EAI
bimestrale dell'ENEA
anno 58

Speciale

KNOWLEDGE, DIAGNOSTICS AND PRESERVATION OF CULTURAL HERITAGE

SPECIALE II - 2012

Energia, Ambiente e Innovazione

Speciale

Knowledge, Diagnostics and Preservation of Cultural Heritage
A cura di Paolo Clemente, Paolo Di Lazzaro, Rossella Giorgi

Per informazioni e contatti: *infoeai@enea.it*

Pre-stampa
FGE Srl - Fabiano Gruppo Editoriale
Regione San Giovanni, 40 - 14053 Canelli (AT)

Stampa
Varigrafica Alto Lazio
Via Cassia, km 36,300 (Zona industriale) - 01036 Nepi (VT)

Registrazione
Tribunale Civile di Roma - Numero 148 del 19 aprile 2010 del Registro Stampa

Pubblicità
FGE Srl - Fabiano Gruppo Editoriale
Regione San Giovanni, 40 - 14053 Canelli (AT)
Tel. 0141 1768908 - Fax 0141 1768900
e-mail: *info@fgeditore.it*

Finito di stampare nel mese di dicembre 2012

Prodotto realizzato impiegando carta Symbol Freelife certificata FSC

II-2012

Indice

Foreword

Paolo Clemente, Paolo Di Lazzaro, Rossella Giorgi

Foreign people usually say that Italians are best known in the world as experts and lovers of music and arts. Actually, our country has given birth to several musicians and artists, and also to very famous engineers and architects that imposed their works all over the world. This is one of the reasons why most of the worldwide cultural heritage is in Italy, giving us the duty to preserve this heritage in the frame of a sustainable development.
The safeguard of cultural heritage must be ensured for future generations not only in reason of the cultural identity of the population it represents, but also because cultural heritage is a driving force of the economy, especially in a period of economic global crisis.

This challenge is not easy. Both in the past and recently, cultural heritage was seriously damaged due to different causes. The natural aging process is worsened by the combined effects of air pollution and the 'normal' impact of visitors and tourists, as well as by the absence of adequate maintenance. In addition, natural disasters such as earthquakes, landslides and floods may cause terrific losses or heavy damage to historical centres that (at least in Italy) host the most important part of cultural heritage. The recent earthquakes that struck Abruzzo in 2009, Emilia-Romagna in 2012, and Pollino in 2012, are only the last of a long chain of natural disasters.

A careful prevention policy is strongly recommended for conservation of the cultural heritage survived up to date to be definitely guaranteed, which demands a huge effort by Governments. Such an effort should concern the preservation of cultural objects, the safety of a large number of people and the ability to "propose" and implement appropriate measures for a low-impact enjoyment of artworks and cultural assets.

Fortunately, nowadays new technologies offer effective tools for a wide range of analyses related to the knowledge and diagnosis, modelling, evaluation on the one hand, and those related to restoring and improving interventions on the other. The knowledge of materials, execution techniques, restoration products, the environment with its chemical, physical, biological and mechanical actions, is mandatory to preserve the overall cultural heritage. Over and above that, the natural aging, the environmental deterioration agents, the seismic risk and the risks associated to human activities are factors that must be studied and controlled. With this aim and with the contribution of different scientific disciplines, the modern conservation science was born: Chemists, Physicists, Biologists, Engineers, Geologists, Architects cooperating with Archaeologists, Art Historians and Restorers have developed diagnostic techniques, technological instruments, monitoring systems, synthetic restorations products, software programs to carry out studies, research and interventions on cultural heritage.

Sp

The great contribution of scientific research to conservation started in the decade 1950 - 1960, although some examples of application of nuclear technologies were previously demonstrated. Nowadays the conservation science involves knowledge and techniques often developed for other applications: analytical, optical, organic, spectroscopic, photonic, biological, imaging, mechanical, structural, anti-seismic, nuclear methodologies are now applied to determine the composition and the state of conservation of different works of art, from the excavation samples to historical structures, monuments and archaeological sites, passing through paintings, statues, pottery, mosaics, bones, textiles.

The multidisciplinary approach is the basis of the ENEA intervention in the cultural heritage. Since the pioneering studies in the ‘80s by a small group who began to analyze materials and structures of works of art using technologies developed for the nuclear sector, the range of applications enlarged greatly, both in terms of works of art studied and of technologies and methodologies –now including new anti-seismic technologies, in situ and on shake table seismic tests, geomorphologic survey, environment monitoring, biotechnologies, laser technologies, photonics, information and communication technology. More than 1500 diagnostic interventions on historical structures and objects of art in collaboration with Restorers, Art Historian, Archaeologists and officials of the Italian Ministry of Culture have been carried out in the past few years. Research projects with national and international funds have been performed, education and training programs in collaboration with different universities have been carried out.

This special issue of the ENEA Magazine gives a brief overview of some activities performed by ENEA in the knowledge, diagnosis and preservation of cultural heritage. It is organized in three sections. The first one is dedicated to the safeguard against natural risks, such as earthquakes and landslides, the second to several interdisciplinary approaches to conservation and the third to diagnostics and imaging by lasers, optics and photonics.

The works reported in this special issue point out the collaborations of ENEA with national and international institutions such as universities, Superintendence and others, represented in the two introductory papers by L. Marchetti and G. Bandini.

Have a nice reading!

The 6TH April, 2009 L'Aquila Earthquake: Restoration Choices and Pathways

The restoration choices following catastrophic earthquakes have historically pursued different philosophies and methodologies especially with respect to the historical monuments. In Italy there were "centralist" reconstructions as in the Val di Noto, 1693, L'Aquila, 1703, or more pragmatic interventions, like in Friuli 1976 and Irpinia 1980. On the occasion of the most recent earthquakes, Umbria-Marche and Molise, restoring cultural heritage has been classified among the top priorities at the local and national levels, ensuring the reconstruction in a perspective seismic improvement, i.e., without heavy structural measures. The application of the same logic in the case of L'Aquila, where the earthquake hit the center of a capital city, rich in historical and monumental heritage, very significant and concentrated in a limited area with limited access and narrow streets, reduces the possibility of interventions on several structures simultaneously, imposing the securing of the structures for a long time. Securing actions have been designed so as not to change the structural behavior of the damaged artifacts

Luciano Marchetti

The earthquake strikes heavily and traumatically the inhabitants of a territory, whose stability is severely tested as individuals, families, community and the whole local social system. Regardless of type, extension, and historical-architectural value, each single building always represents the principal reference for the resident population. Hence, its damage or complete destruction always implies a significant loss of identity for the territory, which will hardly be restored showing the original aspect.

The reconstruction initiatives launched after several harmful events – whether natural or wartime – which over time affected the inhabited areas inside and outside Italy, followed different policies and approaches. As a matter of fact, it was decided to proceed case by case with: on-site reconstruction, restoration of the surviving buildings, full replacement of the historical and architectural heritage, delocalization of neighbourhood or town, or a range of interventions based on the damage assessment and the cultural values that places were assigned by their dwellers.

Historically, in Italy decisions were mostly based on absolutist evaluations by the Central Government, who in many cases decided to assign one minister plenipotentiary the task of controlling the reconstruction, often adopting compulsory measures against the populations opposing the government's decisions. In this regard, it is worth mentioning the reconstruction

Luciano Marchetti

Former Director General - Ministry for Cultural Heritage, and Vice-Commissioner for reconstruction at L'Aquila

FIGURE 1 Val di Noto, 11th January, 1693
Source: Author's personal archive

modes implemented in Val di Noto or in L'Aquila after the 1693 and 1703 earthquakes, respectively.
The strong central decision-making power exerted for the demolition of historical buildings and their reconstruction under different form is evident even more recently, at the beginning of last century when the earthquakes of Messina (1908) and Avezzano and Marsica (1915) occurred. Conversely, in the second half of the XX century, the reconstruction choices following the Friuli (1976) and Irpinia (1980) earthquakes were definitely more pragmatic and relevant to the actual extent of the damage to buildings.
In Friuli, large demolitions were made in the areas of Gemona and Venzone: in the former case, besides some isolated monuments, only the buildings overlooking a stretch of urban street were spared, whereas for the latter – mostly thanks to the intervention of Roberto Pirzio-Biroli, Head of the Technical Office for Reconstruction as well as coordinator and founding member of the owner consortia of urban aggregates – the historical centre was reconstructed as and where it was, with the reconstruction of the Dome in terms of careful and rigorous anastylosis by a team headed by Francesco Doglioni, professor of the Venice University.
The type of most proper reconstruction and/or

FIGURE 2 Messina 1908 earthquake
Source: Author's personal archive

restoration is often influenced by the changes that the societal and cultural systems are coping with – particularly in terms of economic development – triggering effects on and changes in the societal texture and the environment that can be evaluated only after a good while. In any case, the cultural heritage of a territory substantially affects the perceptive perspective of the resident population, whether it be a cultural heritage acknowledged preserved by the State Government, or considered as such for history, tradition or mere affection reasons by the local population.
Choosing the right kind of intervention to be implemented is a problem arising all the same also following traumatic events such as floods, wars or other catastrophes, causing the loss of significant references for the societal, economic and productive textures in addition to the shock for what occurred. The same may happen for man-made strategic events purposely caused on the grounds of strong economic interests. Such was the case of the construction of the Aswan High Dam, decided by the Egypt and Sudan Governments to foster the development of Ancient Nubia. This area

FIGURE 3 Securing the Torrino in Foligno, following the 1997 earthquake
Source: Author's personal archive

FIGURE 4 Restoration of the S. Francesco d'Assisi fresco, following the 1997 earthquake
Source: Author's personal archive

was subject to the conflicting economic goals of two nations and attracted the cultural interests of the international community, so that under the aegis of UNESCO many countries bore the very high costs for moving monuments to other places, to save them from being doomed to be submerged: the international interest for the local cultural heritage made it worth choosing its full delocalization.

The reconstruction criteria adopted following conflicts were alternatively affected by either the choice to wipe out the signs of events or to leave their trace strong and readable. With regard to the post-World War Two period, most remarkable is the case of Coventry, where the choice was made to leave visible memories of the war events just after the war itself. The same was decided for Berlin's Cathedral. Conversely, in the case of Dresden, it was decided to fully reconstruct the city only after a long time since the end of war during such period the city kept showing the ghostly signs of destruction and, with them, the entire memory of its recent history. Such a choice was shared by Warsaw also, albeit immediately after the end of war.

In many of such cases, the abstract cultural assessment ended up with being replaced by much more forceful and cogent factors, such as people's expectations about the future of their own territory and, at the same time, the valorization of their cultural heritage. The local or central governments' choices were basically oriented to follow this dual vision of the future of the affected territories.

In the light of the above, the need to inform, stimulate and sensitize the awareness of the affected populations is crucial to start up and manage the reconstruction. Essentially, each city changes its structure and functions over time, evolving in accordance with the societal and economic changes it is affected by, even as a consequence of the development of new building technologies (just think about the invention of reinforced concrete and its effects on the urban context). Such changes usually occur in a natural,

Sp

FIGURE 5 Securing the bell gable of the Basilica di S. Bernardino in L'Aquila, following the 2009 earthquake
Source: Author's personal archive

FIGURE 6 Restoration and screening of the ruins in the Church of S. Maria di Collemaggio in L'Aquila, following the 2009 earthquake
Source: Author's personal archive

balanced and progressive way, taking its historical heritage into account, it too modified and consolidated over time, representing a strong identity element in the urban context. The reconstruction interventions following catastrophic events likewise represent an evolutionary moment of the urban texture, a stage when the traumatic component acts as an incentive to restore the memory of what has been wiped out by events not dependent on the citizens' will.

In the case of the latest national earthquakes, the prevailing trend acknowledged by the Government was to restore the cultural heritage, as clearly stipulated in the related laws in favour of the restoration of the heritage under protection (simpler procedures, fewer technical restrictions, higher economic funds for owners, etc.).

The choice between "seismic upgrading" and "seismic improvement" was strongly debated–where "seismic upgrading" stands for all the works required to ensure that the building safety level is elevated to that of a new building regardless of the original functioning; on the other hand, "seismic improvement" means all interventions are made with almost no alteration of the building while providing it a much better seismic response. Such choice ended up with adopting the seismic improvement, which became one of the qualifying elements of the whole related regulation procedure. At the same time, interventions on the law-protected buildings were made considering the different "restoration charts" and cultural evolutions in Italy, upon which technicians and restorers had based their work.

When the latest earthquakes occurred, particularly those of Umbria and Marches, and the immediately following Molise quake, the cultural heritage restoration was set among the top priorities at the local and national levels. It was in fact unconceivable not to restore the Upper Basilica in Assisi or the "Torrino" in Foligno, the churches in Fabriano or the damaged parts of the Ducal Palace in Urbino, as well as many other churches and monuments spread all over the affected territories. Any intervention on the cultural heritage posed a serious conceptual, technical and method dilemma: whether following the criteria of scientific restoration as much as possible, restoring just what did remain, or else making interventions to reconstruct the heritage exactly in its original form, though with possible, even substantial integrations in the case of demolitions or collapses.

In Umbria, a mixed criterion correlated to the actual damage was opted for, so as to make interventions as much accurate as possible; nevertheless, should this not be possible due to collapse, intervention of mere actual reconstruction could be envisaged. Typical examples of the kind are the above-mentioned "Torrino" of the Municipal Palace in Foligno (where only the belfry collapsed, whereas the actual medieval tower was saved thanks to the protection facilities), the Civic Tower in Nocera Umbra (severely damaged and then restored and partially reconstructed), or the Upper Basilica in Assisi (where the vaults, partially collapsed, have been reconstructed with techniques and materials similar to the original church, providing an anti-seismic consolidation system for both the surviving and the reconstructed parts, so ensuring that the complex has an effective, homogeneous seismic response; the decorations of the vaults with frescoes of the greatest value have undergone a massive restoration campaign, based on the strict compliance with the Brandian restoration criteria, and completed with the in-situ repositioning of the restored parts and the neutral ("a neutro") treatment of those remaining.

Following the Umbria emergency, the first securing measures were implemented over the whole damaged territory, allowing to begin the following restoration in a very short time and in a functional and fruitful way, thanks mostly to the optimal architectural conservation methodology and to the consequent opportunity to set-up many building sites at a time, without any interference with one another.

By doing so, it was possible to employ securing facilities particularly innovative and effective, as shown by the manufacturers' certifications, whose actual duration over time had never been tested before. The use of the so-called "crick" belts – i.e., synthetic belts made of nylon and polyester, provided with proper fastener and traction mechanisms, typically used in transporting, handling and fastening of loads – stemmed from the need to work as fast and easy as possible against drastic curbs on costs. Based on the analyses of damage mechanisms, the application technique was then coded by the Office of the Vice-Commissioner for Umbria, whereas the special VVF squads[1] took care of the installation and set-up of securing facilities. Actually, the suppliers' information about duration and resistance of synthetic belts was very cautious, since these devices did remain fully efficient even after three years of exposure to atmospheric agents.

Opting for the intervention described above has considerably reduced the amount of economic funds to be specifically allocated, which was also possible thanks to the unexpected availability to implement and set up securing measures by the special fire department squads who, unlike the past, did not limit themselves to removing the unsafe elements that are dangerous for population.

The whole operation was carried out on the basis of an accurate analysis of the damage and the mechanisms caused by the earthquake, taking into account the research conducted over time by the GNDT group[2] and in-situ investigations by several damage detection groups. In this way, it was possible to code the mechanisms of the damage to square-base towers and one- or multi-storey belfries. By so doing, the related securing systems resulted as more agile, functional and effective, so as to avoid redundant or unnecessary interventions. The effectiveness of the implemented systems has been fully confirmed on site, even in the case of late restoration interventions. Another factor taken into account was that the seism did not cancel the network of major and minor historical centres, so that no intervention on the urban texture was demanded.

Conversely, a different scenario is shown for L'Aquila, where interventions were made in a context particularly difficult and complex due to the extensive damage and the reduced area, just a few hectares, of the related historical centre, characterized by an extraordinary concentration of buildings with a high artistic and historical value. Another constraint was the likelihood of very long-term restoration interventions with respect to their complexity, the reciprocal interference of sites and the huge amount of funds to be allocated. In addition, due the size of the historical centre, particularly binding were the interactions between what was law-protected and the remaining part of buildings to be correlated to monumental emergencies: this necessarily implied that restoration interventions were to be included in the more general context of urban planning, inevitably delaying their execution. In any case, this slowed the decision process down, although such delay could have offered better conditions and chance to re-design L'Aquila in terms of both the historical centre development and the requalification of the city outskirts.

