glass (Thickett et al 2017). ATR FTIR analysis was performed on an IR microscope (Continuum on Thermo Is-10 FTIR) with a Germanium ATR head. The Germanium ATR head collects information from a 150 x 150 µm area and calculations have shown that at 1100 cm^{-1}, the information depth is approximately 0.5 µm. Near infra-red spectroscopy was performed with an Analytik Labspec 4 spectrometer with large area fibre optic head, following the method of Zaleski et al (2019).

Confocal micro-Raman spectroscopy was performed with a Horiba Jobin Yvon Infinity using a 532nm Nd-YAG laser and 100 µm confocal aperture. This has an information depth of 3.8µm which can be tracked through the depth of transparent samples using the microscope.

Surface ion analysis was performed by swabbing a known area, extracting and analysing sodium and potassium concentrations with ion chromatography. Sampling was performed by wetting a cotton wool swab with 1 ml of 3:1 water/IMS and rolling the swab over a 5 by 5 cm rectangular area. The sample was then extracted in 5 ml of water at a resistivity of 18.2 MΩ-cm. The extracts were filtered and analysed using a Dionex ICS 1100 ion chromatograph with an Ionpac CS12 column and 18 mM methane sulfonic acid eluent.

Ultra highresolution (UHR) OCT operating at a central wavelength of 810 nm has a depth resolution of 1.2 µm in glass, with a depth range of a few millimetres is capable of collecting a 3D image cube of a 5 x 5 mm area at a transverse sampling resolution of 10 µm in 10 s (Read et al2019).

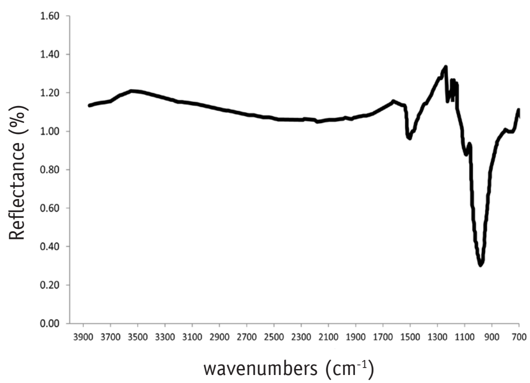

Fig. 1 IRRAS spectrum of blue enamel.

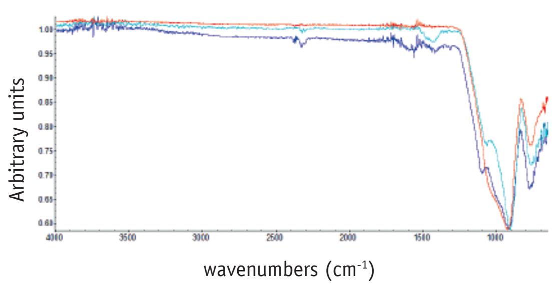

Fig. 2 Ge ATR-FTIR spectra from plates.

Results

Figure 1 shows a typical external reflection (IRRAS) FTIR spectrum for one of the enamel plaques and Figure 2 ATR spectra for the plates (right).

The beam is known to penetrate the full depth of the enamel glass during IRRAS (Thickett et al 2017). The relative contributions from each depth segment (upper alteration layer, unaffected glass, lower alteration layer) are unknown. Clear splitting was observed in all the enamel spectra taken. At the early stages of glass deterioration, the alteration layers are very thin. No splitting could be observed in the daguerreotype plates. It is possible that peak fitting, multivariate calibration or chirped algorithm calibration (Shalaby et al 2020) may improve sensitivity, but this was beyond the scope of this work. Clear splitting is observed on both interior and exterior surfaces. All surfaces of all the cover glasses showed clear splitting, including the 1996 replacement glass. Most of the spectra include a shoulder at around 1020cm^{-1}, indicating unreacted glass. This probably indicates the alteration layers are less than 0.5µm deep, the information depth of the system at this wavelength.

The 100-µm diameter analytical IRRAS area can accommodate some curvature of the surface. More curved surfaces could be analysed with more highly focused FTIR microscopes, but longer collection times would probably be needed. The ATR head has to be pressed against the glass to achieve optical contact and good spectroscopy. This was certainly easier with flat objects but may be impossible with highly deteriorated and fragile glass surfaces, although the question of stability may be already answered for glass objects in such condition. The ATR head can deal with the degrees of curvature expected for the vast majority of glass objects. With this technique, once the alteration layer extends beyond 0.5 µm, no further change in spectra is expected.

Figure 3 shows the NIR spectrum of a purple enamel glass and more degraded plate.

The isolated bound water peak at 1910 nm is clearly visible in the enamel spectrum. No peak above background noise level was observed for the cover glasses.

The Raman spectrum from the surface layers of the enamels showed displacement of peaks at 500 and 1070 cm^{-1}. These are clearly shifted from 530 and 1100 cm^{-1} in the deeper un-degraded glass. No peak shifts were observed with the plates. The information depth of the micro Raman system is too large to detect the thinner alteration layers present on the plates.

Figure 4 shows the concentrations of ions swabbed from the cover glass surfaces.

The concentrations are well above detection and limit of quantification, even for the least degraded replacement glass. The method (swab area, extraction volume, and ion chromatography) can also be altered to improve the detection limit (Thickett et al 2022).

The increase in alteration layer thickness can be estimated from the ion concentration, original glass composition and density (Thickett and Ling 2021). The composition of the replacement glass has been measured

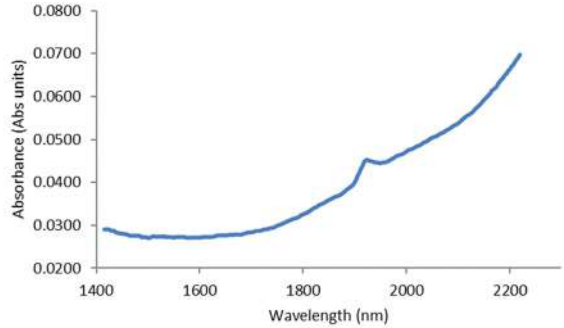

Fig. 3 NIR spectrum of enamel.

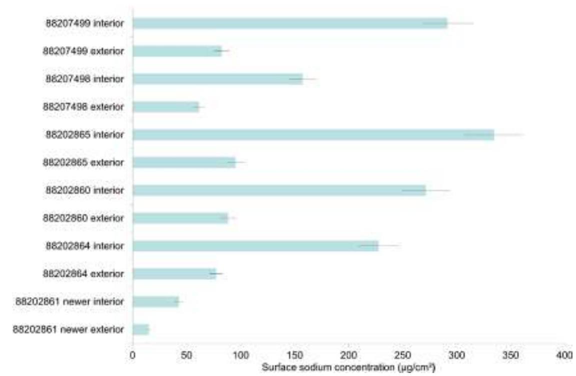

Fig. 4 Ion concentrations on plate surfaces.