For this earthquake too it was necessary to allow the population to immediately have their retrievable belongings back, which demanded implementing

Sp

all measures to ensure people to access their own dwellings as much easily and safely as possible.
In the light of the above-mentioned factors and the will to fully safeguard the principles of the "restoration charts" and the lessons of past experiences, it was thought to preserve everything as much as possible albeit damaged, so that the surviving architectural structures, or what remained of them, could be re-used and integrated in following restoration interventions. Such criterion was also applied to minor buildings in their role as necessary general context of monumental buildings.
This guideline has been widely shared by the municipal administration –who was in charge to materially ensure the emergency securing interventions– and the Italian Ministry of Cultural Heritage in concert with the Vice-Commissioner for the protection of Cultural Heritage, so that in L'Aquila and in the other towns affected by the earthquake no authorization was issued to demolish cultural heritage elements, just like it previously happened in Umbria.
It is clear that in many cases the surviving parts were so small that the reconstruction of the damaged heritage was not possible. Yet, by preserving them a modern intervention can be made taking into account the pre-existing parts and including them in the framework of an overall design. That is what already happened for the Church of San Gregorio Magno, in San Gregorio dell'Aquila: the Vice-Commissioner issued an international design contest for the restoration of the church.
The earthquake of 6th April, 2009 severely affected the city of L'Aquila, also regional capital, hosting almost a hundred thousand people, with a very rich artistic and monumental heritage, mostly included in its historical centre. Choosing to implement securing measures and restore this essential part of L'Aquila has proven to be an unprecedented effort in the national cultural heritage scenario, due to the need to secure a very high number of monuments and movable heritage, some demanding very urgent, complex and delicate interventions.
Each catastrophic event is a moment for testing and improving the techniques and methods used in the previous emergencies. In 1997, when the Umbria-Marches earthquake occurred, the Office of the Vice-Commissioner for Cultural Heritage, assisted

FIGURE 7 Securing and roofing the transept in the Church of S. Maria di Collemaggio in L'Aquila, following the 2009 earthquake
Source: Author's personal archive

by external consultants and the special VVF squads, developed an innovative set of securing techniques which has been effectively implemented in the following earthquakes, thus becoming the key know-how and expertise used in L'Aquila emergency events. For instance, the analysis of damage evolution in the belfry of Santa Maria Assunta in Sellano provided the outline for the intervention on the belfry of the Basilica di San Bernardino in L'Aquila, whereas Doglioni's studies on the collapse mechanisms of great churches in Friuli, re-elaborated and enhanced during the emergency in Umbria, allowed to build provisional works in Abruzzo, just limited to the parts of structural complexes more at risk, such as façades and apses.
The lesson learned by experience is that securing interventions are effective when they do not alter the structural behaviour of the damaged buildings, which must consequently be restored if needed, as in the case of the detachment of the façade from the rest of the walls or when the wall resistance is interrupted. Such interventions must never hamper the following restoration operations, but rather be a functional tool propaedeutical to the execution of works.
While designing the securing systems it is important to keep in mind that earthquakes are dynamic events which, regardless of their violence, do not end with

FIGURE 8 Securing the dome of the Church of S. Maria del Suffragio in L'Aquila, following the 2009 earthquake
Source: Author's personal archive

one stress action but rather they repeat over time with further stress on the already damaged structures. In the light of this, solutions based on structures in contrast must be avoided, because they could cause hammering, due to the aftershocks, badly damaging the buildings to protect. Therefore, the securing intervention stems from the observation of structures and their damage, allowing to exactly detect the collapse mechanism and implement the provisional solutions most suitable and effective.
With the Umbria-Marches emergency of 1997, the securing intervention techniques were considerably enhanced, mostly thanks to the use of innovative methods and materials and the support of specialized operators of the SAF (speleo-alpine-fluvial) squads of the fire department. The scientific progress lead the sector to further improve its operative capabilities through a set of new technologies such as, e.g., the laser-scanner detecting systems, stainless steel braided wires, high-resistance fiber artifacts, and FRP section bars, all resources that have been widely and differently used in the provisional works in L'Aquila.
Composed of a huge amount of art works, paintings, sculptures, books and documents, the mobile artwork heritage affected by the Abruzzo earthquake has been retrieved and/or made safe with large use of technical and human resources, often working in dangerous conditions because not always clearing could be carried out once the provisional works had started. Examples are the recovery interventions of the materials of the Archivio di Stato[3] in the Prefecture Palace, and the National Museum in the semi-collapsed part of the Spanish Fort, which were made before the securing interventions, in order to avoid the risk of further damaging due to atmospheric events. In these cases, the VVF played a key role, so did the volunteers of the Civil Protection Department. As a whole, over 5,000 mobile artworks and 250,000 books have been removed and recovered. Thanks to the recovery of all these books the Archivio di Stato was opened in a new palace after only a few months.
Due to the particular scenario of L'Aquila a dual intervention approach was implemented, as it was not possible to make the huge quantity of damaged buildings safe only by the support of VVF. In fact, the monuments recorded in the whole affected territory are about 1,800, single buildings and building complexes, besides all the buildings representing the urban texture of the centres belonging to such a context. This heritage is mostly concentrated in the historical centre of L'Aquila. Taking into account these conditions, the Vice-Commissioner Office ensured, through the VVF or private enterprises in the worst cases, that most important buildings protected by laws were made safe, whereas the municipal governments were responsible for the provisional interventions on the remaining buildings, in accordance with projects elaborated with the Vice-Commissioner Office in cooperation with private firms.
The need to quickly reduce the spreading of the so-called "red zone", i.e., the no-access area subject to armed surveillance by the Army, was immediately

clear for two reasons mainly. On the one hand the need to allow the population to retrieve their belongings basically safeguarding their personal identity, on the other the need to give the citizens of L'Aquila access to their life places (actually only some main streets) as sooner as possible, in order to prevent them from disaffection phenomena, further delaying the following reconstruction. This phenomenon already occurred in Umbria, precisely in Nocera, where the whole historic centre was indiscriminately closed, and the population built their new dwellings out of that area, thus losing interest in and motivation to the following recovery opportunity.
In the light of the above, and urged by the need to avoid that the provisional works could hamper the reconstruction phase, an intervention design criterion was defined, aimed at restoring the vertical load-bearing capacity of masonry buildings by using vertical elements capable of ensuring the plane stability of the perimeter walls (along with opening ringing, filling of the collapsed portions, etc.), devices ensuring the good cohesion of the external walls (wooden or iron beam grids on the external surfaces), and systems of metal tie beams properly tightened between the walls so as to ensure that the structure had a "box" behaviour. Specific completion facilities (provisional roofing, rockfall protection structures, etc.) were provided wherever needed.
The above resulted in extended and non-invasive safe condition allowing to plan the final works without rush, so as to provide streets reasonably accessible, use of some of commercial spaces and the possibility for citizens to access their own dwellings and still be able to partially live the historical centre.
This choice was correlated to the will of safeguarding what remained of L'Aquila historical centre and the law-protected parts of the minor centres of the territory, being well aware that indiscriminately demolishing the non-law-protected buildings would not have saved time, just as it happened in some hamlets of L'Aquila, e.g., in San Gregorio or Onna, with the false illusion to speed up the reconstruction works. As easily verified, also in these places the restoring times depended on the complexity of problems rather than on the administrative will. In this sense, the hamlet of Paganica

FIGURE 9 Securing and roofing the Church of S. Maria di Paganica in L'Aquila, following the 2009 earthquake
Source: Author's personal archive

with its ruins tenaciously protected by the population is a virtuous example of heritage safeguarding.
The Vice-Commissioner Office, with the support of VVF squads mainly, ensured that the law-protected and particularly important heritage was made safe, intervening on the severely damaged structures whose collapse could have caused them further damage. Some examples are the recovery of the remains of San Bernardino in the convent of the same name, and the securing interventions to the belfry and the dome of the Basilica dedicated to the saint, directly borrowed from the interventions made in Umbria after the 1997 earthquake. By other means yet by the same technique that led to the private housing projects, the stability of the most ancient part of the XVI century Castle was ensured by tying the internal double-lodge structure (almost overturning on the court) with the robust external masonry of the fortress by way of stainless steel tie beams and metal partition structures placed on the internal façade, also affected by some collapses on the second floor.
In the framework of assessing the damage to cultural heritage, the Church of Santa Maria del Suffragio (or delle Anime Sante, built following the 1703 earthquake in memory of the casualties) drew a particular attention, mainly for the very severe conditions of its dome, a valuable architectonic element attributed to Giuseppe Valadier, mostly collapsed and for this reason to be

FIGURE 10 Securing the Duomo in L'Aquila, following the 2009 earthquake
Source: Author's personal archive

necessarily secured to ensure its correct restoration. The intervention was characterized by many dangerous aspects both for the reiterating quakes and for the precarious situation of the artifact remains. Using a sophisticated laser-scanner to survey the damaged structures was fundamental to design the system of provisional works required to ensure the complex stability. Besides providing very-high-precision measurements, the laser-scanner device allowed the technical staff to investigate the dome in complete safety, since the overall operation was carried out with automatic-control mobile machines transported on site by a remote-control mechanical shaft.
The laser-scanner survey allowed to define a securing intervention to be carried out in more phases and times: firstly an outer ringing to prevent the stump from overturning; then the prefabrication of three metal structures: two of them allow to restore the tambour continuity interrupted by the collapse, and the third one acts as internal contrast element allowing to avoid the implosion of the whole structure (remaining parts of the dome and the tambour). The laser-scanner investigation also allowed to make proper simulation to fine-tune the times and modes of operation, and to schedule a specific training of the VVF squads responsible for the intervention.
Many observers criticized the efforts to safeguard the surviving parts of the dome and the tambour of the Anime Sante, erroneously thinking that they would be demolished anyway in the following reconstruction phase. Such evaluation was completely wrong since the project, designed by Italian and French technicians, provides the preservation and integration of all surviving parts, making the reconstruction of the lacking elements as much accurate as possible, enabling to follow the traces and remains of the elements lying on site. On a much larger scale, this may be said for the whole city of L'Aquila, where the historical centre could not certainly be consolidated in the state it is secured today, however it will be reconstructed in a proper and philologically correct way thanks to the traces left by the preserved parts.
Another intervention with a very remarkable effort was that made on the Basilica di Santa Maria di Collemaggio, which consisted in recovering the remains of Pope Celestine V, securing the whole complex (by selecting the collapsed materials, retrieving the gravestone elements and saving the pipe organ), and setting-up and installing a massive metal roofing structure, allowing to re-open the Basilica for Christmas 2009. The provisional works were inspired by several different technologies, as shown by the synthetic-belt ringing of the columns of the naves, the steel wires to avoid the possible overturning of the side walls, the centering of the arches most at risk and installing on the transept a light translucent roofing, supported by steel trusses standing on reticular metal bases. Besides fast re-opening the Basilica to the public, the intervention allowed retrieving, with archaeological methods, all the fragments from its interiors, thus also enabling to fully recompose the decorations in the choir of the organ (a valuable high-age piece made of carved and gilded wood) and the related sound-amplifying apparatus.
The most complex interventions were subject to continuous instrumental monitoring by several Italian and international Universities: IUAV in Venice, Faculty of Engineering – University of L'Aquila, Building and Transport Department – University of Padua, Faculty of Engineering - Politecnico di Torino, the Tokyo Japan Society for the Promotion of Science Tokio, the Istituto Superiore di Conservazione e Restauro of the Italian Ministry of Cultural Heritage.
The principal danger for L'Aquila and, mostly, its historical centre, is that the very long-term reconstruction – due to

FIGURE 11 Securing historical palaces in the historical centre of L'Aquila, following the 2009 earthquake
Source: Author's personal archive

FIGURE 12 Securing historical palaces in the historical centre of L'Aquila, following the 2009 earthquake
Source: Author's personal archive

many complex problems and above all the "physically" impossible setting-up and management of hundreds of site yards in a few hectares area – might make the population lose their motivation, determination and interest in making their city rise again, a city surely made of dwellings, churches and monuments, but mostly of a widespread sociality without which other essential realities and activities are impossible. Securing interventions were made in the attempt to avoid such a risk, and some streets and areas symbol of the town were re-opened as sooner as possible, so that all citizens could keep their link with what will be possibly restored strong and alive. In this sense, securing the old Convent of Sant'Agostino – the headquarters of the Prefecture Office – so criticized in terms of opportunities, is a kind of intervention propaedeutical to a restoration capable of integrating the surviving parts into a great project of re-use and completion well integrated in the urban texture of the city. The careful work of conservation and restoration of all that has not been completely destroyed by the earthquake will allow, starting from the existing elements, to reconstruct L'Aquila in complete accordance with its soul and its millenary past, learning from the earthquake event the lesson to make the city, its historical centre and the entire territory safer, more welcoming and functional, being aware of the Nature's dangers and the possibility to face and overcome them.

Notes

1. Special Fire Department squads.
2. GNDT is the acronym for Gruppo Nazionale Difesa dai Terremoti (the Italian National Group for Earthquake Protection).
3. The Public Records Office.

Art and Science: Parallel Yet Converging Realities. The Importance of Technology in the Preservation of Art

There is prevalent preconception of a strong dichotomy between Science and Art. But if we take a closer look, there is no reason why this duality should exist. Actually, there has always been an interdependent relationship between Art and Science, but as of today, this tie has changed, because a part of what is commonly called science is in reality a technological application. Indeed, contemporary culture is not a culture of "ars" and of "scientia" (separate worlds), but rather a "techno-culture", a hybrid in which diversity does not prevail over identity. But there is an area in which the convergence of these two apparently opposite worlds occurs, and this is the preservation and restoration of works of art. And this is where 'techno-culture' as well comes to the rescue of Art; in fact, positive results have been attained thanks to the collaboration between experts in physics, geologists, IT specialists, art historians, biologists, chemists, archaeologists, and restorers drawn together by the mutual intent to understand, safeguard, and conserve significant testimony of our Civilisation

Giovanna Bandini

What is the relationship between Art and Science? Can it be hypothesized that we are dealing with two opposite entities: the intuitivism of art – a product of human irrationality – on the one hand, and the positive structure confirmed by scientific knowledge on the other? Yet, is it actually correct to judge a work of art as a product of human irrationality, the result of impulsive emotionality, lacking in rules and canons? Whilst would science (scientia) – as its opposite – be the result of an unerring rationalism, the sum of widely verified procedures, the search for a univocal, certain, and indisputable truth?

There is a common preconception of a profound diarchy between Science and Art. Many believe Art to be nobler, just as many others think that science is something characterized by 'hybris', by a sort of superb tendency to abuse its power over other realms of knowledge. But if we look more closely, this is not the case: in science there are profound values that are important for all of society. The fundamental instrument of science is, in fact, the scientific method, which drives mechanisms of verification and confutation unique to our culture. It is an artificial method, constructed by

Giovanna Bandini
Restorer-Coordinator, Head of Restauro I Dept.
Soprintendenza Speciale per i Beni Archeologici di Roma

man but effective precisely because it eliminates many of the dogmatic components that may flaw our way of reasoning. Science convinces us to accept a lifetime method comprising a fundamental intellectual honesty, to accept the fact that what happens in the world can always prove our hypotheses to be wrong, or urge us into taking steps forward in order to learn from our mistakes. Fakes are rampant, and in no other field are truths – with a lower-case t – discovered and even confuted so quickly as in science. Moreover, the vision of science as something algid, boastfully exact and enlightening, has contributed to distancing two cultural sectors, and worse, to confining science to a sort of ghetto, reducing it to an "ugly subject", or even a mere utilitarian instrument.
But it can also be said that art, like science, must construct both a visible and an invisible at-las, because according to Francis Bacon, there is a need for "...a realism that is the result of true invention, of a truly new way of capturing reality in something arbitrary."
Thus, having arrived so far, art clashes with reality in exactly the same way science does. And Art and Science discover almost contemporaneously that this specific reality is much more elusive and complicated than it had ever been imagined before. Indeed, as is well known, the Greeks always paid the utmost attention to attaining aesthetics, attempting to find a supreme degree of harmony and formal perfection in every form of artistic expression. The main characteristics that distinguished their production from that of other ancient civilizations were their relentless attention and fidelity to realism. Indeed in sculpture, this translated into a detailed observation of the human anatomy; in painting instead it was expressed in their striving to represent a perspective of space and a conveyance of volumes, whereas in architecture, the close correspondence between form and function was the direct consequence of a rational ap-proach to their comprehension and knowledge of the world.
In turn, the creation of a work of art in the XV and XVI centuries was a complex and articulate expression of science and artistic skill, where the choice of objects, measurements, proportions, and perspective were carefully calculated according to precise "canons", with the rules established by the artist and/or the discipline itself. Truthfully, this portrayal of the existing antinomic relationship between Art and Science is inexact, above all if one glances toward the past (for example, during the Italian Renaissance, Leon Battista Alberti, Piero della Francesca, Luca Pacioli, as well as Leonardo da Vinci, were not only artists, but also eminent scientists and mathematicians).
But the philosophical antinomies produced in comparing Art with Science are poorly suited to a contemporary comparison. Indeed, as was mentioned above, the relationship between Art and Science has always been quite close, but nowadays, this connection has also changed, in that a part of what is commonly called science is in reality a technological application. Indeed, contemporary culture is not a culture of "ars" and of "scientia" (separate worlds), but rather a "technoculture", a hybrid in which diversity does not prevail over identity. Furthermore, we can no longer dub it a so-called "western culture", given that today both Art and Science are universal values, recognized in every corner of the globe, objectives pursued in all nations and all cultures, characteristic of the global and simultaneous knowledge of the XXI century, conveyed and diffused by means of telematic networks. Therefore, these are not "opposite" factions, considered in a dialectical vision (a conception that today seems obsolete), but rather complementary and overlapping aspects of present and future civilizations, functions by now deeply-rooted in the social and universal being.
Moreover, there is an area where the convergence of these two apparently opposite entities occurs, and would be in the preservation and restoration of works of art. In fact, it is in the highly specific sector that activities and studies happen to converge, in the mutual intent to acquire 'knowledge'. Knowledge, intended as an 'unveiling' of the work of art, of the material from which it is made, of its ties with the environment that surrounded it then and does now, and what actions must be taken to thwart the inevitable decay of the tangible substances it is made of. Knowledge as a field where it is necessary to channel a wide variety of skills that - although they may start from different viewpoints, use distinct methodological circuits, and follow parallel paths – in the end pursue an objective that is one and

FIGURE 1 Decoration on the inside of the podanipter from the so-called Marbles of the Ascoli Satriano complex
Source: I Marmi dipinti di Ascoli Satriano, catalogue of the exhibition edited by A. Bottini, E. Setari, Milan 2009, p. 45

the same; in other words and more specifically, that of understanding the mechanisms that regulate the behavior of the material from which the work is made and the impact of the environment on it.

Hence one investigates the "flesh", the "life", and the "world" of a work of art, beginning with different viewpoints, but with the intention of knowing it intimately (to the point of perceiving its quasi spiritual essence) and moved by the desire to find systems aimed at contrasting aggressive and pathogenic factors; these, in fact – as occurs for man – can harm the artistic testimony to the point of bringing it to its final stage of "life", or "death" (of the matter itself).

But this research plan, targeted at attaining the knowledge necessary to pursue the common objectives of safeguarding works of art, requires a convergence of synergetic skills, that are also sustained by the latest in technological innovations. Hence, experts in various fields necessarily join their efforts: physicists, geologists, IT specialists, art historians, biologists, chemists, archaeologists, and restorers – all with the mutual intent to know, safeguard, and conserve significant testimony of art and culture.

It is this spirit that, over past decades, has been the driving force of a close and profitable collaboration between ENEA (the Italian National Agency for New Technologies, Energy and Sustainable Economic Development) and the Ministry of Cultural Resources and Activities. Such a collaboration has resulted in important works being studied, investigated, and analyzed by various specialists of two different bodies, with the intent of understanding them better in order to safeguard and preserve them for future generations.

This has given rise to the creation of 'task forces' that, regarding the Soprintendenza Archeologica di Roma, (now the Soprintendenza Speciale per i Beni Archeologici di Roma), have studied specific and significant works, like the bronze statues of the 'Boxer of Quirinal', and the so-called 'Hellenistic Prince', the marble 'Lancelotti Discobolus', the earthenware complex of Ariccia; the frescoes in the Colombarium of Villa Pamphilj, the obelisk in Piazza San Giovanni in Laterano, and more, confirming the need for these collaborations also through specialistic publications.

More recently, and precisely in the year 2009, the Soprintendenza Speciale per i Beni Archeologici di Roma – together with other bodies, including a fundamental contribution by ENEA – dealt with the study, research, and conservative intervention applied to the so-called marbles of Ascoli Satriano, a stunning complex of sculptures dating back to the IV century B.C.– bearing unusual and highly sophisticated polychrome decorations as well as gold leaf ornaments (the latter have been lost, but their undeniable traces still do exist).

The intense and worthwhile work of the team was conducted the day after their restitution – requested and obtained – from a foreign museum, which had illegally acquired these inestimable archaeological artifacts, as a fruit of clandestine excavations that took place in the Apulian territory (in the ancient Magna Graecia). This above-mentioned, extraordinary collection of marbles – some exceptionally painted and undoubtedly of Greek origins - enables us to understand how serious the loss of archaeological data caused by clandestine

FIGURE 2 The two ideograms, or morphemes, that explicate the word 'crisis'

excavations is; data that were recovered, albeit only minimally, through targeted studies, comparisons, and investigations, some of which were scientific-analytic.
Yet, beyond 'knowledge', 'research' – aimed at safeguarding, preserving, and restoring our enormous artistic heritage – is the new frontier, the most cogent objective that today has become a top priority in the world of Cultural Resources. Research must make use of experts – whether with a more 'humanistic' and/or 'scientific-technological preparation– who, beginning by the knowledge of the work intended as testimony of the past, as well as the material from which it is made, are capable of interpreting and discovering the inter-relationships among the results of the investigations conducted. This in function of the restoration and conservation of our cultural Heritage, even publishing both the results and the scientific principles underlying each field of expertise.
Research, therefore, considered as the fundamental moment at the base of every work; research that necessarily underlies any activity, especially those benefitting from the latest technological innovations; research that – precisely in these most recent years and due to the economic crisis that has swept over so many Countries, including Italy - has seen a notable decrease in the distribution of financing. Article 9 of the Italian Constitutions says: "The Republic promotes the development of culture and scientific and technical research". This dictate of our Constitution would oblige our government to make strategic and long-term choices in this sector, to invest in Research, Education, Universities, and Cultural Resources, to sustain the young people who decide to dedicate their own lives to Science, and especially the group that is at 'the service' of Art. Yet, it is common knowledge that Italy invests little and badly in research, in her huge cultural heritage and, consequently in her human capital, which is an inseparable condition. But what consequences will this have for Italy? If this trend is not successfully inverted in the long term and by looking toward the future, there is a risk of marginalization or, worse yet, the progressive loss of national sovereignty. Science, as has been seen, is above all knowledge, or 'unveiling' and if knowledge is developed and detained only by some countries, the inability to participate in this unveiling process, of bringing knowledge it-self into the light, inexorably compromises the active, conscious and aware presence of Italy, even in choices concerning the conservation of our immense historical-artistic heritage. So, to this view, what consequences is the permanence of this negative economic-financial situation now causing and eventually giving rise to in the world of research, activities, and studies di-rectly connected to Cultural Resources?
In the Chinese language, the word 'crisis' consists of two ideograms, or morphemes, which mean 'risk' and 'opportunity' (Fig. 2). Indeed, every crisis is at once risk and an opportunity for recovery, regeneration on different principles, on different assumptions. Therefore, hopefully a crisis – this crisis – can be turned into an opportunity for growth, favouring – for example and more specifically – those initiatives for study, conservation, restoration, and improvement aimed at the field of Cultural Resources. Such great opportunity must begin precisely by relaunching the research sector. Only in this way can there be a future for both Science and Art (… that Italy has so much of).

Seismic Preservation of the Cerreto di Spoleto Historical Centre

Earthquakes cause considerable damages to historical centres, so that a suitable prevention policy is necessary to guarantee their conservation. The first step is getting a complete knowledge of the area of interest and of the existing structures. In the selected areas, a detailed analysis to understand the characteristics of the seismic input through the analysis of seismic hazard and microzoning is needed, and so is the seismic performance of buildings by monitoring the seismic response. The paper presents some results of the study carried out on the site of Cerreto di Spoleto and on a complex building of its historical centre

Giovanni Bongiovanni, Giacomo Buffarini, Paolo Clemente, Guido Martini, Salvatore Martino, Antonella Paciello, Dario Rinaldis, Vladimiro Verrubbi, Alessandro Zini

Introduction

Both accelerometric records and damage data testify to the significant role of local response in the distribution of seismic effects. Indeed, given similar vulnerability conditions, differences up to 2 degrees in macroseismic intensity are observed in sites few kilometers far or even inside a single inhabited area. This spatial heterogeneity can be related to local conditions, which modify seismic motion. Quantifying and mapping this phenomenon is a fundamental tool for seismic risk mitigation.

The Cerreto di Spoleto town (Central Apennines, Italy) – composed of the historical centre, located at the top of a carbonate ridge, and the Borgo Cerreto district in the adjacent Nera River valley (Fig. 1) – was selected as a test-site for investigating the local seismic response. This test-site is characterized by some geological and geomorphological features, which predispose it to seismic wave amplification: the thick alluvial deposits filling the Nera River valley, the ridge-shape of the Cerreto di Spoleto hill, the significant variations in the jointing conditions of the outcropping limestones. The choice was also supported by the presence of a local accelerometric array, owned by ENEA, which has been in operation since the late 1980s, and by the urban fabric of the village, which hosts numerous valuable historical structures, such as the City Hall, the Theater Building and the CEDRAV building, all of which were instrumented.

Giovanni Bongiovanni, Giacomo Buffarini, Paolo Clemente, Antonella Paciello, Dario Rinaldis, Vladimiro Verrubbi
ENEA, Unità Tecnica Caratterizzazione, Prevenzione e Risanamento Ambientale

Guido Martini, Alessandro Zini
ENEA, Unità Tecnica Sviluppo di Applicazioni delle Radiazioni

Salvatore Martino
Università di Roma La Sapienza

Local Seismic Response: In Site Investigation and Seismometric Measurements

Test-Site and Seismometric Measurements

The Cerreto di Spoleto area has always been characterized by a local seismicity with frequent low/moderate-magnitude earthquakes, felt with macroseismic intensity (e.g., IX MCS, both the 1328 "Appennino Reatino" and the 1703 Norcia earthquakes) [1]. In recent years, an earthquake sequence characterized by a maximum magnitude Ml=5.8 began in September 1997 and induced an increase in the rate of occurrence of low-magnitude earthquakes that persisted for more than three years. The Cerreto di Spoleto ridge is a NE–SW-trending calcareous relief, with an elevation up to 650 m a.s.l. (Figs. 1, 2). The outcropping lithotypes belong to the Umbria-Marche Apennines succession and include limestones, marls and marly-limestones from upper Jurassic up to middle Miocene. In particular, the marly limestones of the Scaglia Rossa Formation (upper Cretaceous–middle Eocene) span the entire eastern portion of the ridge, where the Cerreto di Spoleto historical centre is located (Fig. 2).

A NE-SW oriented synclinal fold represents the main structural element of this portion of the ridge, which may be ascribed to an early compressive stage during the upper Miocene–lower Pliocene. The outcropping strata show an about N315 dip southward the synclinal axis and an about N135 dip northward the synclinal axis. Strike slip and normal faults dislodged this fold in a subsequent tectonic stage, which started in the upper Pliocene [2]. More in particular, two main fault systems were identified: the first, transtensional, with an approximately NS direction; the second, extensional, with an about N330 direction.

Close to the Borgo Cerreto district, the Nera River alluvial valley is characterized by a width varying from 210 to 350 m along a distance of about 1 km. The valley is primarily filled with coarse to sandy–silty alluvial deposits, while its edges are characterized by slope debris that laterally pass to the alluvial deposits. The geological substratum of the valley is composed of limestone and marly limestone, ascribable to the Umbria-Marche succession; these deposits are intensely folded and faulted. In particular, close to Borgo Cerreto the Nera River valley hosts a main thrust associated with E-verging folds and north–south trending thrust faults linked by southwest–northeast trending right strike-slip faults [3]. The geological setting of the bedrock of the Nera River valley close to Borgo Cerreto district is characterized by northwest dipping strata up to 50° in the western edge of the valley and up to 30° in the eastern edge. In the southern portion of the valley, the bedrock is set as an asymmetric anticline with axis north–south oriented, which may be ascribed to an early compressive stage during upper Miocene–lower Pliocene. In the considered area, the geographical orientation of the Nera River valley is controlled by a north–south oriented main fault, which is also responsible for a lowering of the Meso-Cenozoic Umbria-Marche pelagic succession outcropping all along the western side of the alluvial valley. This fault is part of a strike-slip and normal-fault system that dislodged the preexisting folds in an upper Pliocene tectonic stage [2]. On the basis of some collected borehole data, the alluvial deposits that fill the valley result very heterogeneous, since they consist of silty–sandy clays and sands with interlayered coarse-gained levels and travertine deposits (mainly composed of concretionary silty sands). The maximum thickness of the alluvial deposits is 55 m. The shape of the Nera River valley, in correspondence of the Borgo Cerreto district, is characterized by a constant depth and a variable width from north to south, inducing a significant variation in its depth/half width (H/D) shape ratio [4]. Moreover, the remarkable heterogeneity of the alluvial deposits induces high lateral contrasts of impedance and can strongly modify the local seismic response.

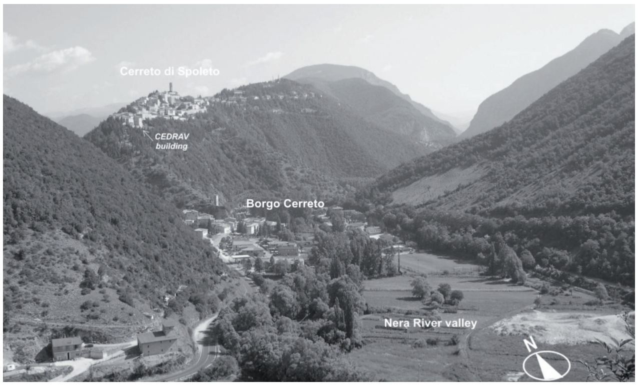


FIGURE 1 Panoramic view of the Nera River valley, close to the Cerreto di Spoleto ridge
Source: ENEA and Sapienza University of Rome

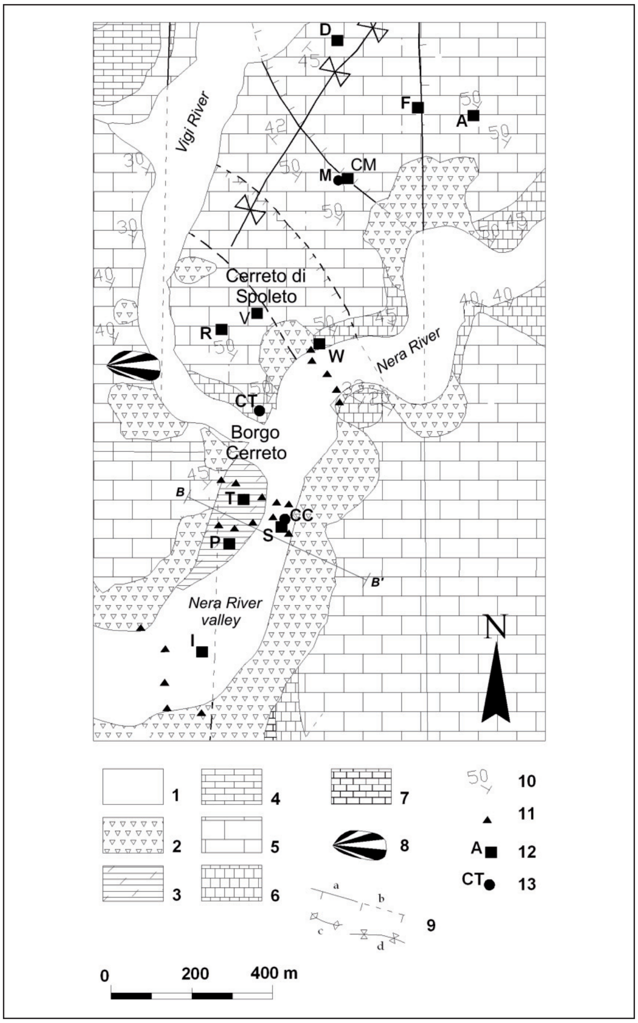


FIGURE 2 Geological map of the Cerreto di Spoleto area: 1) alluvial deposits; 2) slope debris; 3) travertine deposits; 4) Scaglia Variegata Formation (middle-upper Eocene); 5) Scaglia Rossa Formation (upper Cretaceous – middle Eocene); 6) Scaglia Bianca Formation (lower Cretaceous – middle Cretaceous); 7) Marne a Fucoidi Formation (lower Cretaceous); 8) alluvial fan; 9) certain fault (a), uncertain fault (b), anticlinal axis (c), synclinal axis (d); 10) attitude of beds; 11) noise measurements; 12) velocimetric temporary ENEA stations; 13) accelometric permanent ENEA stations
Source: ENEA and Sapienza University of Rome

In autumn 2001, a temporary velocimetric array was installed both on the ridge and in the alluvial plain. The stations (Fig. 2) were instrumented with data acquisition units (K2 KINEMETRICS), triaxially arranged short-period seismometers (SS1 KINEMETRICS) and GPS for absolute timing. A reference station (R), representative of the local outcropping bedrock, was installed at the bottom of the ridge, far from tectonic elements. The array operated for about two weeks in STA/LTA acquisition mode. Owing to the high seismic activity of the area, probably still related to the 1997 seismic sequence, about 40 small-magnitude earthquakes were recorded on the whole. Moreover, three ambient noise surveys were carried out in the Nera River alluvial valley (Fig. 2); recordings were obtained in each site by three triaxially arranged short-period seismometers, connected to a K2 data acquisition unit, and by a TROMINO recording device.