(Thickett et al 2022) and the density was calculated from physical measurements. This indicated an alteration layer thickness of 0.08 µm.

Reconstructed virtual cross-section images (known as B scans) produced by the UHR OCT of the blue enamel is shown in Figure 5.

The alteration layer is clearly visible on the upper face of the enamel, but not continuous. Separation of the glass from the metal has occurred over about half of the contact area. A thin alteration layer is also visible on the inner face, in contact with the metal.

No alteration layer is detected in the images of any plates. The salts are clearly observed (points marked A) and the relative refractive indices can be determined

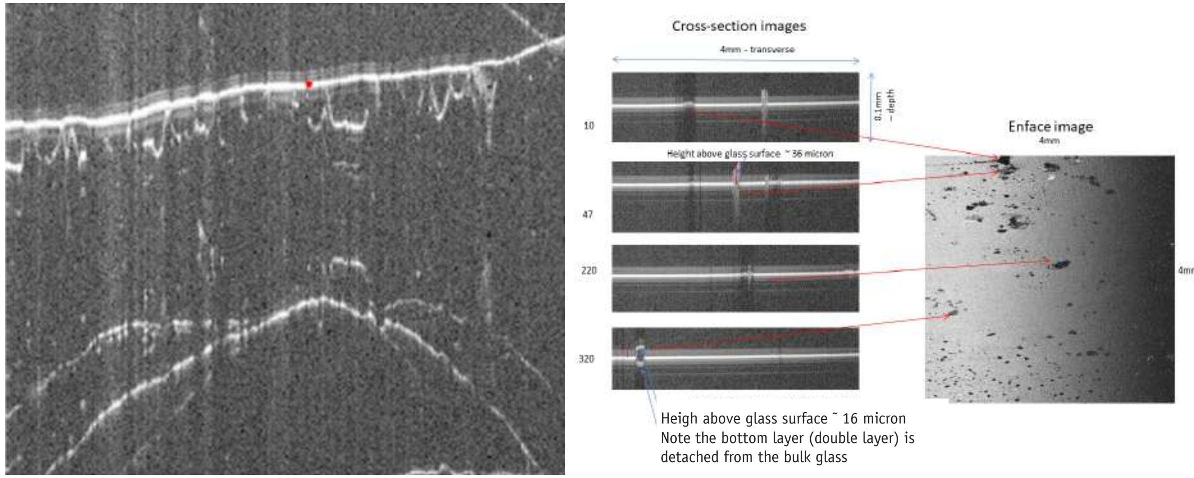

Fig. 5 Z scan from UHR OCT of enamel; enface and Z scan of plate.

Tab. 1

	Portable	Enamels	Cover Glasses	Issues	Impact of cleaning
R-A FTIR	Y	Y	N	Scattering can give distorted spectra	Some, dust will contribute to spectra
Ge ATR-FTIR	-	Y	Y	Limited to surface 0.5µm.	N, avoid dust/salts by visualization under magnification
NIR	Y	Y	N		N
Raman	-	Y	N	Glass must be transparent to laser wavelength	N, avoid dust/salts by visualization under magnification
IC	N	Y	Y	Can be wicking under mask for curved surfaces. Cleaning resets.	Y, removing sodium and potassium negates analysis
OCT	Y	Y	N		

from the height above the surface and the apparent depth. Even with the improved UHR OCT, the alteration layer is not seen in the early stages of glass deterioration, despite observing leached salts.

Tab. 1 summarizes the results for the techniques investigated.

For this approach to be effective, portability is important to analyse large numbers of objects quickly. Whilst portable ATR-FTIR microscopes and Raman exist, the sensitivity of the microscope control required can limit their use. Whilst ion chromatography is generally not portable, samples are taken with a swab, and these can readily be transported to the instrument.

Conclusions

Both ATR-FTIR and surface ion analysis have been proven able to detect the very early stages of glass deterioration and determine a glass object's stability. Whilst the other techniques worked for relatively degraded glass, they could not detect the early stages. Significant research is required to determine the critical alteration layer depth for different glass types degrading under different conditions. Some empirical observations have been made for weeping glass and ion chromatography (Verhaar et al 2020). However, these results only apply to the glass compositions present (which were not described in detail) and the environments experienced. The Horizon Europe project GoGreen will investigate further aspects of such analyses for glasses and limestones.

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Scientific analyses for preservation and restoration of XIII – XV century stained glasses

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Abstract
Our study is devoted to the identification of alteration processes at the stained glasses' surface and to support conservation and restoration works that require a deepest information on factors which influence the state of preservation for these vulnerable systems of cultural heritage. Broken fragments of glasses with different provenance, fabrication period, morphologies and state of preservation have been compared, namely samples from the Siena Cathedral, work of Duccio di Buoninsegna, and from the church of St. Giovanni in Monte and the St. Petronio Basilica in Bologna, works of the Cabrini family. By means of optical and electron microscopy analyses, we observed two main phenomena of surface alteration: Neocrystallization and leaching process, known for being the principal cause of alteration for this type of ancient glasses. These alterations reveal both different causes and morphological aspects. Leaching process could depend on the cycle of rain and humid period following very dry ones, which are responsible for a variation of pH and for mechanic tension at stained glasses surface.

Keywords: stained glasses, alteration phenomena, SEM + EDXRS analysis, optical microscopy, neocrystallization, leaching process.

Introduction

The term "stained glass" designates the technique of implementation of canopies composed of pieces of glass, cut according to a cardboard, which could receive a suitably painted decoration called grisaille, of a color of cementation called silver yellow, or even of enamels, and are then assembled in a network of lead rods [1,2]. In the windows the grisaille is a particular painting that is done on the inside, to add some pictorial effects, otherwise impossible due to the chromatic uniformity of the glass. This technique involves the use of an amalgam obtained from crushed glass powder combined with some minerals such as iron or copper oxide, mixed with a liquid (initially wine); based on the mineral used, the grisaille took on a different green, brown or black tone. By means of the grisaille technique, the *chiaroscuro* is painted on the figures, as well as the features of the faces, the folds of the clothes and other details are drawn. Lead is also used in the areas of attachment, to attenuate the contrasts between the color of the metal and that of the glass.

Phenomena of alteration and degradation

Fragile walls which are at the border between architecture and the work of art, the stained-glass windows have undergone, over the centuries, many destructions and alterations, due to men (vandalism, wars, modifications of liturgical arrangements, etc.), bad weather (rain, hail, thermal shocks), atmospheric pollution (chemical alterations of glass and greyness), micro-organisms, or quite simply lack of maintenance.