Results for the Ridge

The recorded ambient noise was sampled with a 40 s moving time window and FFT transformed to the frequency domain in order to get, for each station, the average spectra of the 3 components (NS, UP, WE) and the average Horizontal to Vertical Spectral Ratio (HVSR). The only significant effect was observed at station M, where the average HVSR points out a clear amplification band on the NS component, in the 6-8 Hz frequency range.
The recorded seismic events were analyzed in both time and frequency domains. The individual wave forms were examined in order to identify possible recurrent characteristics in the different stations. Also in this case the only significant effect was observed at station M (Fig. 3a), where most of the records show a clear wave train after the arrival of S waves, corresponding to an about 6 Hz frequency. The shape of the time-histories is typical of trapped waves [5, 6] and the delay between the disperse phase and the direct P-wave points out a deep trapping channel [7]. Subsequently, all the earthquake records were FFT transformed to the frequency domain and smoothed by a running average Hanning window. From the resulting spectral amplitudes, average spectral ratios referred to the reference station were computed for each station. Additionally, the azimuthal distribution of energy [8] on the horizontal plane was analyzed using a 10°step, both on complete and filtered signals. In

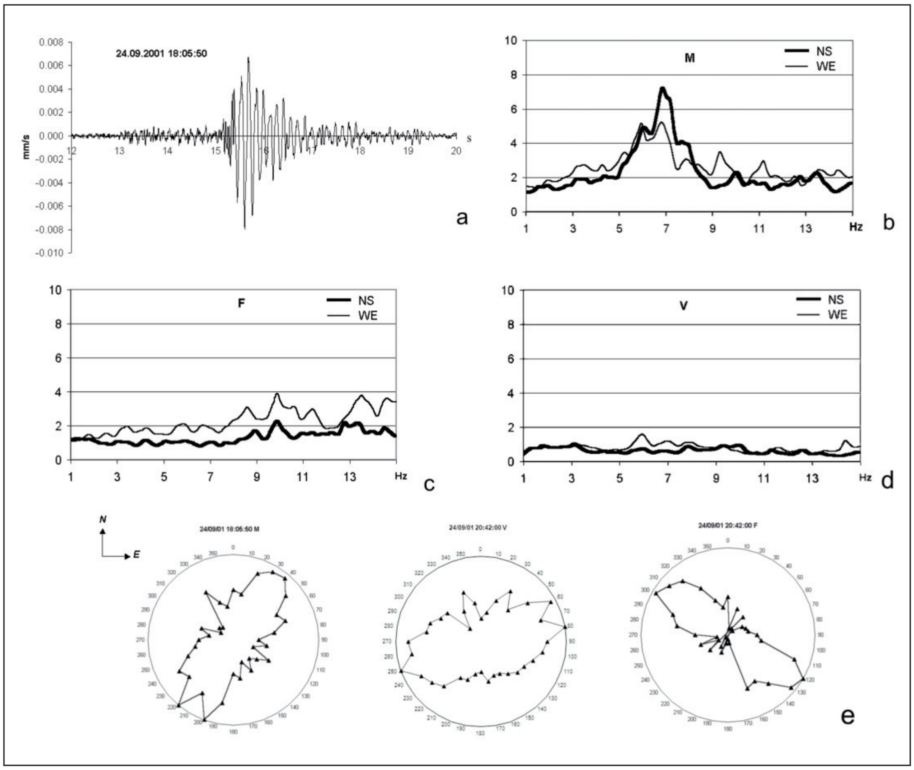


FIGURE 3 a) Example of velocimetric record obtained at station M; b) Average SSR recorded by the velocimetric array at station M; c) Average SSR recorded by the velocimetric array at station F; d) Average SSR recorded by the velocimetric array at station V; e) Examples of azimuthal distribution of energy obtained at stations M, V and F (see Fig. 2 for location) on total signals
Source: ENEA and Sapienza University of Rome

line with the results obtained from ambient noise data and time history analysis, the spectral ratios at station M exhibit a clear peak in the 6-7 Hz frequency range, significantly higher on the NS component (Fig. 3b). The azimuthal distribution of energy at station M, computed on the signals filtered in the 6-7 Hz range, points out a N20°-40°E direction for 8 out of 14 events (Fig. 3e, left). The amplification at station M can be associated with a wave train arriving after the direct S wave, with an apparent dispersive character. In general, both these features are indicative of fault-trapped waves. However, differently from the findings obtained in other studies on trapped waves [7, 9], the main direction of ground motion amplitude at station M is not parallel to the fault strike, which is about NW-SE oriented in proximity of the station.

Stations A and F show an energy distribution (Fig. 3e, right) roughly perpendicular to the direction of the ridge (NE-SW); in line with the reports by Chavez-Garcia et al. [10], and considering that these two stations are located near the top of the relief, the above findings can be ascribed to a topographic effect. The same effect is not observed at station V (Fig. 3e, middle), which is indeed located far from the top, along the western slope of the hill. Stations F, M, V are located in fault zones (Fig. 2), though neither amplification nor evidence of trapped waves are observed at stations F (Fig. 3c) and V (Fig. 3d). Since the stations are on the same outcropping geological formation and this formation is characterized by significant jointing, the assessment of rock mass condition was considered as a further feature to be taken into account. Hence, geomechanical surveys were carried out. The map of rock mass classes (Fig. 4) thus obtained shows that the contact between intensely jointed rock masses astride fault zones and moderately jointed rock masses does not appear all along the tectonic elements. In particular, station M is located on one of these contacts, whereas at stations F and V the fault zones are surrounded by a low-velocity,

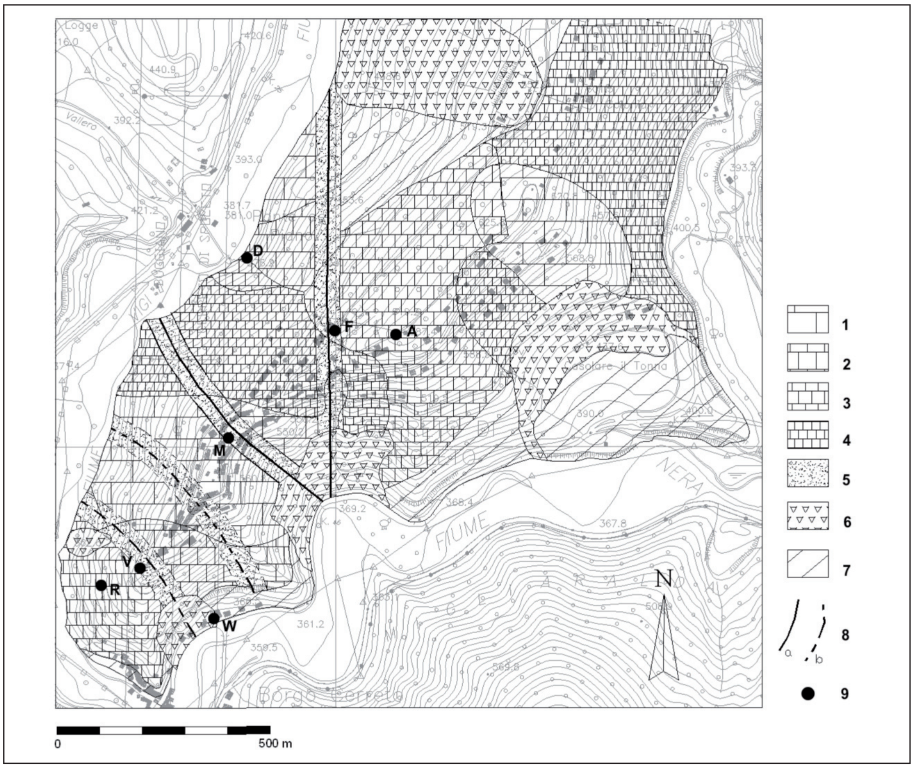


FIGURE 4 Map of rock mass classes: 1) moderately jointed rock mass (Class A); 2) highly jointed rock mass (Class B); 3) intensely jointed rock mass (Class C); 4) very intensely jointed rock mass (Class D); 5) rock mass from intensely jointed to mylonitic, lying astride each fault (Class E); 6) slope and landslide debris; 7) not classified rock mass; 8) certain (a) and uncertain (b) fault; 9) velocimetric station

Source: ENEA and Sapienza University of Rome

intensely jointed, rock mass. The high velocity contrast between the fault zone and the surrounding rock mass at station M could be assumed as responsible for the observed trapped mode and the related amplification effect, while at stations F and V the low impedance contrast at shallow depth (< 1 km) does not allow the trapped mode eventually originated at greater depth to be observed and, above all, does not induce ground motion amplification. It is worth noting that the velocimetric array was deployed in order to highlight possible topographic amplification effects along the ridge; the findings however, at least with the low energy level of the recorded ground motion, do not point out any topographic amplification. As a matter of fact, the only station of the ridge, where amplification was observed (M), does not show the energy polarization orthogonal to the ridge axis, which could be expected [10] in relation to a topographic effect and is observed in the other stations (A, F) located at the top of the ridge [11].

Results for the Alluvial Valley

Bard & Bouchon [4] showed, via numerical modelling, how both geometries and physical parameters of soft soil and bedrock control the 2D seismic amplification effects within a valley-like system. Their results proved that the higher is the shape ratio H/D (with H=maximum depth of the alluvial deposits and D=half-width of the valley), the greater are the constructive interferences between S and P waves, which are scattered by the soft soil/bedrock interface [12], and the near surface waves, which are originated by reflections and scattering phenomena at the edges of the valley. This interaction is responsible for 2D amplification phenomena, characterized by a clear resonance frequency recordable all over the alluvial fill (generally well recognizable by the HVSR obtained from noise measurements as well as by the receiver functions obtained from the weak motion records), whose value depends on SH and SV waves. When the shape ratio H/D decreases for a given impedance contrast, the constructive interference still exists, leading to wave propagation being dominated by both 1D and laterally propagating surface wave effects (i.e., 1D+lateral wave amplification). This last condition was observed in the Nera River valley close to Borgo Cerreto; the recorded seismic response is indeed characterized by a more complex spectral evidence, where both 1D resonance peak and higher frequency peaks, due to the interaction of lateral waves, can be distinguished by the spectral ratios to the reference station – SSRs (Fig. 5). The performed 2D numerical modelling [13] demonstrated that the wave amplification is close to the fundamental frequency and is increased by the contribution of the surface waves propagating throughout the entire sediment fill. It proved, moreover, that the effects due to lateral waves are much more intense close to the valley edges and assume a symmetrical distribution within the valley, if homogeneous conditions of the alluvial deposits are modelled; on the other hand, this effect loses its symmetrical distribution if a heterogeneous alluvial fill is considered (Fig. 6).

Seismic Monitoring of a Complex Building in the Historical Centre

Buildings of historical centres are usually masonry construction, often characterized by materials with very low strength, very poor mortar, ineffective connections between orthogonal walls and between the walls and the floors. The analytical study and the numerical modelling of these structures are very hard. Therefore, especially if the attention is focused on the seismic behaviour, the experimental dynamic analysis becomes of great importance and is often the only way to investigate their actual behaviour. The dynamic response of a structure can be analysed in presence of both free and forced vibrations. It is worth reminding that the use of forced vibrations is not always possible for old structures. In fact, the construction could be damaged, especially if it is in bad conditions or already damaged [14, 15, 16, 17].
As previously reported, three buildings located in the Cerreto di Spoleto historical centre were object of an experimental dynamic study. A complete analysis, as described above, was carried out on the building of

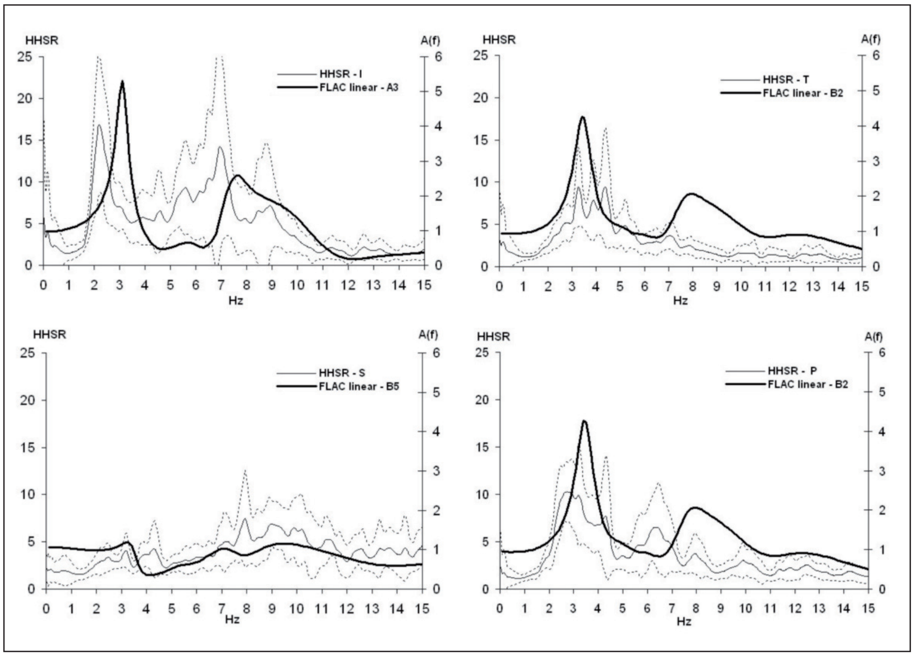


FIGURE 5 Comparison between SSRs ± standard deviation (dashed lines) from weak motions and 2D numerically modelled A(f), for the velocimetric stations I, T, S and P (see Fig.2 for location)
Source: ENEA and Sapienza University of Rome

the Centre for Anthropological Documentation and Research in Valnerina (CEDRAV).

The CEDRAV Building

The CEDRAV building, built as a monastery in the 14th century, presents a very irregular geometry both in plan and elevation (Fig. 7). The foundations are not at the same level and the first level is partially embedded into the ground and is mostly founded directly on the rock. Also the second level is partially founded on the rock, and for the N-W portion of the building the foundation is not known in detail. The main structure also includes S. James' Church. Three additional structures are connected to the main building: a small squared shape structure at the E side; a rectangular building at the N corner; another rectangular building at the W side, connected to the CEDRAV by means of a masonry arch. All these connections have a strong influence on the dynamic behaviour of the CEDRAV building. In particular, torsional modes with very low damping and possible coupling with principal modes of the buildings will be generated.