We can classify the causes of alteration and degradation of the stained glasses according to their constituent parts: The alterations of the metal reinforcement; those affecting the lead network; the glass alterations; damages to the external face [3,4].

In the first case, the frame of the canopy, most often in iron or steel, is generally made up of a network of main irons of rectangular section, on which the panels are fixed by flat irons. Intermediate bars of circular section support the panels to which they are fixed by lead fasteners. Under the effect of runoff water, and very often poor maintenance, these iron bars oxidize and no longer support the panels properly. These will therefore deform, bulge, sometimes causing the glasses to become rise up, and even water infiltrations are found due to poor sealing of the mastic flashings placed between the irons and the panels. This latter phenomenon is also due to alterations to the lead network which, under the effects of the weight of the panels, the pressure of winds or deterioration of the reinforcement, deforms, the wings of the leads lift or crack at the level of the welds and do not maintain correctly the glass parts.

The most common glass alterations are breakages due to mechanical phenomena, shocks, deformations of the metal reinforcements or the lead network. However, glasses also undergo alterations of a chemical nature linked to their composition and environmental attacks. Old glasses are mainly composed of silica (sand) and alkaline oxides, either potassium (coming from wood ashes or ferns), or sodium (coming from salts or marine plants), called fluxes, as well as calcium. This composition has evolved from the Middle Ages to the present day. Medieval glasses are most often potassic-based, while glasses from the end of the Middle Ages and from the modern era are sodium-based. The grisaille, which initially comes in powder form, more or less finely ground, is made up of a vitrifiable flux obtained from a glass, rich in lead, and metal oxides intended to colour the mixture. It is then applied to the glass using water, vinegar or gasoline, then fired at approximately 630 °C.

Silver yellow, whose use appeared in the fourteenth century, is a set of silver (chloride or sulphide) applied in a mixture with ocher, the most often on the external face of the glass, and which reacts with cooking with this one to give a transparent coloration ranging from lemon yellow to orange. The enamels on glass, the use of which spread from the sixteenth century, are composed of a coloured vitreous matrix very rich in lead, applied to the glass and fired at a temperature of approximately 600°C. With silver yellow, they make it possible to obtain several different tones on the same piece of glass.

Finally, as for alterations of the external face of the stained glasses, medieval glasses, with a potassium flux and a relatively low silica content, undergo significant selective dissolution, known as the modifying elements of the vitreous network (potassium, calcium), under the effect of the water, whether from condensation or runoff, and air pollution, particularly sulfur dioxide. This leads to a depletion of the vitreous matrix and the development of a hydrated disturbed layer, also called a gel layer, most often covered with a layer of alteration products, generally formed of gypsum or syngenite (double sulphate calcium and potassium). In other cases, we observe an alteration in craters which deeply affect the glass and are filled with alteration products. Uniform layers of corrosion and craters lead to darkening of the glasses which sometimes makes them completely opaque. These phenomena primarily affect the external face of the glasses, the most directly exposed to environmental aggressions. They essentially concern medieval glasses, with potassium flux, and not the sodium flux glasses of the end of the Middle Ages and of the modern period, which are much less leachable. In addition, biological developments sometimes contribute to degradation phenomena, consisting in proliferations of microorganisms, fungi, algae, bacteria. The latter are suspected of being the cause of browning due to the oxidation of the manganese contained in the glasses.

Moreover, the internal face also suffers attacks from the environment due to condensation, frequent on cold walls in buildings where the relative humidity is high. These condensates lead to darkening of the glass and sometimes risings of grayness.

Scientific analyses

By the 12th century, complex techniques of stained-glass manufacture had evolved but the essential methods have remained more or less unaltered to the present day. In many cases, the glass has been destroyed or replaced by other similar or white pieces. Therefore, it is often difficult to identify original or substituted stained glasses and determine the elemental composition for restoration and conservation aims. In St. Petronio Basilica (Bologna, Italy), for instance, the stained glass has been extensively restored in 1879, but there is very few recorded information about that operation and it is difficult to discriminate between original ancient and more recent substituted parts [5].

Therefore, both to determine the materials used and the executive techniques, the related degradation phenomena, and to identify restoration interventions and renovations/replacements carried out over time, it is necessary to resort to non-destructive and non-invasive investigation techniques. Modern electron microscopy instrumentation no longer requires treatment of the sample - usually taken as a fragment produced by degradation phenomena - which can therefore be repositioned during restoration.

This scanning electron microscopy (SEM) technique has been applied, for instance, to the study of ancient glasses, to determine whether repairs have been carried out or substitutions made of damaged parts [2]. Also, the transmission electron microscopy (TEM) has been applied to the characterization of paint layers

Fig. 1 The stained glasses in the Vaselli Chapel just after the 1951 restoration (on the left, photo by A. Villani & figli, 1951); the actual status of the stained glasses (centre), and the plant of St. Petronio basilica (on the right: the Vaselli Chapel is the fifth on the left side).

[6], making ultra-thin sections in which the paint and ground layers are preserved intact. In comparison with usual SEM measurements, the TEM technique is more precise, because of the higher spatial resolution in both the microanalysis and diffraction modes, of the order of 10-20 nm.

In our work, cross sections of each sample were analyzed in the ENEA laboratory in Bologna, first by reflected light optical microscope REICHERT-JUNG-MF3 than by SEM Quanta Inspect S and for chemical composition by EDX Falcon. Complementary XRF chemical characterization, in order to improve heavy element detection on stained glasses surface were realized with a PANanalytical Axios Fast instrument, in University Paris-Sud 11, Orsay. For these tests, samples' surfaces were exposed without any preliminary preparation, so that we obtain a spectra average on the whole sample surface [7].

Objects of our investigation have been three important stained glasses: (1) The stained glass window of the Cathedral of Siena drawn by Duccio di Buoninsegna, accomplished by unidentified glass masters, and then painted in grisaille by Duccio himself. Made to cover the large oculus of 5.6 m in diameter which is located high up in the apse of the Cathedral of Siena, the stained glass window was recently restored [8,9] and placed in the nearby Museo dell'Opera del Duomo (a copy has been placed in the Cathedral). It is the only work of this type by Duccio di Buoninsegna, datable from written documentation to 1287-1288, so very important for defining the painter's artistic career. Then, we studied (2) the two stained glass windows on the façade of the St. Giovanni in Monte church in Bologna, including that of the large central rose window, dated to 1467-1481, made by the brothers Giacomo and Domenico Cabrini based on a drawing by Francesco del

Cossa [10,11]. Finally, (3) we analyzed samples from the large stained glasses that adorn Vaselli Chapel (Chapel of St. Sebastian) in the St. Petronio Basilica of Bologna [11-14] (fig. 1). They consist of two *quadrifore* composed of rectangular panels concluded by lobed panels and surmounted by two polylobed roses and by a rose window. They have been commissioned in 1487 by the canon Donato Vaselli who granted the chapel under a concession on the commitment to decorate it within ten years. Therefore, the work has been accomplished in the range of years 1487 – 1497, on documentary evidence, based on design of Lorenzo Costa and assistants, and executed by the Cabrini workshop. Recently [15], the discovery of the payment receipt for the stained glass of the Vaselli Chapel not only sheds light on the personality of its creator, Giacomo di Agostino Cabrini, but also redefines the chronology of the works carried out inside the Chapel by the canon Donato Vaselli at the end of the fifteenth century.