Experimental Analysis and Numerical Model

The structure was damaged by the Umbro-Marchigiano earthquakes of September 26th and October 14th, 1997. Most of the cracks were opened by the event of October 14th, because the epicentre was closest to the site and the structure had already been damaged by the previous shocks. Following these two earthquakes, the structure was first instrumented using temporary arrays in order to characterize its dynamic properties. Then a permanent accelerometer network was installed, using 36 channels. The permanent deployment recorded several seismic events in about one year [18].
Spectral analysis allowed to point out the following considerations: the building behaves like a very complex and rigid system; translational and torsional frequencies are close to one another; mode coupling occurs; damping percentage is low. Coupling of the frequencies and low damping caused beating effect even under low level shaking. The results obtained from the permanent array were very similar to those from velocimetric network. As a matter of fact, seismic

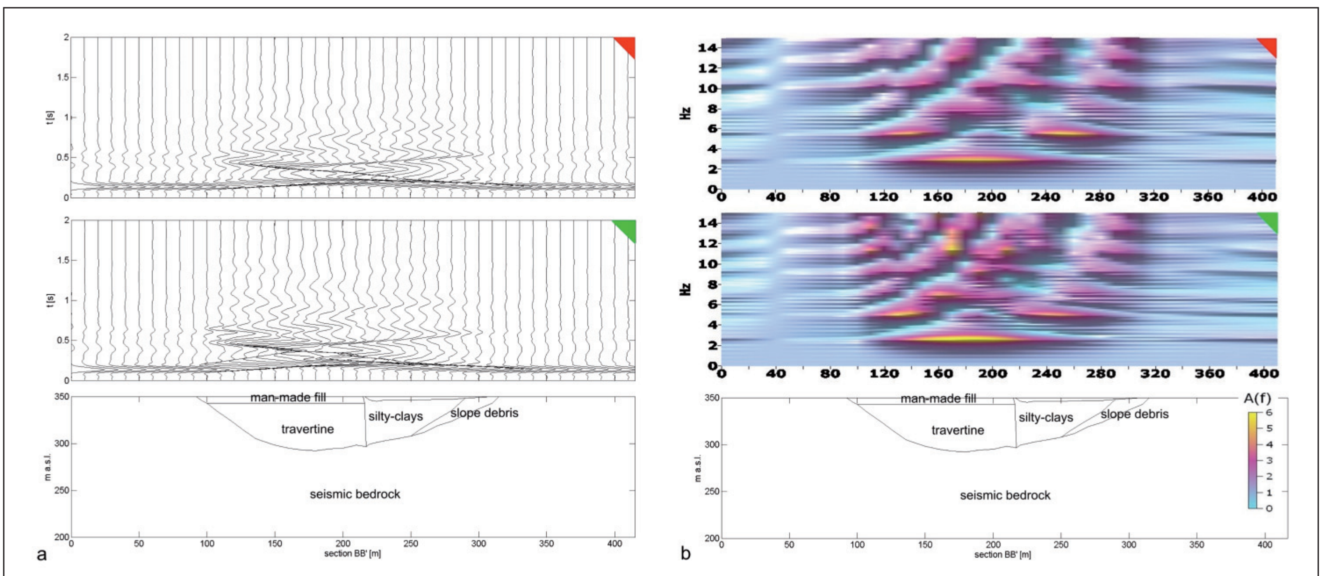


FIGURE 6 S_wave propagation (a) and A(f) function (b) resulting by the 2D numerical modelling along section BB' of Fig.2, for both homogeneous (red right corner) and heterogeneous (green right corner) conditions
Source: ENEA and Sapienza University of Rome

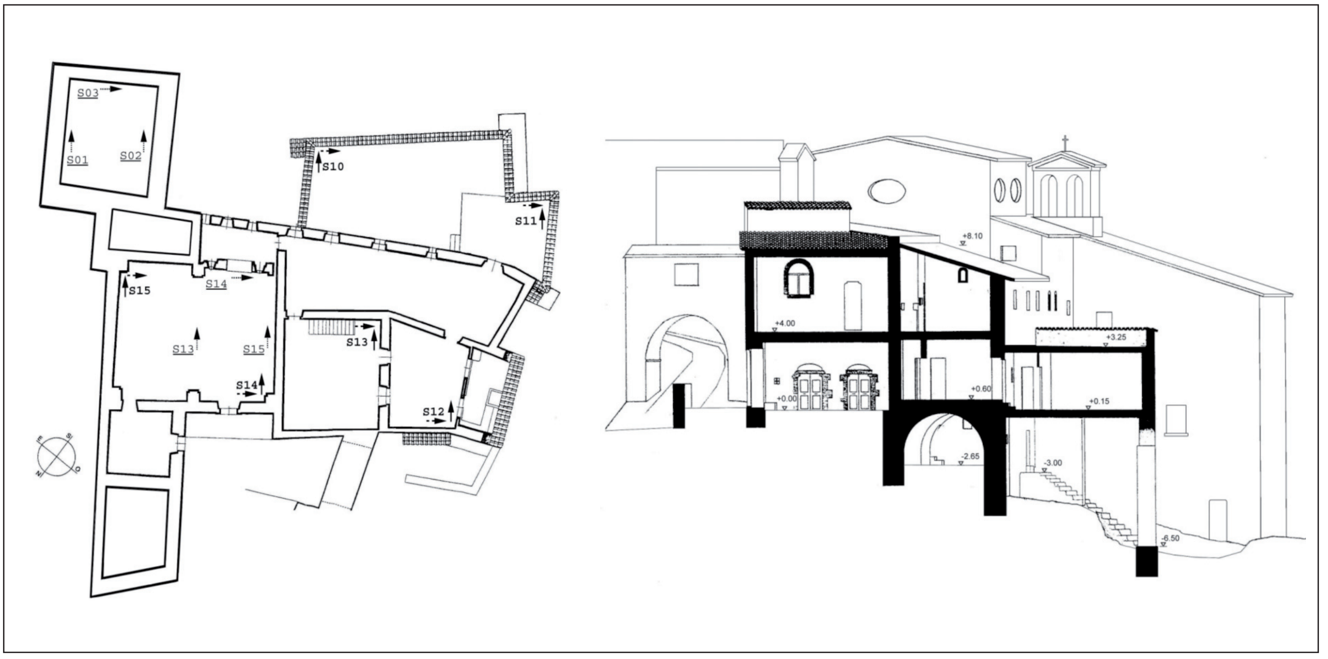


FIGURE 7 Plan and vertical section
Source: ENEA

events of almost the same intensity levels were recorded with the temporary array.

The experimental results were compared with those obtained from the finite element analysis. Due to the low energy level of the recorded events, a linear model was used, which included also the adjacent structures in order to reproduce the complex behaviour raised from the onsite measurements [19]. Walls, floors and vaults were modelled using 4-node shell elements, having both membrane and bending behaviour. The final model contained about 5100 elements and 4900 nodes, and then 27000 degrees of freedom. The structure was supposed to be constituted by a unique homogeneous and isotropic material. The Young's modulus was chosen, so that the first numerical frequency matches the first experimental frequency. In this way, we obtained a quite good correspondence between most of the numerical and experimental frequencies.

As reported in Table 1, very close frequencies were found, due to the structural complexity. The experimental data showed this behaviour too. In fact, many substructures behaved also as separated structures, but being linked they mutually influence each other.

Conclusions

The Cerreto di Spoleto ridge case-study pointed out that rock sites can show seismic amplification effects other than the topographic one. In particular, the seismic response in a rock mass ridge can be affected by rock mass jointing: adjacent rock masses with significantly different jointing and specific geometries can be regarded as responsible for trapped wave

Mode	1	2	3	4	5	6	7	8	9	10
Freq. (Hz)	6.35	7.01	7.17	7.61	7.98	8.55	9.26	9.27	9.69	9.71

TABLE 1 Numerical frequencies
Source: ENEA and Sapienza University of Rome

amplification. On the other hand, the results obtained in correspondence to the Nera River alluvial valley close to Borgo Cerreto highlighted the main role of the combined effect due to the heterogeneity of the alluvia and to the shape of the valley bedrock in causing amplification effects. The experimental analysis of the building pointed out that its structural behaviour is typical of historical constructions in which several changes, repairs and additions have been made over the centuries and allowed to analyze some aspect of the structural behaviour, such as the presence of resonance frequencies in small intervals, and the dynamic coupling between two frequencies very close to one another.

References

[1] DBMI11 (2011). Database macrosismico Italiano. http://emidius.mi.ingv.it/DBMI11/

[2] Centamore E., Fumanti F. and Nisio S. (2002). *The Central Northern Apennines geological evolution from Triassic to Neogene time.* Boll. Soc. Geol. It., Special volume 1, 181-197.

[3] Barchi M., La Vecchia G., Galandini F., Messina P., Michetti A. M., Peruzza L., Pizzi A., Tondi E. and Vittori E. (2000). *Sintesi delle conoscenze sulle faglie attive in Italia centrale: parametrizzazione ai fini della caratterizzazione della pericolosità sismica.* CNR-GNDT, Volume congiunto dei Progetti 5.1.2, 5.1.1, Esegrafica Roma.

[4] Bard P.Y., Bouchon M. (1985). *The two-dimensional resonance of sediment-filled valleys.* Bull. Seism. Soc. Am., 75, 519-541.

[5] Rovelli A., Caserta A., Marra F., Ruggiero V. (2002). *Can seismic waves be trapped inside an inactive fault zone? The case-study of Nocera Umbra, Central Italy.* Bull. Seism. Soc. Am., 92, 2217-2232.

[6] Peng Z., Ben-Zion Y., Michael A.J., Zhu L. (2003). *Quantitative analysis of seismic fault zone waves in the Landers, California, earthquake: evidence for a shallow trapping structure*, Geophys. J. Int., 155, 1021-1041.

[7] Li Y., Vidale J.E., Aki K., Ku F. (2000). *Depth-dependent structure of the Landers fault zone from trapped waves generated by aftershocks.* J. Geophys. Res. 105(B3), 6237-6254.

[8] Clemente P., Rinaldis D. and Bongiovanni G. (2000). *The 1997 Umbria-Marche earthquake: analysis of the records obtained at the ENEA array stations.* Proc. XII World Conference on Earthquake Engineering (Auckland, NZ), paper n. 1630.

[9] Cultrera G., Rovelli A., Mele G., Azzara R., Caserta A., Marra F. (2003). *Azimuth-dependent amplification of weak and strong ground motions within a fault zone (Nocera Umbra, Central Italy).* J. Geophys. Res., 108, B3, 2156-2170.

[10] Chavez-Garcia F.J., Rodriguez M., Field E.H. and Hatzfeld D. (1997). *Topographic site effects. A comparison of two non reference methods.* Bull. Soc. Seism. Am., 87, 1667-1673.

[11] Martino S., Minutolo A., Paciello A., Rovelli A., Scarascia Mugnozza G., Verrubbi V. (2006). *Seismic microzonation of jointed rock-mass ridges through a combined geomechanical and seismometric approach.* Natural Hazards, 39, 419-449.

[12] Amirbekian R.V., Bolt B.A. (1998). *Spectral comparison of vertical and horizontal seismic strong ground motions in alluvial basins,* Earthquake Spectra, 14, 573-595.

[13] Lenti L., Martino S., Paciello A., Scarascia Mugnozza G. (2009). *Evidences of two-dimensional amplification effects in an alluvial valley (Valnerina, Italy) from velocimetric records and numerical models.* Bulletin of Seismological Society of America, 99, 1612-1635.

[14] Clemente P., Bongiovanni G., Buffarini G., Rinaldis D. (2003). *Strategies for the seismic preservation of historical centres.* Proc., 7th International Symposium of the Organization of the World Heritage Cities (Rhodes, Sept. 23-26), OWHC, Quebec City, Canada.

[15] Clemente P., Rinaldis D. (2005). *"Design of temporary and permanent arrays to assess dynamic parameters in historical and monumental buildings".* In Ansari F. (ed), Sensing Issues in Civil Structural Health Monitoring (Proc., North American Euro-Pacific Workshop, CSHM (Honolulu, 10-13 Nov. 2004), Springer, 107-116, (invited paper).

[16] Clemente P., Buffarini G. (2009). *"Dynamic Response of Buildings of the Cultural Heritage".* In Boller C., Chang F.K., Fujino Y. (eds), Enciclopedia of Structural Health Monitoring, John Wiley & Sons Ltd, Chichester, UK, 2243-2252.

[17] De Stefano A., Clemente P. (2009). "Structural health monitoring of historic buildings". In Karbhari V.M. and Ansari F. (Eds) Structural Health Monitoring of Civil Infrastructure Systems, Woodhead Publishing Ltd.

[18] Rinaldis D., Celebi M., Buffarini G., Clemente P. (2004). *"Dynamic response and seismic vulnerability of a historical building in Italy".* Proc., 13th World Conference on Earthquake Engineering (Vancouver, 1-6 August), Paper No. 3211, IAEE & CAEE, Mira Digital Publishing, Saint Louis.

[19] Clemente P., Rinaldis D., Buffarini G. (2007). *"Experimental seismic analysis of a historical building".* Journal of Intelligent Material Systems and Structures, Vol. 18, No. 8, 777-784, SAGE Publications.

The Geomorphological Hazard of Machu Picchu Citadel and Aguas Calientes Village

A practical application to assess the natural risks which the Inca citadel of Machu Picchu and the Aguas Calientes village (Cusco, Perù) are subject to was carried out under the INTERFRASI and FORGEO projects. The area is prone to debris flows, low angle rock slides, high-angle rock slides and rock falls. The development of landslides in the bedrock is influenced by the orientation of the joint sets with respect to the topography, whereas those in the coverage essentially depend on the slope angle. The triggering mechanisms are to be found in seismic activity and intense precipitation. In the past, landslides have seriously damaged the archaeological and especially the civil structures, and in Aguas Calientes there have been many casualties. For this reason a procedure to understand the vulnerability and the risks for the anthropic exposed elements, both archaeological and civil, was adopted

Claudio Puglisi, Luca Falconi, Augusto Screpanti, Vladimiro Verrubbi, Guido Martini, Salvatore Paolini

Introduction

The historic sanctuary of Machu Picchu is one of the most important Inca archaeological sites of Peru and, since 1983, the area is included in the UNESCO World Heritage list. The Machu Picchu citadel (Fig. 1) and the other Inca remains attract about 2000 visitors daily, who find accommodation facilities in the village of Aguas Calientes (Fig. 2). The area is a strategic part of the Cusco touristic circuit and a key area for the entire Peruvian economy. Yet, at the same time, tourism causes a strong human impact on the environment and archaeological structures.

Luca Falconi, Claudio Puglisi, Augusto Screpanti, Vladimiro Verrubbi
ENEA, Unità Tecnica Caratterizzazione, Prevenzione e Risanamento Ambientale
Guido Martini, Salvatore Paolini
ENEA, Unità Tecnica Sviluppo di Applicazioni delle Radiazioni

Moreover, the area is subject to natural hazards such as landslides, earthquakes and floods, with a direct effect on the conservation of the archaeological sites, on the accommodation facilities, on road and railway infrastructures, and on the safety of workers, inhabitants and tourists as well. The hazard for the archaeological remains as well as for site residents and visitors was recognized by UNESCO that, in 2008, threatened to expel Machu Picchu from the list of the World Heritage Sites.
In addition, past studies (Sassa et al., 2002) hypothesized the presence of a deep-seated planar low angle rock slide, which would lead to a collapse of the ridge on which the citadel of Machu Picchu rises. This hypothesis raised great clamour from the scientific and political points of view, impacting the tourist flow. On these assumptions, a scientific analysis of the risks which the Machu Picchu historical sanctuary, the Machu Picchu

FIGURE 1 View of the Machu Picchu citadel from the Mount Machu Picchu. The shot shows also the Mount Wayna Picchu (in the background) and the Mount Putucusi (on the right) surrounded by the Urubamba river
Source: ENEA

citadel and Aguas Calientes are subject to was carried out under the Interfrasi (2001-2005) and Forgeo (2008-2009) ENEA projects.

Study Area

The Historic Sanctuary of Machu Picchu, 80 kilometers from Cusco, covers an area of 325,92 km^2 in the Vilcanota-Urubamba basin (Cusco Region) and is one of the protected areas of the National System of Protected Natural Areas. In the Sanctuary, besides the Machu Picchu citadel (2.430 m a.s.l.) several other archaeological sites and the Aguas Calientes village (2050 m a.s.l.), connected to the citadel of Machu Picchu by a road of about 10km, are present.