Unfortunately, the stained glasses were in an advanced state of deterioration before restoration: On the external side the deposit of singenite due to the corrosion process is very conspicuous. The detachment of the grisaille is clearly visible in the white glass of the architectural scores.

In the samples of the Siena's stained glasses, it is observed a K-Ca high concentration, which explains why the stained glasses of Duccio di Buoninsegna are particularly subject to the alteration. Leaching is the result of a pH modification due probably to rain and condensed water forming at the surface. Hydrogen diffuses from the water into the glass matrix and substitutes to modifiers cations present in the silica network (Alkali and Alkaline-earth elements). These cations diffuse toward the glass surface and escape from this layer, which thus remains impoverished in modifiers and enriched in silicate [4]. This modified layer presents an arborescence aspect and a system of fractures parallel to the surface. This morphology reveals a radial alteration front. Leaching process begins in isolated points at the interface and progresses on radial front which finally joined each other.

As for the Cabrini stained glasses in the Vaselli Chapel, the sample Cab B4 from the saint figure in the bottom left side of the right-hand-side stained glass in the *quadrafora* presented an advanced state of corrosion. Morphological analysis of Cab B4 shows a crust on the glass surface that could be directly related to corroded zones; the surface reveals a high rugosity, where grisaille layer and glass are heterogeneously corroded, while sane glass presents wells dug. The XRF analyses on the surface deposits of the same sample reveal an high concentration in potassium, calcium and iron (fig. 2). Traces elements as manganese, cobalt, copper, titanium and chrome are responsible for the deep blue color of this sample.

Iron and lead are principal component of grisaille, but in this case iron is present in a higher concentration compared to other samples with grisaille, a fact which can explain the red color of deposits. It is worth noticing also the Kα line of sulfur on the XRF spectrum; presence of sulfur, and a high level of calcium and potassium reveal probably neocrystallization products as gypsum ($CaSO_4 \bullet 2H_2O$) and potassium carbonate (K_2CO_3), products due to atmospheric pollution. Previous studies

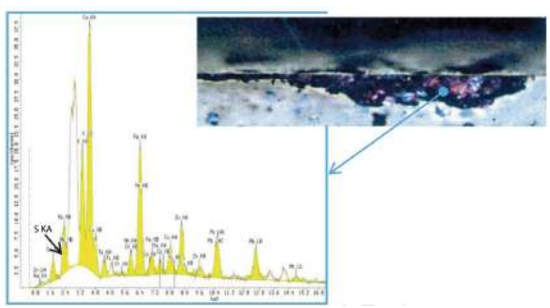

Fig. 2 XRF spectra acquired on the Cabrini Cab B4 sample surface.

[16] have shown that potassium carbonate has a dramatic impact on stained glasses surface since it induced corrosion process of the network in contact with an alkaline environment.

In conclusion, our study shows two main phenomena of surface alteration, namely neocrystallization and leaching process. These alterations reveal both different causes and morphological aspects. Leaching process could depend on the cycle of rain and humid period following very dry ones, which are responsible for a variation of pH and for mechanic tension at stained glasses surface, as confirmed by the present optical and SEM analysis. Nevertheless, neocrystallization occurs more in an environment protected from humidity but exposed to atmospheric pollution, particularly high sulfur and CO_2 concentration. Neocrystallization creates an alkaline environment, favorable for corrosion process.

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Evaluation of the porosity of natural and artificial stones by Infrared Thermography

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Abstract

With the designation of Filippo Juvarra as the first architect of the Savoy kingdom, Turin saw the flourishing of new monuments in which he used an interesting variety of natural stones. Prominent among these is Chianocco marble, recognisable on the Turin façades of Palazzo Madama and Rivoli Castle. This material, which is easy to work on, nevertheless needed to be well selected to reduce its strong inhomogeneity and contain its high porosity, leading to even intense degradation over time.

The need expressed by restorers to find relatively quick in situ methods to check the behavior of the stone material for conservation purposes, e.g., by assessing the possible presence of surface protectants, provided the opportunity to start an experiment that made use of infrared thermography. The use of TIR makes it possible to non-destructively analyse surface heat exchange during and after the contact sponge method. In the present work, the contact sponge method was integrated with thermographic monitoring to observe the evolution of the process of spatial diffusion and moisture evaporation over time, in a dynamic manner.

The path adopted started with the analysis of the stone directly onsite. It continued in the laboratory with tests on altered samples of the same material taken in situ and unaltered samples taken in the quarry according to the principles of the inductive method.

The project now goes on by testing materials with similar characteristics, but with greater uniformity. The data obtained show the effectiveness of the thermographic technique for analysing the porosity of the stone; in the cases under examination, it was possible to characterize the material's response to absorption and diffusion of water.

Keywords: infrared thermography, natural stone, artificial stone, water diffusion, moisture.

Introduction

The artistic vision of Filippo Juvarra, in charge as the first civil architect at the Savoy court in 1714, led to the realisation of significant architectural works in Turin. His working method was based on studying ancient monuments, also taken as a model for choosing materials. He used Piedmontese marble and stone of different origins to construct the façades of the royal palaces and mansions he designed and built. In particular, in the case of Palazzo Madama, the starting point of this study, he selected the Chianocco marble of the lower Susa Valley. This material, which came from reopening the old Roman quarries, offered the exceptional possibility of producing large blocks in huge quantities.

Juvarra was aware of the sensitivity of this material to moisture. He, therefore, eliminated rising dampness in the lower part of the façade by inserting a full thickness *serizzo* plinth. Even in the upper part, there are problems of decay, mainly due to the difficulty of disposing of the large rainwater amount carried by the roof of the castle to which Juvarra's front was leaning. This problem, which had already become apparent a few decades after the construction of the façade, has remained unsolved to this day and is one of the issues addressed in the latest restoration project.

The non-destructive diagnostic investigations conducted within the study and restoration site on the central portion of the façade of Palazzo Madama[1] provided the basis for the development of experimental activities. Starting from in situ and laboratory tests on natural and artificial stones of different porosity, the research aims to characterise the response of the materials tested to the absorption and diffusion of water to contribute to the scientific debate prompted by the need for heritage conservation.