FIGURE 2 Aguas Calientes village: view from the Mount Putucusi
Source: ENEA

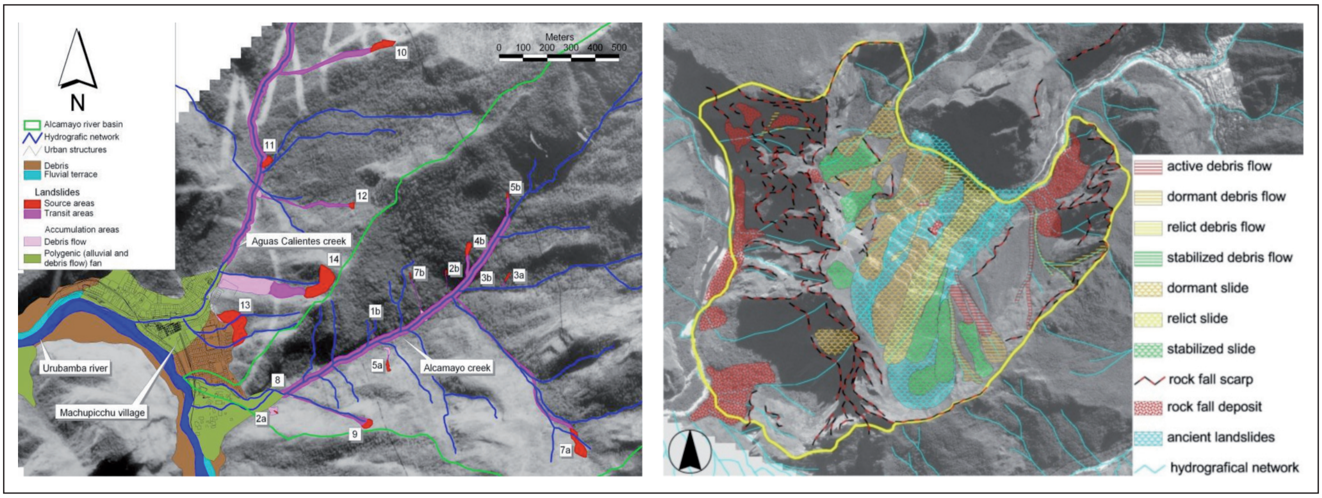


FIGURE 3 Landslides inventory in the areas of the Aguas Calientes village and the Machu Picchu citadel
Source: ENEA

The territory of the Historic Sanctuary of Machu Picchu belongs to the Eastern Cordillera, a WNW-ESE chain characterized by metamorphic and igneous rocks. The high Eastern Cordillera of Peru formed as a result of the inversion of a Late Permian-Triassic rift system. The Quaternary deposits are shaped as terraces and alluvial cones, deposited through mixed fluvial and slope processes, and also characterized by catastrophic dynamics as debris flows. Alluvial fans occur at the mouth of the tributary drainage (e.g., the fans of the Aguas Calientes creek and Aobamba river), and fluvial terraces mainly outcrop along the Vilcanota valley at different altitudes. The deepening of the river beds determines erosion processes at the foot of slopes, favoring landslide phenomena. Considerable talus bodies lie at the foot of the steeper rock slopes, which are mainly composed of heterometric sediments with granite boulders in a sandy-clay matrix. A thick (1-5 m) colluvium mantle resulting from bedrock alteration processes is distributed throughout the slopes.
Joints and failure surfaces are widespread structural features of the intrusive bodies (Mazzoli et al. 2005). The morphological features of the area, which is characterized by steep and high-energy slopes, are strictly linked to regional uplifting evolution.

Geomorphological Hazard Analysis

The Machu Picchu Sanctuary is regularly affected by several slope instability phenomena (Canuti et al. 2005; Carreño and Kalafatovich 2006; Vilimek et al. 2007; Carlotto et al. 2009; Puglisi et al. 2011): rock falls, high-angle rock slides, low angle rock slides and debris flows (Fig. 3). Kinematic conditions for landslide type and evolution are closely depending on structural and topographic factors. Besides the structural setting, rock falls and slides are highly dependent on the geomorphological evolution and anthropic activities and are mainly triggered by regional seismic activity. Instead, abundant local rainfall is the main triggering factor for debris flows due to the rapid saturation of the shallow portions of the soil layer.

Historical Analysis

In order to better characterize the geomorphological features, the historical analysis of landslides and floods was conducted. Technical and scientific publications containing information on damage produced by landslides and floods were analyzed. The chronology of floods and landslides that affected the area since 1950 was reconstructed: 12 floods and 13 landslides were identified and classified as the most significant. In particular, the towns of Aguas Calientes, Santa Teresa and Yanatile seemed to be the most prone to flooding with heavy damage and several victims (e.g., in 1998 and 2004). The most important landslides of the area occurred on December 26th, 1995, and January 1st, 1996, damaging the road that connects Aguas Calientes and the archaeological site. Landslides occurred in 2004 and 2010 affected the Aguas Calientes village causing casualties, damage and interrupting the railways Cuzco-Machu Picchu. None of the cited events affected directly the Machu Picchu archaeological site.

Susceptibility

The geomorphological hazard analysis was conducted with different approaches depending on the landslides, which the area is subject to (Puglisi et al. 2011):

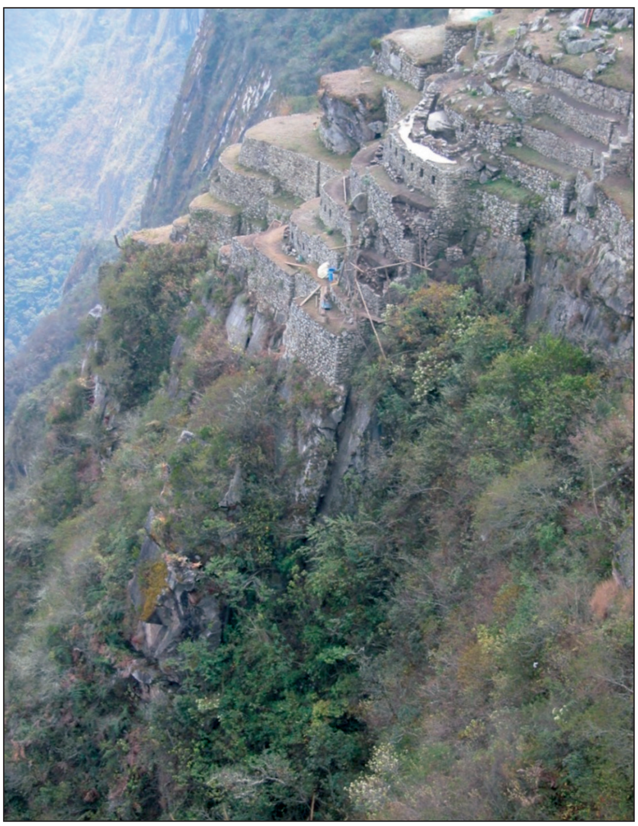


FIGURE 4 Open fractures in the SW flank below the Inca citadel
Source: ENEA

A) slow evolution in bedrock (low angle rock slides);
B) rapid evolution in bedrock (high-angle rock slides and rock falls)
C) rapid evolution in cover (debris flows).

The hazard evaluation of type A and B landslides was performed according to an approach based on the activities and on the speed evolution of the censused landslides.

Among the landslides of type A is included the deep mass movement that affects the citadel (Sassa et al., 2002). The characterization of this potential sliding surface (slope, orientation and nature) was carried out by aerial photo interpretation and field surveys. As result, the orientation of the surface does not seems to be conform to a slip such as that suggested by previous studies, because it dips in the direction NNE (30° E) and not towards the Urubamba Valley (E), situation that makes it incompatible with the rock mass sliding. Furthermore, it has been documented as the rocks overlying the potential sliding surface have an integrity that improves downwards, contrary to what would have been in the case of a slide. In fact, the energies involved in this potential movement, that would develop under a mass of granite over 50 m thick, would have to form a band of rock fragmentation close to the sliding surface. Instead, the rock in this band is almost unaltered. The results of a low environmental impact monitoring system (GPS, multitemporal laser scanner survey, ground based radar interferometry and satellite interferometric synthetic aperture radar) confirm field evidences and the lack of significant deep sliding processes.

Other landslides of type A are inside the citadel along the structural system with orientation 30° and slope 30°, but are currently inactive. Their activation can be dated before the citadel construction, being stabilized during the construction. Also the NE flank below the Inca citadel is affected by type A landslides, that develop prevalently along the 30°/30° and 30°/60° structural sets. The intersection of slope orientation with the structural system makes the slope evolution active with a retrogressive distribution of activities, with slow evolution. The entire SW side has an almost vertical slope and the pattern of joints is determined by the intersection between the 225°/65° and 130°/90° systems (Fig. 4). The frequent open fractures and the

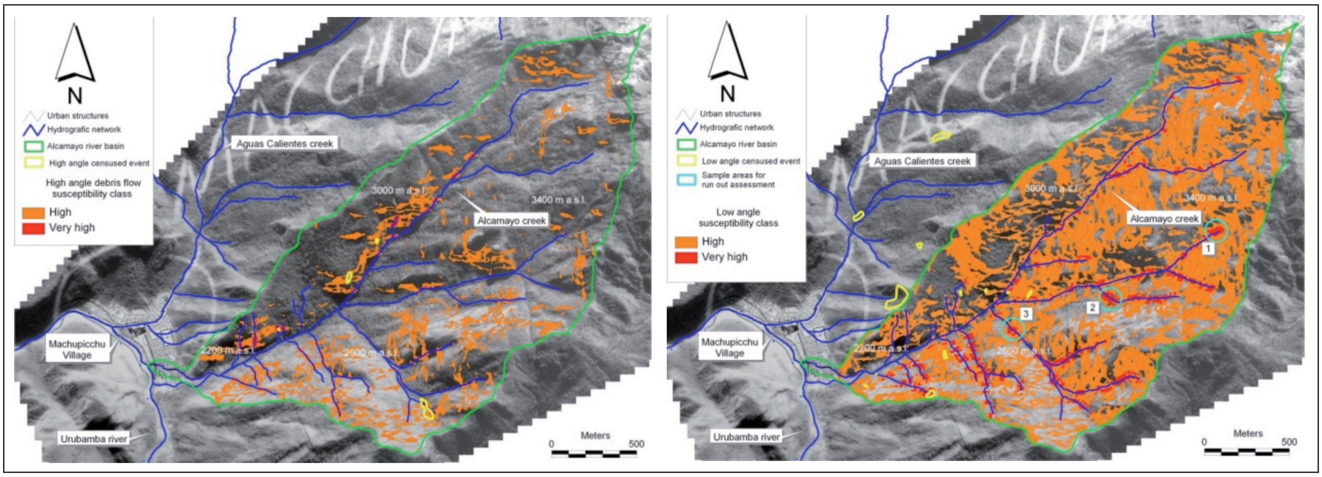


FIGURE 5 High angle (left) and low angle (right) debris flow hazard maps in the Alcamayo catchment above the Aguas Calientes village
Source: ENEA

current deformation of the archaeological structures (andenas) implies that type B landslides are active, and therefore the hazard related to this portion is high.
A different approach was used to evaluate the hazard relating to landslides of type C, because these have neo-formation character and because they are responsible for the damage and the casualties that occur almost every year in Aguas Calientes. A parametric approach was used to assess the debris flows hazard (Casagli et al., 2004; Abbattista et al., 2005; Leoni et al., 2009), and the base maps produced for the analysis are constituted by: a landslides inventory; a Digital Elevation Model with a 5 m grid.
Comparing the landslide inventory and DEM derived maps, slope and aspect classes of the areas affected by landslides in the past have been identified. Two general trends for the source areas have been identified: high angle phenomena occurring on the steeper slopes (50°-70°), where soil is moderately thick, and low angle phenomena with thicker soil bodies lying on smoother slopes (25°-55°). Debris flow hazard maps of both types have been produced for the Alcamayo catchment (Fig. 5).

Triggering Factors

The average annual rainfall, registered in the Machu Picchu citadel's meteorological station (2563 m a.s.l.) between 1999 and 2006 (Registro pluviometrico de la estación de Machupicchu, SENAMHI), reached 2038,70 mm, with a maximum of 333,31 mm in February and a minimum of 60,78 mm in August. According to the hydrological balance calculated for this area, 67% of the precipitation corresponds to superficial runoff and only 18% to infiltration (Carreño and Kalafatovich 2006). The comparison between average monthly rainfall occurred in the year range 1964-1977 and the monthly distribution of collected floods and landslides (Fig. 6) shows that floods and landslide events are strictly connected with the most humid period (November-April).
Rock falls and slides are mainly triggered by regional seismic activity. The seismological characterization of the Machu Picchu area was performed by analyzing the information contained in the Catalogue for the Seismic Andean Region and the associated database of local intensity, managed by CERESIS - Centro Regional de Sismología Para America del Sur. The distribution of epicenters and their relative intensities (Fig. 7) allowed the selection of earthquakes most significant for the Cuzco-Machu Picchu area, with epicentral intensity greater than the VI Modified Mercalli scale (MM). These events were critically reviewed on the basis of the available historical-documentary information,

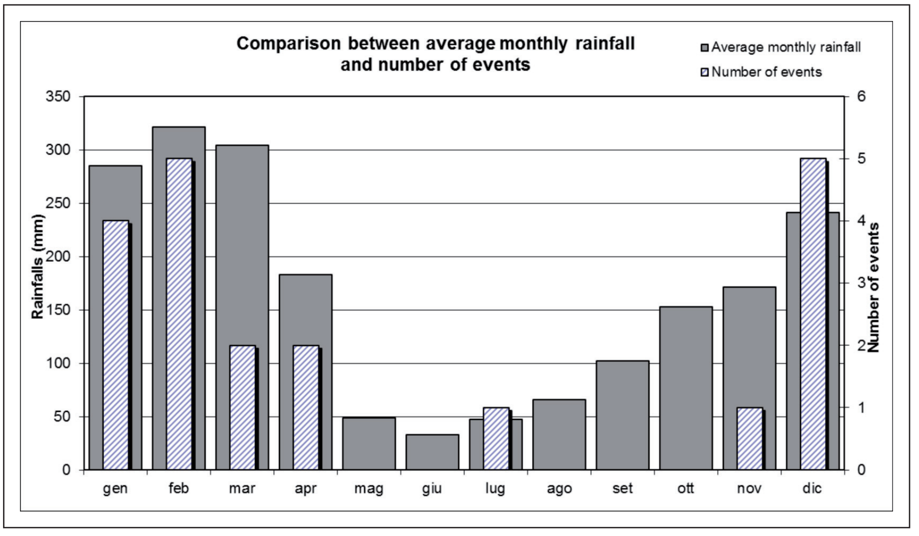


FIGURE 6 Comparison between average monthly rainfall (mm) and the monthly distribution of collected events
Source: ENEA

in order to verify the reliability of seismical and macroseismical parameters.

Exposure and Vulnerability Maps

The analysis of exposure and vulnerability of the remains present in the citadel was carried out by classifying each single Incaic structure (Delmonaco, 2009). 180 different elements at risk have been analyzed, inventoried and stored in a GIS and represented graphically. For each element at risk an Index of Exposure (IE) has been assessed, taking into account two main indicators: an historical/cultural index and an economical/tourist index. For each element at risk an Index of Static Structural Conditions (IS) has been assessed, based on a survey of the specific static-structural conditions and the damage of the structures exposed to landslide risk. Finally, the Vulnerability index (IV) of the area, in terms of capacity resistance, is the combination of the Index of Exposure (IE) with the Static Structural Conditions (IS).
Similarly, elements existing in the inhabited area of the Aguas Calientes village were classified and an exposure map including the location of the elements at risk and the attribution of a relative value index was developed for the Aguas Calientes village.

Risk

GIS overlay of the hazard and vulnerability maps allows to attribute a qualitative level of risk to the study areas. Since there is no evidence about deep active landslides in the citadel area, the geomorphological risk level deriving from the collapse of the whole ridge seems to be very low. Nevertheless, shallow phenomena in the SW flank of the citadel and on the ridge may damage andenas and, for retrogressive evolution, the monumental area, raising the risk level locally. Along the NE slope, the risk level is high for the potential activation of debris flows that may damage the road between Aguas Calientes and the citadel and jeopardize the tourist buses, just as it happened lately.
In the village of Aguas Calientes, buildings located in the morphological depression near the railroad station are in the higher risk areas (Puglisi et al. 2011; Fig. 8). Another important risk for the lower part of the village involves constructions on the banks, very close to the river water level. This scenario raises the damaging potential of the Vilcanota river floods. If a debris flow, originating from one of the tributaries, dams the river downstream of the village, the Vilcanota water level could increase and flood Aguas Calientes. Material accumulated by previous debris flows on the

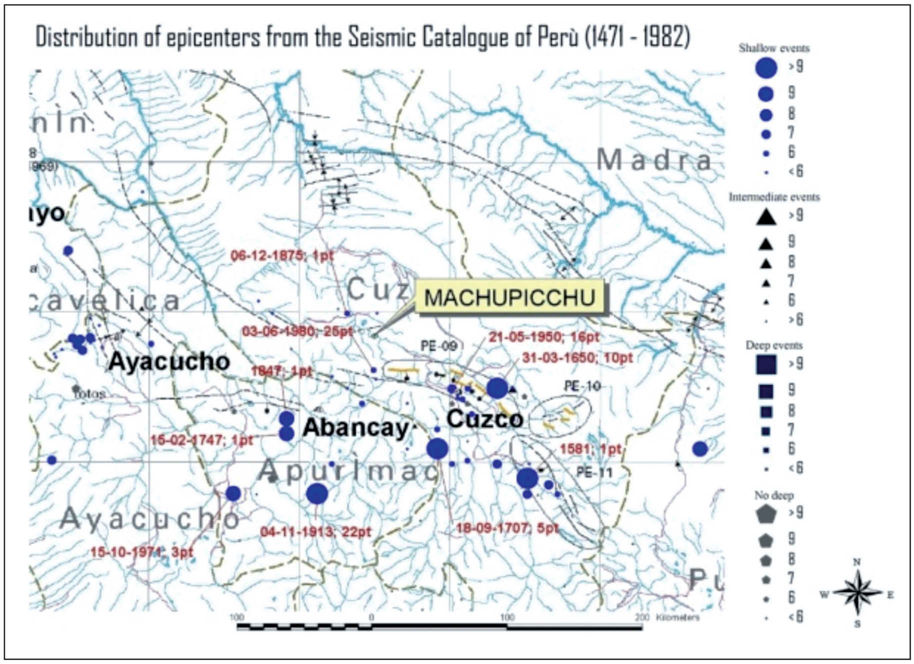


FIGURE 7 Earthquakes occurred in the Cuzco area graduated by focal deep; for the most important events, the date (day–month–year) and the number of points in the macroseismic field (local intensities) are reported
Source: ENEA

river bed could elevate the Vilcanota river bed level and would facilitate the overrunning processes. The damming of the river upstream of the village would be even more damaging. Reopening a complete or partial dam would lead to a dramatic increase in the damage potential.