In situ tests

In the first phase of the diagnostic site, thermographic scans[2] of the Juvarra front made it possible to identify the areas under the greatest thermal stress and

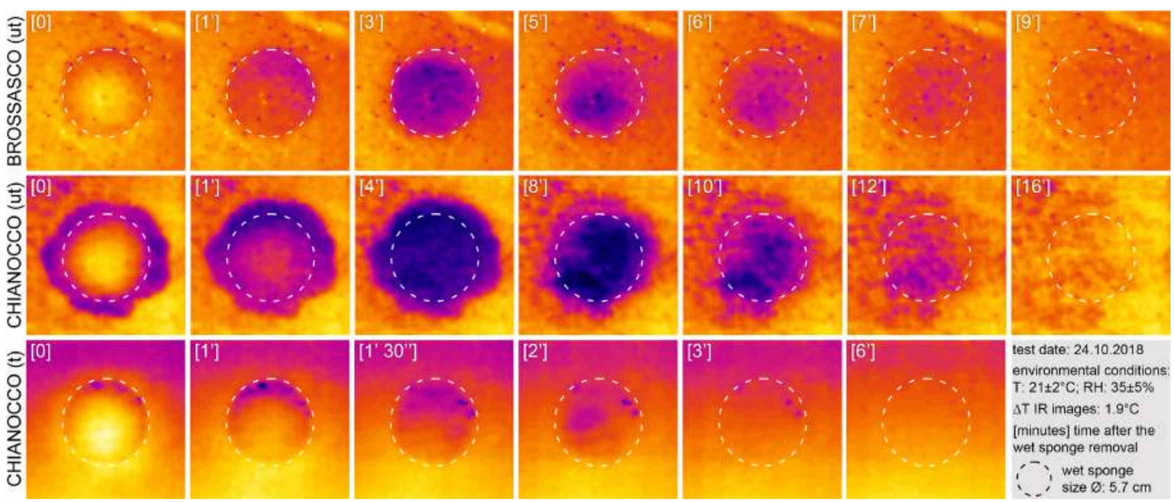

Fig. 1 Brossasco and Chianocco marbles treated (t) and untreated (ut): selection of IR images at significant times after the wet sponge removal.

to locate the most porous areas. The check of the detachment of the slabs was excluded in advance due to their high thickness. Once the scaffolding was installed, it was possible to approach the stone surfaces directly. Based on the thermographic results and the restorers' requests (presence of protective agents on the stone surface), five areas were selected on two different lithotypes (treated and untreated): Chianocco[3] and Brossasco[4] marble, on the façade and statues, respectively. Thermographic monitoring was conducted on these areas, in the same weather conditions, while measuring the water absorbed following the contact sponge method[5] (Fig. 1) [Ludwig *et al.*, 2018; Pardini *et al.*, 2004]. In this way, it was possible to highlight the evaporation front and thus show the diffusion of water in the stone, both in space and time, allowing the maximum extent of the cooling surface and the drying time to be defined.

The results show the effectiveness of the test conducted and the congruence between the IR data and the amount of water absorbed by the stone following wet sponge contact. A comparison between the untreated marbles indicates that the Brossasco (absorbed water: 0.0231 g), compared to the Chianocco (a. w.: 0.335 g) (Fig. 2), has a more spatially limited diffusion of water through the pores (1.1 cm vs. 2 cm compared to the sponge contact diameter). The evaporation phenomenon lasts less than half as long (7' vs. 15'30"). Completely different is instead the behavior of the Chianocco marble in which protective layers are still present (a. w.: 0.048 g) where the extension of the surface involved in evaporation is minimal (max. 0.4 cm) and the signal total abatement occurs only 3' after removal of the sponge.

Laboratory tests on Chianocco marble

The research was developed by carrying out experimental tests under controlled lab conditions.

The first two samples analysed were taken directly from the ancient quarry face. However, these only represent the material used in Palazzo Madama in terms of composition, not texture, as they come from a residual portion of the quarry. However, the need was to refer to a sample with features more comparable to façade marble. Therefore, a fragment of the lower portion of a column of the top balustrade that had been replaced during

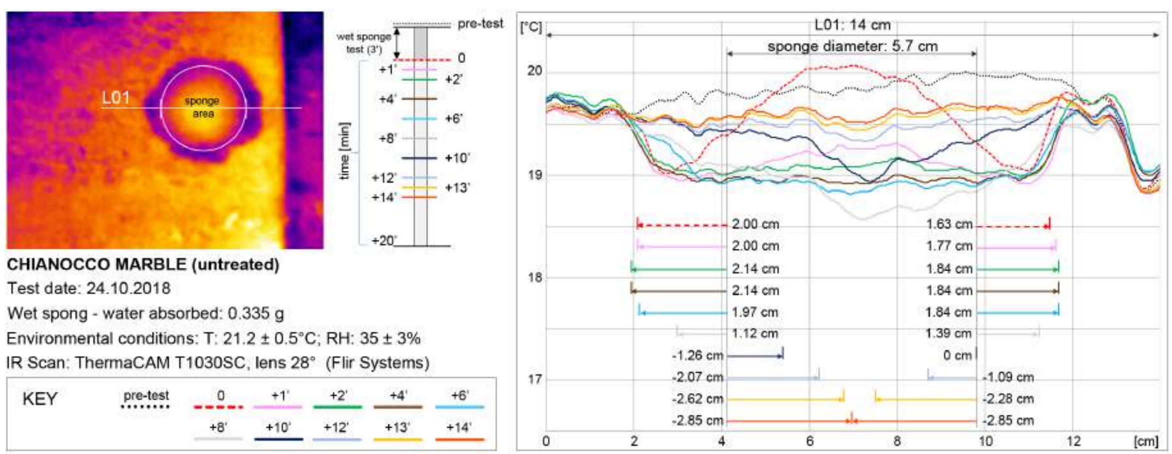

Fig. 2 Chianocco marble untreated. Data from IRT sequence (20 min) after the removal of the wet sponge. Temperature profiles on the horizontal centre axis (L01) at significant times.

an intervention in the last century was analysed. Found in the Palazzo's gardens, this sample is representative as it is altered by prolonged exposure to the external environment and without surface treatments that may have modified its physical behaviour over time (Fig. 3).

The specimens, examined on both faces, were subjected to IRT scans during tests to verify the dynamics of water absorption and diffusion. In addition to the sponge method already used, the stones were subjected to absorption tests by imbibition following immersion and evaporation tests adapting the standards UNI EN 13755:2008 and UNI EN 1925:2000 to the experimental activity. For the latter tests, the analysis on both sides of the sample taken *in situ* had the objective of simulating the evaporative thermal behaviour in the case of water present in the structure and the times and methods of imbibition of the stone in the case of heavy rain for example, in the awareness of working on a slab that was thinner than the one in the façade.