Conclusions

The ENEA studies in the Machu Picchu Sanctuary exclude any activation of the deep sliding surface above the Machu Picchu citadel, indicated by previous studies as a possible surface of a planar landslide, since morphological and instrumental analysis have detected no actual sign of movement. The surface lesions found on archaeological buildings are due to local tilting caused by the inhomogeneity of the bedrock on which they are founded, formed by loose granite, juxtaposed blocks. Being subject to sudden falls, the SW slope of the citadel shows a higher risk level. Similar level of risk is attributable to the road accessing the citadel, frequently interrupted by small debris flows.

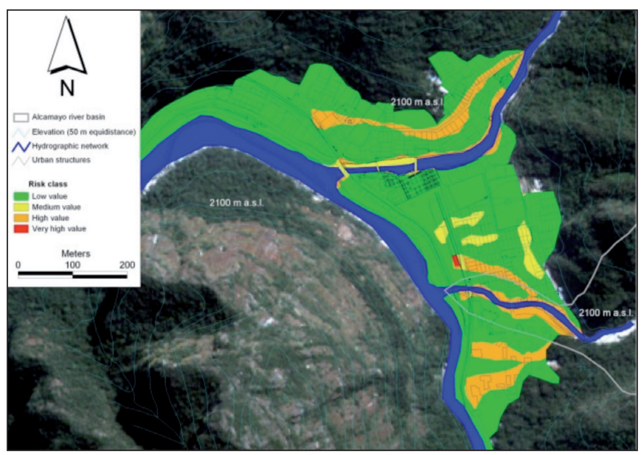


FIGURE 8 Debris flow risk map in the Aguas Calientes village
Source: ENEA

Much more serious is the risk in the Aguas Calientes village, where the periodic occurrence of debris flows in the upstream basins causes annual damage to anthropic structures and consequent casualties, also seriously compromising the usability of the archeological site.

These critical conditions have been further worsened by the rapid urban development over the last few decades. The depressed zones of the fan present an elevated residual risk level and the railway station is characterized by the highest risk of debris flow. At present, aside from proper territorial planning and the restriction of new settlements, a program that includes real-time monitoring and effective alert and evacuation tools seems to be necessary. The results of both projects have been useful to administrative authorities involved in natural risk management in the Machu Picchu area.

References

[1] Abbattista F, D'Agostino G, Delmonaco G, Di Filippo L, Falconi L, Leoni G, Margottini C, Puglisi C, Romano P, Spizzichino D (2005). *La valutazione della suscettibilità da frana: applicazione alle colate rapide di Cervinara (AV).* Geologia tecnica & ambientale, n° 1/2005. ISSN 1722-0025.

[2] Canuti P, Margottini C, Mucho R, Casagli N, Delmonaco G, Ferretti A, Lollino G, Puglisi, C, Tarchi D (2005). *Preliminary remarks on monitoring, geomorphological evolution and slope stability of Inca citadel of Machu Picchu (C101-1).* Proceedings International Consortium on Landslides General Assembly, Washington DC, 39-47.

[3] Carlotto V, Cárdenas J, Fidel L (2009). *La geología, evolución geomorfológica y geodinámica externa de la ciudad inca de Machupicchu, Cusco-Perù.* Revista de la Asociación Geológica Argentina 65(4): 725-747 (2009).

[4] Carreño R & Kalafatovich S (2006). *The Alcamayo and Cedrobamba catastrophic debris flow (January, March and April 2004) in Machupicchu area-Perù.* Landslides, 3 (1), pp. 79-83.

[5] Casagli N, Catani F, Puglisi C, Delmonaco G, Ermini L, Margottini C (2004). *An Inventory-Based Approach to Landslide Susceptibility Assessment and its Application to the Virginio River Basin, Italy.* Environmental & Engineering Geoscience, X (3).

[6] Delmonaco G, Margottini C, Spizzichino D, Falconi L (2009). *Exposure and vulnerability of cultural heritage affected by Geomorphological Hazard: the Machu Picchu case study - Protection of Historical Buildings (PROHITECH 2009)* First International Conference Rome, June 21st - 24th 2009 pp 905-909.

[7] Leoni G, Barchiesi F, Catallo F, Dramis F, Fubelli G, Lucifora S, Mattei M, Pezzo G & Puglisi C (2009). *GIS methodology to assess landslide susceptibility: application to a river catchment of Central Italy.* Journal of Maps, v2009, 87-93. 10.4113/jom.2009.1041.

[8] Mazzoli S, Delmonaco G, Margottini C, (2005). *Role of precursor joints in the contractional deformation of the granite pluton, Machu Picchu batholith, Eastern Cordillera,* Peru. Rend. Soc. Geol. It., I(2005), Nuova Serie, 3 ff.

[9] Puglisi C, Falconi L, Lentini A, Leoni G, Ramirez Prada C (2011) - *Debris flow risk assessment in the Aguas Calientes village (Cusco, Perù).* The Second World Landslide Forum, 3-9 October 2011, FAO, Rome.

[10] Sassa K, Fukuoka H, Shuzui H, Hoshino M (2002) *Landslide risk evaluation in Machu Picchu World Heritage, Cusco, Peru.* In: Proceedings UNESCO/IGCP Symposium on Landslide Risk Mitigation and Protection of Cultural and Natural Heritage, Kyoto, pp 1-20.

[11] Vilímek V, Zvelebil j, Klimeš J, Patzelt Z, Astete F, Kachlík V, Hartvich F (2007). *Geomorphological research of large-scale slope instability at Machu Picchu, Peru.* Geomorphology 89, 241-257.

Safeguard of Historical and Cultural Values in the Teramo Area: From Hazard Integrated Analysis to Urban Vulnerability

An integrated analysis of spatial and satellite data has been applied on an area of the province of Teramo in Abruzzo region, Italy. Two case studies are presented: one on the gullies of Montefino, as an example of natural heritage at risk, whilst the second case concerns the municipality of Bisenti, as an example of historic centre at risk.
Geomatic methodologies have been used for a preliminary analysis of the study area. In fact, based on the cartographic data, hazard maps were overlaid to high-resolution satellite images, showing a high risk for cultural heritage. The integrated analysis is therefore proposed as a monitoring tool to safeguard the territory and the historical and natural heritage by providing knowledge of both their conservation status and relations

Elena Candigliota, Serena Castellani, Salvatore Cavaleri, Francesco Immordino

Introduction

In Italy there is no certain data on the historical, architectural and landscape heritage exposed to natural hazards. This systemic approach requires the study and assessment of the effects of some factors of degradation (hydrogeological, seismic, meteo-climate, etc.) on the state of conservation of cultural heritage, such as historic centres or landscape.
And not as single monument.

Elena Candigliota, Francesco Immordino
ENEA, Unità Tecnica Ingegneria Sismica
Serena Castellani
Università di Bologna, Student
Salvatore Cavaleri
Università di Ferrara, Student

To this end, a spatial approach is proposed using geomatic methodologies for the assessment, monitoring, and hence prevention of the natural and anthropic risks for the preservation of the historical and architectural heritage and landscape.

Geographical and Geomorphological Features

The study area includes the municipalities of Bisenti, Castiglione Messer Raimondo and Montefino, located on the hills of the province of Teramo (Abruzzo region) between 250 and 350 meters above the sea level (Figure 1).
The landscape is characterized by smoothed hills eroded by streams arising from the Gran Sasso massif and reaching the Adriatic Sea. The urban centres of medieval age are arranged on top of the ridges. The

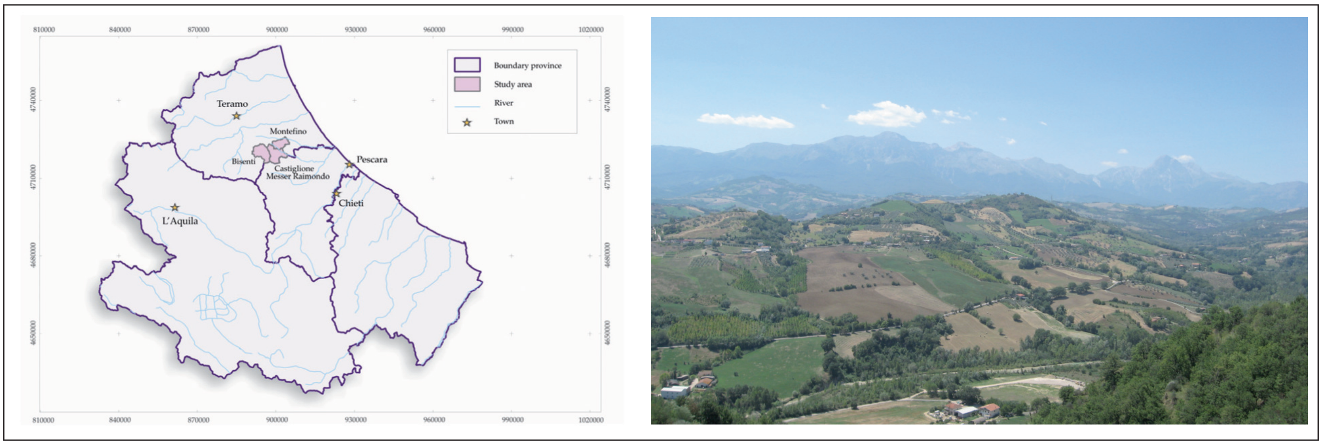


FIGURE 1 Localization and a view of the study area
Source: ENEA

hilly landscape is also characterized by small scattered settlements among the green patches of woods, olive-grove fields and vineyards, and areas planted with crops, the uncultivated fields and grazing.
The morphology of this area is closely linked to its lithology, the study area is characterized by three lithological classes: the first consists of sandstones with intercalations of marl sandstone called "Formazione della Laga", the second from marl and gray-blue clays, and the third from sands and clayed molasse.

The main morphological processes that occur in the area are represented by gravitational phenomena, such as landslides and erosion, affecting gullies and the landslide and slope edges. Landslides, in the literature, are defined as a "movement of rock, debris and / or earth along a slope, under the influence of gravity" [1]. Landslides in this area are of five types: for falling; for Toppling; for rotational slide (slump); for translational sliding (slide); for dripping (flow).
The combination of two or more landslides gives rise to

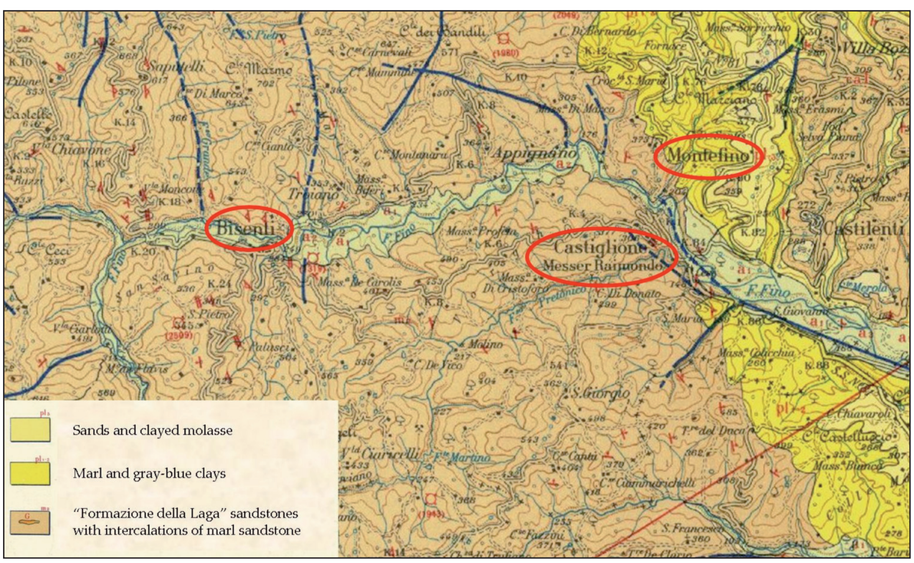


FIGURE 2 The geology of the study area
Source: from Geological Map of Italy scale 1.100:000 sh.140, Servizio Geologico d'Italia

the so-called complex landslides, whereas the erosion processes affect all the surfaces with forms of run-off, gullies surfaces and similar forms. If there is a high concentration of instability, the possibility that other events occur, or that phenomena already present will reactivate is higher, resulting in an increased hazard. The instability phenomena taking place in this region, affecting the urban centers and the surrounding landscape, result in an increase in the risk for historical, archaeological and landscape heritage.

Integrated Analysis of the Study Area: Spatial and Satellite Data

The following work has been accomplished through the use of cartographic data taken from the PAI, Hydrogeological Plan, of the Basin Plan for the Hydrogeological "landslides and erosion", drawn up by the Abruzzo Region. The Plan is a cognitive tool to manage the territory and its natural dynamics through the analysis, validation and updating of existing data [2]. Within the Plan, to complete the geological framework, a series of cartographic maps have been made, as the Geomorphologic Map, and the Hazard and Risk Maps. The data used for this study are those relating to hazard; the data is obtained by overlapping data on steepness, geo-litology, geomorphology and inventory of landslides and erosion.

Figure 3 shows the study area between the municipalities of Bisenti, Castiglione Messer Raimondo and Montefino, which overlapped data by PAI on landslide hazard (polygons with different green tones), gullies (blue polygons) and slopes (red lines), unique instability phenomena on the study area.

Hazard is defined as the probability that a danger of instability phenomenon occurs on a specific area. For each category of hazard the PAI has assigned four classes: P3, P2, P1 and Ps. In hazard P3 (very high hazard), all the areas affected by active or seasonally reactivated instability are taken into account, including active landslides (active), i.e. those that at the time of observation appear to be in motion. In hazard P2 (high hazard), the areas affected by landslides with a high possibility of reactivation are included, whereas P1 (moderate hazard) includes areas affected by landslides with low possibility of reactivation. Hazards

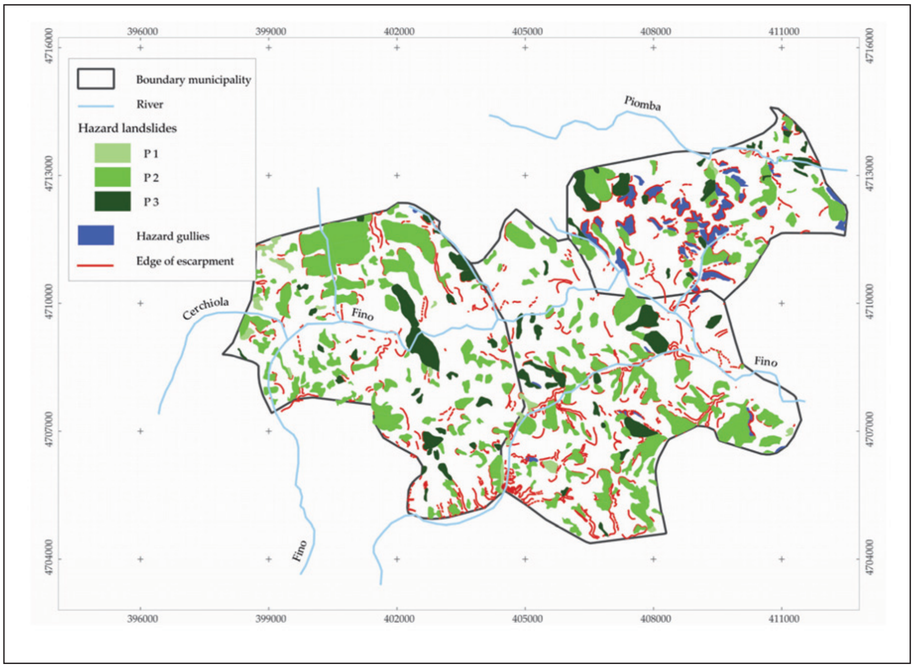


FIGURE 3 Instability phenomena in the study area
Source: ENEA

P2 and P1 include quiescent landslides, in which the movement can be reactivated by the causes which gave rise to it, and inactive landslides, those that have moved the last time before the last seasonal cycle. Instead, Ps hazard includes all slopes regardless of their state of activity.
With regard to the erosion processes, i.e. the gullies surfaces and similar forms are included in hazard P3, regardless of their state of activity, because once these phenomena are activated, they usually continue to move.
The processing of the map data was aimed at a preliminary analysis of the study area through an integrated analysis of spatial data with satellite data. In fact, the cartographic data considered were overlaid on a high-resolution satellite GeoEye image [3]. GeoEye-1 is the commercial satellite with high-resolution optical technology to capture images of the earth, which was launched in September 2008. The satellite is able to capture images with a resolution of 0.41 meters in panchromatic (gray) and 1.65 meters in the four multispectral bands (red, green, blue and near infrared).