The tests conducted on Chianocco marble show a highly non-homogeneous material in its thermal behaviour in the presence of water absorption and evaporation phenomena. The response to absorption is characterised by rapidly evolving dynamics in which areas subject to strong evaporation coexist, just a few centimetres apart, with others that are significantly inert and whose geometries change over time even with significant temperature differences; these thermal dynamics are apparently not directly correlated with the distribution of porosity and are only partially related with the Chianocco marble's textural anisotropies.

Laboratory tests on fired clay bricks

The characteristics of Chianocco marble, which were particularly complex to verify the applicability of water diffusion assessment, suggested continuing the research on porous but more homogenous materials.

Two series of tests were conducted under controlled environmental conditions on several historical and contemporary fired clay bricks. The contact sponge technique was applied to all the samples, and, as in the previous tests, the induced effects were monitored by IRT. The temperature variations were analysed with an algorithm [Cernuschi et al., 2001] conceived to measure in-plane thermal diffusivity. But water diffusion can be described by the same mathematical apparatus.

The data analysis starts from the observation that once the wet sponge is removed, a temperature drop occurs in the area affected by the imbibition due to evaporation; it is also observed that over time the shape of the

Fig. 3 Sample altered by external exposure: in situ location (left), laboratory cutting steps (center), specimens obtained for testing (right).

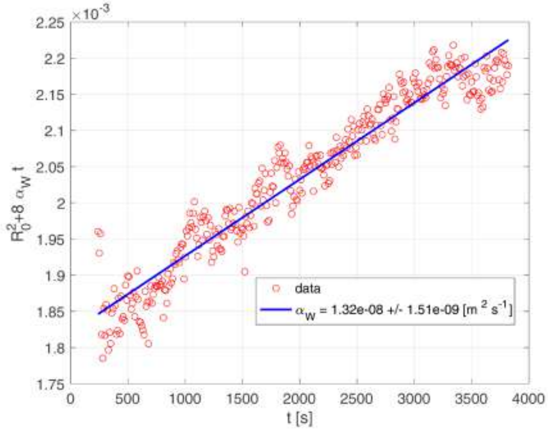

Fig. 4 The diameters of the temperature profiles increase in time as a straight line. The slope is water diffusivity.

thermal alteration changes, initially increasing, depending on the material and surface treatment. Evidently, the two phenomena, water diffusion and heat diffusion, are working at the same time. It is hypothesised that the temperature signal is mainly due to the diffusion of water, rather than to the diffusion of the heat generated by the temperature decrease due to evaporation. The diameters of the temperature profiles, as shown in Fig. 2, increase in time as a straight line whose slope is the water diffusivity. Fig. 4 shows the data fitting where R_0 is the initial diameter of the imprint, αw is water diffusivity, and t is time. As shown in the legend, the value of water diffusivity is one order of magnitude less than the thermal diffusivity of the dry material, which was obtained from the measurement of thermal conductivity, specific heat, and density[6]. This fact proves that the two phenomena, water diffusion, and heat diffusion, are working at different time scales and, therefore, can be separated in principle.

Conclusions

IRT has proven to be an effective and relatively quick technique for the *in situ* assessment of stone porosity and the verification of surface protection. At this stage, it is a comparative assessment from known samples of the same material, dependent on the wet contact sponge technique.

Laboratory tests have made it possible to characterise the material's response to water absorption and diffusion. However, the separation of thermal effects due to heat and water diffusion should be better understood. The experimental tests conducted probably need further fine-tuning of the analysis method and a more significant number of samples on which to conduct extensive tests to constitute a statistically reliable set of results.

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Notes

[1] Study entrusted to the Centro Conservazione e Restauro ‘La Venaria Reale’ in 2018. Thermographic surveys by the Non-Destructive Diagnostics Laboratory, Politecnico di Torino (2018-19).

[2] IR scan by Flir T1030 SC (spectral range: 7.5 – 14 µm).

[3] Chianocco marble is a very fine-grained, slightly yellowish crystalline marble with a calcitic and dolomitic composition in varying proportions. The most evident degradation phenomenon on the surfaces of this material is washout. This washout also occurs by removing considerable material thicknesses due to very high porosity, which is uncommon for a marble family stone.

[4] Brossasco marble is a slightly pinkish-white, heterogeneous-grained crystalline marble of essentially calcitic composition. In addition to the possibility of the formation of rusty haloes at the dark veins, this material's most evident degradation phenomenon consists of a slight form of washout that leaves some more resistant crystals in relief on the surface. Its porosity is average for crystalline marble.

[5] Tests performed by Centro Conservazione e Restauro ‘La Venaria Reale’ based on UNI11432:2001. Wet sponge contact time: 3 minutes.

[6] Thermal conductivity was measured by Hot Disk TPS2500 apparatus, the specific heat by Netzsch STA 449 C and the density by hydrostatic balance.

Some data about rising damp from 30 years of analysis in Venetian buildings

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Abstract

Venice, famous for its urban peculiarity, artistic and architectural heritage, is one of the richest cities in marble and stones, which have been used over the centuries both as building materials and as decoration. But this city suffers from a serious flooding problem, called "acqua alta", which has given rise to its fragility since ancient times, causing many damages to buildings and individual constructive materials. The causes of material degradation are various, but the main problem is rising damp.

An analysis of the rising damp behavior in masonry is proposed, basing on previous studies on Venetian buildings, considering both the construction period and the location. Results have been collected from partially destructive and non-destructive tests carried out on the walls of the building to determine the moisture content at different heights and depths. The purpose is to understand whether there is a general behavior of the results obtained in the wall structure of the buildings, correlated by high water, material and/or exposure, or, if these outputs are specific of each individual building. The salt water exfoliates the brick and plaster, and the water rises up until 2.5-3 meters, with serious problems from thermal, mechanical and indoor comfort point of view.

The final goal is to propose targeted remedial action to limit losses from rising damp by supplying a basic knowledge of the moisture process related to external conditions (environment) and intrinsic parameters (materials and their composition).

Keywords: moisture content, rising damp, cultural heritage, flood.

Introduction

Venice is famous for its urbanistic peculiarity, artistic and architectural heritage, but this city is affected by a serious problem about tides and floods, called "acqua alta", that originated its fragility. This problem is well known from ancient times and aggravated in the last century, caused by a water level increase of + 7.00 cm from 2000 to 2020 [1] and a frequency increase of the phenomena, due to natural and human reasons [2], [3].

The soaked masonries of the buildings, built on a porous ground in contact with salty water, become damaged. This is because water penetrates into porous material by many processes (i.e. condensation, atmospheric agents, drying-wetting cycle, capillary rise) and is involved in several mechanisms, from nanometer scale (swelling of clay) to centimeter/meter scale (fracture) [4]. This damage process begins in the mortar joints and then propagates also in the internal layers, disintegrating the entire masonry.

The restoration problem and the conservation of materials is fundamental in this city because materials are subjected to mechanical stress, deposition, surface alteration and fragmentation, internal erosion and dissolution.

Almost all Venetian buildings have foundations made of wooden piling (usually in the perimeter walls in direct contact with the water canals or in the buildings with high dimensions) and a masonry structure made of clay bricks and lime mortar, with visible finishing or cladding with plaster [5]. The rapid use of clay brick was chosen for need of building techniques and required durability for the peculiar environment conditions. One of the systems historically used for limiting the decay of "acqua alta", especially in prestigious buildings, is the Istrian stone, still visible both as a surface element and as a structural one. Finally, other methods used for obstructing the moisture entrance in Venice building, where the masonry weaving does not own an architectural value, consist in the realization of mechanical intervention, with the removal of one masonry wythes and the successive application of lead or bitumen sheets, between two mortar layers. These are all the methods adopted for the singular building, but the MOSE system has been in operation since 2021 [6], to protect the entire city and its ecosystem.

This work about rising damp measures in Venice would continue the work of Falchi et al. [7], to create a trend evaluation in the years, not in a specific case study but with a wide area of analysis.

Diagnosis method

The diagnosis of rising damp can be carried out in a variety of ways, from invasive to noninvasive systems. For the past 30 years, the most popular approach for quantitative measurements of moisture in walls has been the gravimetric method, with the determination of Moisture Content (MC%) [8]. This is a destructive test, which consists in measuring the percentage of direct water in a material by weighing a sample (powder or piece) extracted from the drilling masonry. The weight difference between wet weight (W_w [g]) and dry weight (W_d [g]) of the sample, indicates the MC% (Eq. 1)

$$MC\% = [(W_w - W_d) / W_d] \cdot 100 \qquad (1)$$

This procedure can be performed at different heights or sampling depths and is specific to each building. Moreover, it is not always made in historic buildings because of the difficult reproducibility of data measurements and the difficulty of taking a sample in frescoed or decorated walls.

In this work 17 Venetian case studies are analyzed (Fig. 1) [4], [7], [9]–[14], collecting a total of 250 obser-

Fig. 1 Venice case studies of rising damp (Moisture Content [%] in the masonry).

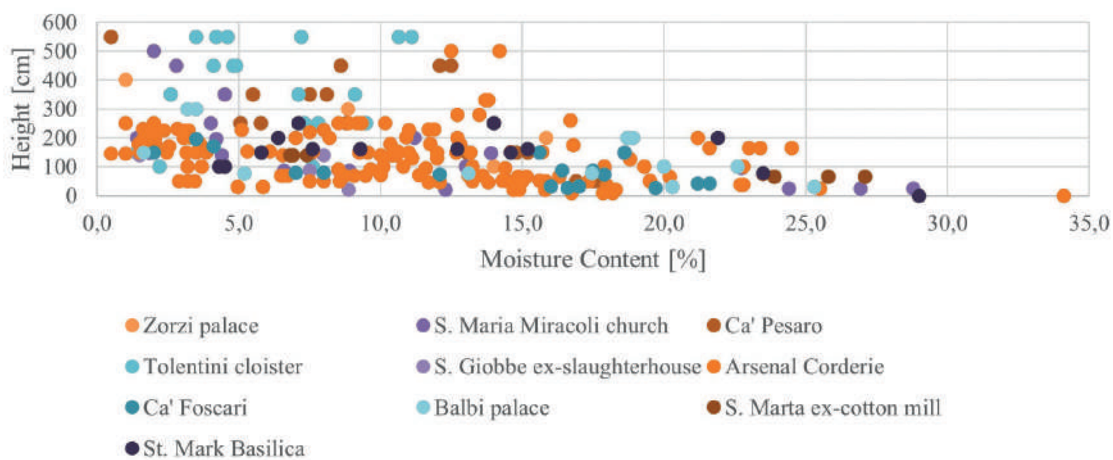

Fig. 2 Relation between MC% and sampling height [cm] in some case studies in Venice.

vations to create a dataset of the past 30 years. The analysis is not constant over these years, but is concentrated between 1980-1990 and 1995-2000, mainly when conferences on the topic were organized or funding regarding Venetian land conservation were published. This survey highlights the lack of data for long time periods

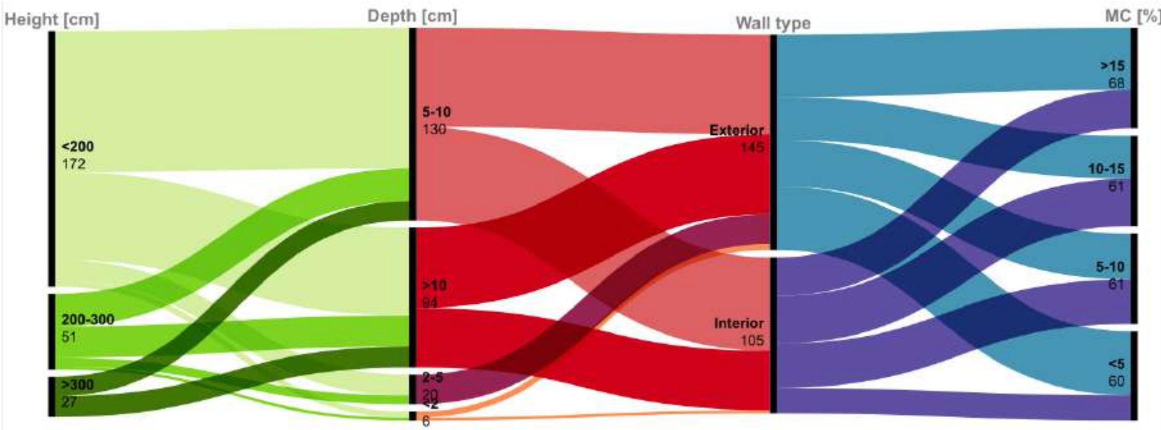

Fig. 3 Feature selection of rising damp in Venice; the variables considered are sampling height [cm], sampling depth [cm], wall type and moisture content [%].

because testing requires many years of investigation, and difficulties in data processing and high expenses incurred from time to time.

The parameters used in this evaluation are (i) wall type – interior (105 data) or exterior (145 data), (ii) sampling height [cm], (iii) sampling depth [cm] and (iv) building floor height with reference to the location of "Punta della Salute" ZMPS [cm] [15]. A correlation can be found between MC% and height of sampling (Fig. 2): the higher the masonry drilling height, the lower the water content recorded. Therefore, 3 areas in the walls can be observed: (1) at the base a wet area (below 200 cm) with a higher MC%; (2) the intermediate region as a transition phase (between 200 cm and 300 cm); (3) the dry area on the top of the masonry (over 300 cm) [7].

Conclusions

Regarding the study of rising damp in cultural heritage, it is clear how many variables participate in the phenomenon, intrinsic and extrinsic, and in different quantities.

The movement of water within the masonry has shown a trend somewhat related to the tidal level. Samples taken at 1978 to 1987 recorded an increase in moisture content (+14.5%, mean value recorded on 107 data), and an increase in tidal level of +4.00 cm (maximum recorded level)[1]; from 1987 to 1997 there was a 15.6% decrease in moisture content (55 data) and -13.00 cm on tidal level; finally, since 1997 there has been a slight increase of +7 MC% (88 data) and +15.00 cm on tidal level (excluding the exceptional flood of 2019).

By means of feature selection analysis, it is possible to identify in a small database with multiple attributes, such as the one adopted here (of 250 observation MC% in Venice) those features that are more significant than others. The most important evaluated variables are sampling height (ii) by 50%, sampling depth (iii) by 16% and wall type (i) by 8%. The remaining 26% are related to the analysis building, a variable of little significance in this case since each building is stand-alone.

After identifying the most important attributes, the distribution of the data can be seen from Fig. 3. Sampling was done at different heights, with a dissimilar distribution; 69% on masonry at height < 200 cm, a zone classified as wet area. Here, the MC% is evenly distributed between 1 to 15%. Depth sampling is concentrated above 5 cm, to investigate the core of the masonry without the influence of the surrounding environment. Finally, tests were carried out on 145 samples of masonry exposed to the outside and 105 samples to the inside. However, from the samples taken on the different types of walls, the moisture content is distributed in the same percentage among them (24-27%), so it is significant that the water content in the walls is independent of the interior or exterior location.

The identification of buildings to be analyzed begins with a visual survey of the level of capillary rise front, brick erosion or salt band, and then a decision can be made to investigate deeper the internal MC% distributions, thus integrating qualitative and quantitative approaches. This monitoring, if planned properly, will provide knowledge both on the specific building and at the urban level, and of the relationship with the MOSE system.

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What medical imaging has to offer in art conservation

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Abstract
Since the discovery of X rays by Roentgen in the late 19th century, medical imaging has been used to investigate and validate art in a number of different ways. It is almost impossible to describe all of the available technologies and recent advances in artificial intelligence have further complicated the arena. Below are some of current techniques with speculation about more recent applications.

Keywords: art conservation, archeology, non invasive imaging.

When Wilhelm Röntgen described Xrays in 1895 he was probably unaware of the massive impact his discovery would make in medical imaging and while Godfrey Hounsfield was credited with the development of 3D imaging in the 1960s, the first description of 3D Xrays was by Davidson only a few years after Roentgen. Reformatting of CT (computerised tomography) data by Arridge et al allowed model milling and subsequently 3D printing. Clearly this has been important in non destructive imaging of items such as mummies. More recently the new science of radiomics has evolved where AI techniques are applied to CT data sets with a view to getting diagnostic and prognostic information.

MRI (magnetic resonance imaging) was initially pioneered in *1882 by Nikola Tesla with the concept of a Rotating Magnetic Field*, however it was not until the 1980s that the technique was used in clinical practice. This has allowed the acquisition of information in the living, but also non invasively in the deceased where it has displaced the formal (surgical) postmortem examination, especially in stillborn and neonatal deaths. One technique that has yet to translate into widespread use in paleoanthropology is "black bone" MRI. Complex computation of MRI data sets allows bone to be seen as "black" with appearancies similar to CT images. There is also AI work in progress – this may well have applications in art where it should be possible to produce a painting passport for artwork.

Teraherz imaging is a topic that seems to have been underutilised in medicine since its first forays into dermatology. Mainly used in security systems and by the military, there has been considerable interest in looking "through" surfaces of for example paintings. There has also been work done on Egyptian mummies where it is claimed to be effective in looking for "hidden objects" in wrapped mummies and is particularly useful for looking at dry objects. There are a number of systems such as near field techniques which may improve spatial resolution and may even yield spectroscopic information and these should be applicable to ceramics and paintings alike.

Optical diagnostic systems. A number of diagnostic systems are available, but it is important to be clear about energy in v energy out.

The most efficient system is elastic scattering spectroscopy (ESS). Using this method, a pulse of polychromatic light is fired into tissue where it interacts by absorption, scattering reflectance etc. The resulting signal is captured, fed to a spectroscope then a computer interface where the spectra are cleaned. At specific wavelengths, there is a clear difference between benign and malignant tissue. However, a large amount of information is lost in the process and using AI to use all of the data would yield a great deal of information. Applications in art could well be used to interrogate almost anything. Data acquisition takes less than a second and the equipment is portable and the amount of energy required is small, making it an ideal non destructive technique

All tissues fluoresce – and this technique can be used especially in the evaluation of pigments, many of which fluoresce when excited by a variety of wavelengths of electromagnetic energy. Energy loss in the process is much greater than with ESS but quite sensitive systems are available.

The third of these systems is Raman spectroscopy, where laser light interacts with tissue and the emitted signal has a very small wavelength shift that equates to a biochemical signature. Early work was done on oesophageal cancer, but applications have expanded to the extent that a portable Raman machine has been sent to Mars to try to find historical signs of life. There is some concern that the energy required might cause thermal damage to delicate structures such as artwork and tis needs to be determined before widespread adoption.

Optical Coherence tomography is a laser based system that comprises 4 overlapping laser beams and produces an image that looks a little like ultrasound. In terms of medical uses, it can be used to look at very thin tumours that are not visible on ultrasound and particularly in superficial spreading basal cell cancers where it is able to map the extent of disease. This is easy to do as the tumour is characterised by keratin whorles with the benefit of increasing the complete resection rate. As it is completely non invasive, it can be used in art conservation – for example changes in surface deterioration and cracking of museum pieces. The availability of a probe system allows examination of the inside of cups, pots etc. There is also potential in cosmetic development, where for example the efficacy of rehydration products can be quantified, although as yet this approach has been resisted by the cosmetics industry.

Initially, the techniques used in medicine have been translated into the art world. However, with increasing regulation and onerous ethics requirements in medicine, even for simple non invasive diagnostic techniques, have slowed clinical diagnostics to a snails pace. Perhaps now it is an appropriate time to reverse the information flow and build on existing scientific collaborations.

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