A Natural Heritage at Risk: the Gullies of Montefino

An example of the integrated analysis concerned the territory of Montefino municipality. In Figure 4, the boundaries of Montefino municipality and the polygons of the gullies hazard were superimposed on a GeoEye satellite image.
This territory has geomorphological, lithological and climatic features favorable to the gullies morphogenesis. The gullies can be defined as dense and hierarchical drainage, consisting of deep incisions on clay substrates with narrow and sharp ridges [4]. The presence of clayey slopes, with increased steepness and devoid of vegetation, is a prerequisite for gullies setting. The steepness and the impermeability of the slope, in fact, reduce the infiltration of water into the soil and favor the fast runoff into streams (rills), with the subsequent etching of a dense drainage network; the evolution of the latter gives rise to gullies.
In addition, human activities, especially the removal of the vegetation cover and the consequent denudation of the slopes, can heavily affect the gullies

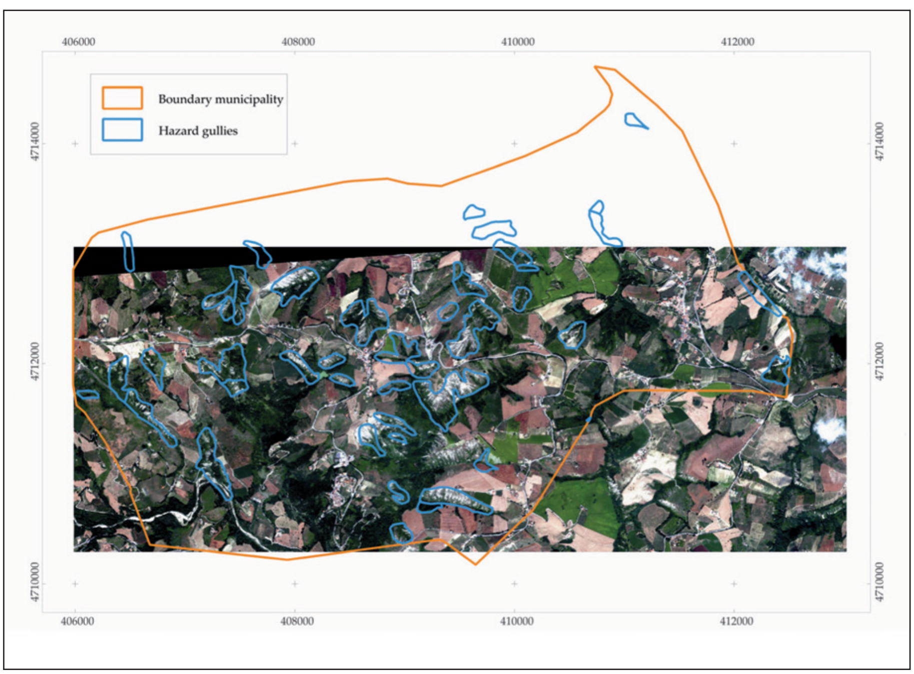


FIGURE 4 The gullies of Montefino
Source: ENEA on E-geos image

FIGURE 5 Landscape and geomorphological features of the study area of Montefino
Source: ENEA

morphogenesis, promoting the accelerated erosion on the slopes. Ultimately, the lithological and structural features of clay, allowing the persistence of steep slopes for various reasons, curb the effects of weather and control the genesis and the form distribution of gullies. Identifying the factors that determine the gullies formation is very difficult, because they are often linked to factors which can prevail one over the other. These factors can be summarized in this way:

- Presence of a layer of clay with a discrete sandy component and geotechnical and mineralogical features
- Steepness of the slope, which promotes rapid drainage of rainwater and the consequent development of the drainage network
- Arrangement of the layers "reggipoggio"
- The aspect towards the sunniest southern sectors
- Erosion at the foot of the slopes by fluvial courses
- Steepness of a slope which may be genetically linked to a geodynamic phenomenon, with the presence of a tectonic dislocation, or a landslide, or that can be connected to a rapid depth of linear erosion by tectonic or climatic causes;
- Climate regime, characterized by dry and long summers and intense rainfall concentrated in certain periods of the year;
- Existence of less erodible layers at the top of the slope; the human activity, in particular farming and pastoral activities (especially poaching of animals) that tend to diminish the vegetation cover and encourage the triggering of erosion processes.
- These instability phenomena lead to the landscape change and degradation; since it is a territory merely characterized by gullies, the hazard is very high. The aggravation of this phenomenon is mainly due to deforestation and the agricultural practices that leave the soil exposed to rain action [5]. With accommodation and terracing of slopes, channeling water runoff, and the environmental engineering techniques, it is possible to reduce runoff and keep it within tolerable limits.

Historic Centers at Risk: the Case of Bisenti

Another example of integrated analysis is the study area shown in the satellite image of the Bisenti municipality, where its boundaries have been superimposed on the slope hazard data (Fig. 6).
The slopes are a particularly important type of instability in the Abruzzo region. These are the linear elements divided into five categories in the Geomorphologic PAI Map: Edge of the fault scarp; Edge of the escarpment of fluvial erosion or torrential; Edge of the escarpment of marine erosion; Edge of the escarpment of glacial erosion; Edge of escarpment degradation and landslide.
In the municipality of Bisenti, slopes fall within just two types of those listed above: the edge of the escarpment and the edge river degradation and landslide (Figure 7); it was possible to zoom on the Bisenti historic center and see the behavior of the slope edges and the urban pattern (Figure 8).
The map shows the edges of slope around most of the town, especially the part of the historic centre (the eastern part): they are slope edges of fluvial erosion in a quiescent state. This means that in the event of heavy rainfall these slopes can reactivate with erosion on the slope base and the formation of degradation phenomena or landslide.

FIGURE 6 Bisenti municipality: satellite image with the data of slope hazard
Source: ENEA on E-geos image

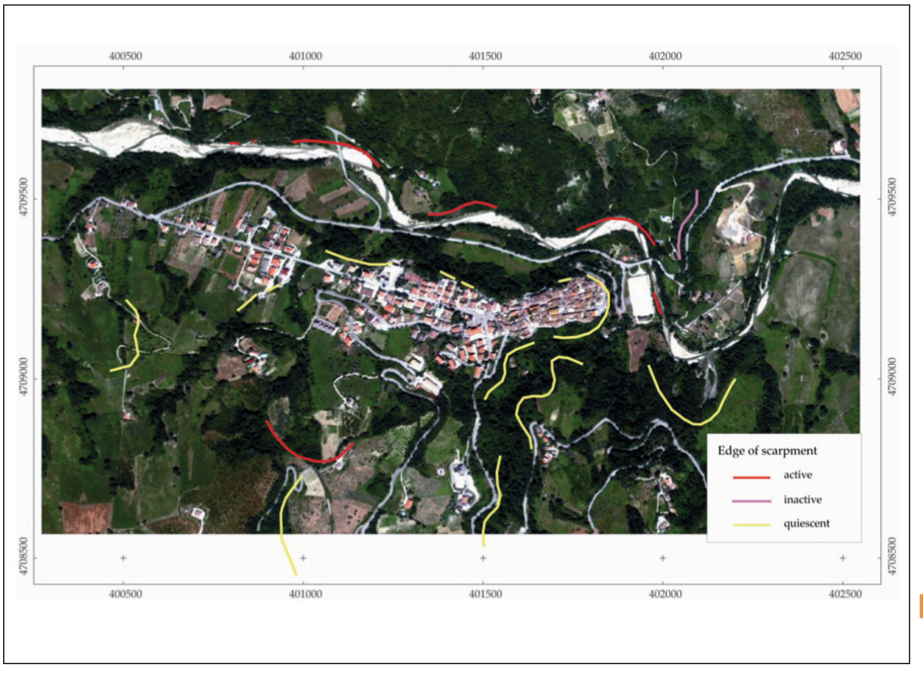


FIGURE 7 Slope hazard in the historic center of Bisenti
Source: ENEA on E-geos image

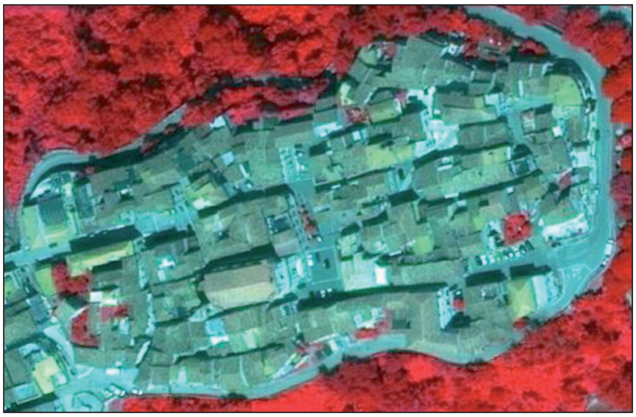


FIGURE 8 Historic centre of Bisenti
Source: E-geos, Geo-Eye high resolution image [3], false colour, RGB 432

These phenomena result in an increase of the hazard, so they should be supervised and monitored continuously. The edges of the active escarpment, instead, are mainly along the river bed (north of the city center), that, being in constant motion, tends to remove material at the base of the escarpment.
Once identified, the hazard on the urban center of Bisenti is shown as the buildings are subject to a greater risk, which is the product of the hazard with the vulnerability and exposure (R = P x V x E). Specifically, the integrated analysis of hazard and urban vulnerability allows to extract risk factors, which can be classified according to severity indexes.
The vulnerability assessment started from the analysis of the conservation state of buildings through the processing of satellite images. Figure 8 has been processed in false colour so as to make evident the contrast between old and new, restored and not in order to get a preliminary analysis.
The investigation will continue through vulnerability assessments of towns; expeditious surveys are ongoing in order to correlate all the data collected. The investigations do not concern the individual buildings but the historic centre as a whole (Figure 9).

Conclusions

In areas, subject to continuous natural phenomena as landslides, floods, earthquakes, there is the need to protect the cultural heritage at risk. Therefore, an integrated analysis control tool for the safeguard of our heritage was proposed.
To this purpose, in the study geomatic techniques have been applied, which enabled the overlaying of spatial data interpreting high-definition satellite images and vector data from local archives (PAI, IFFI, Corine Land Cover). The data processing allowed to create new thematic layers, and especially to query a spatial data in connection with others.

FIGURE 9 Views of Bisenti historic center
Source: Photo1 from the official website of Bisenti Municipality[6], Photos 2-3 ENEA

The integrated analysis of spatial data therefore allowed for the knowledge of several variables that persist in an area and their interdependencies. In this case study the knowledge of land degradation and morphogenesis phenomena is possible, in relation to the stability and preservation of the historic centres that lie on the morphological structures analysed.
The integrated analysis is then a safeguard tool for monitoring the conservation status of the territory and getting knowledge of its relations with cultural heritage, landscape and historic centre seen as a whole and not as a set of individual monuments.

Acknowledgements

The authors thank Carmela Vaccaro, University of Ferrara, for the scientific support during the surveys, e-Geos for Geo-Eye satellite images, in particular Claudio Serafini for courtesy and Lina Maria Calandra, University of L'Aquila, for use of cartographic data by Cartography Laboratory.

References

[1] D.J. Varnes (1958), *"Landslide types and processes",* Landslides and engineering practice, 29, 20-47, E.B. Eckel ed., National Research Council Highway Research Board Spec. Rept., Washington D.C.
[2] http://www.regione.abruzzo.it/pianofrane/index.asp
[3] The GeoEye image was acquired on July 4, 2011; courtesy of e-Geos, ASI/Telespazio.
[4] F. Dramis, B. Gentili, M. Coltorti, C. Cherubini (1982), *"Osservazioni geomorfologiche sui calanchi marchigiani"*, Geogr. Fis. Dinam. Quat., 5, 38-45.
[5] F. Ricci, A. De Sanctis (2004), *"Studio della dinamica temporale del paesaggio della Riserva dei Calanchi di Atri tramite rilievi su foto aeree"*, Riserva Regionale dei Calanchi d'Atri-WWF.
[6] http://www.bisenti.eu/

In Situ Traffic Vibration Monitoring and Non-Destructive Analyses of the Egyptian Obelisk of San Giovanni in Laterano in Rome

The Egyptian Obelisk of Piazza S. Giovanni in Laterano in Rome, Italy, was previously located at the Circo Maximo by emperor Costanzo the IInd; it was positioned at the current location in the XVI century by the architect Domenico Fontana. The obelisk stands on a 10m tall basement and, considering also the crux on the top, the total height of the monument is 45 meters. An extensive campaign of six months ambient vibration monitoring, sonic tomography and radar investigation has been carried out by ENEA for the structural evaluation of the obelisk

Gerardo De Canio, Massimiliano Baldini, Stefano Bonifazi, Alessandro Colucci, Francesco Di Biagio, Marialuisa Mongelli, Angelo Tatì, Paola Giaquinto

Introduction

The "Obelisco lateranense" is 32 m tall, and is composed by three blocks of granite connected to each other and at the base by three joints, the mechanical characteristics of which have been investigated and described in this article. The obelisk stands on a basement 10m tall and, considering also the crux on the top, the total high of the monument is 45 meters. Regarding its general structural conditions, once again it is possible to verify the high level of the Renaissance architectural skill while the three blocks are perfectly connected. The Non-Destructive Analyses have highlighted the ingenious system of "crux joints" realized by the architect Gian Domenico Fontana to recompose the three blocks and the complex and useful dislocation of the blocks of granite at the base of the obelisk. The following in situ experimental campaign has been carried on for the structural evaluation of the obelisk:

- Structural monitoring and dynamic characterization by ambient vibrations;
- Non-Destructive Analyses for the mechanical characterization of materials and identification of the metallic bars in the granite.

Massimiliano Baldini, Stefano Bonifazi, Alessandro Colucci, Gerardo De Canio, Francesco Di Biagio, Marialuisa Mongelli, Angelo Tatì
ENEA, Unità Tecnica Tecnologie dei Materiali
Paola Giaquinto
ENEA, Unità Centrale Relazioni

Structural Monitoring and Dynamic Characterization

The traffic close to the obelisk is regulated by 4 traffic lights, at each green light there is at least one heavy

truck or bus. The traffic-light in via dell'Amba Aradam has a red light time of 40 sec and green light time of 80 sec. Therefore, to achieve the traffic lights vibrations, the time history data are 120 sec long. Figure 1 shows the frequency contribution to the RMS acceleration at different levels of the obelisk recorded on December 1st, 2007, at time 16:37:53. In the graph, the signatures at 1.3 Hz and 6.1 Hz are evident, corresponding to the principal components of the Obelisk in the elastic phase. The figure also shows the time history and spectrogram of the induced acceleration when traffic light is green.
In terms of energy, traffic solicitations can be normalised with respect to a reference spectral acceleration, and evaluated comparing the spectral contents of the reference and the measured accelerations. In other words, a correspondence between the traffic effect and the reference earthquake of the site has been defined This way it is possible to evaluate the effects of the traffic vibrations in terms of normalised accelerations with respect to the reference earthquake. The curve MAX <Sa(T)_Traffic> is the envelope of the spectra at the base of the obelisk at 1.3 Hz and 6.1 Hz (the principal modes of the obelisk). The ratio between traffic spectrum and site spectrum at the principal frequencies of the obelisk are shown in Table 1.
The equivalent seismic action due to the traffic is 0.6% of the seismic demand for the Ultimate Limit State (Ref. OPCM 3431) and 0.04% of the site macro seismic spectrum.
With reference to the UNI9916 of 2004, the maximum ambient vibrations allowed for class 3 structures (monuments) is 0.25 cm/sec. Table 2 represents the ratio between these maximum values and the traffic equivalent velocity spectrum at the natural frequencies of the obelisk.

Sonic and Radar NDT Investigation

The Obelisk is assembled by three blocks of granite jointed by hinges with unknown mechanical characteristics. Up to 4 zones have been identified to characterize the geometrical and mechanical behaviours of the obelisk, therefore both sonic and

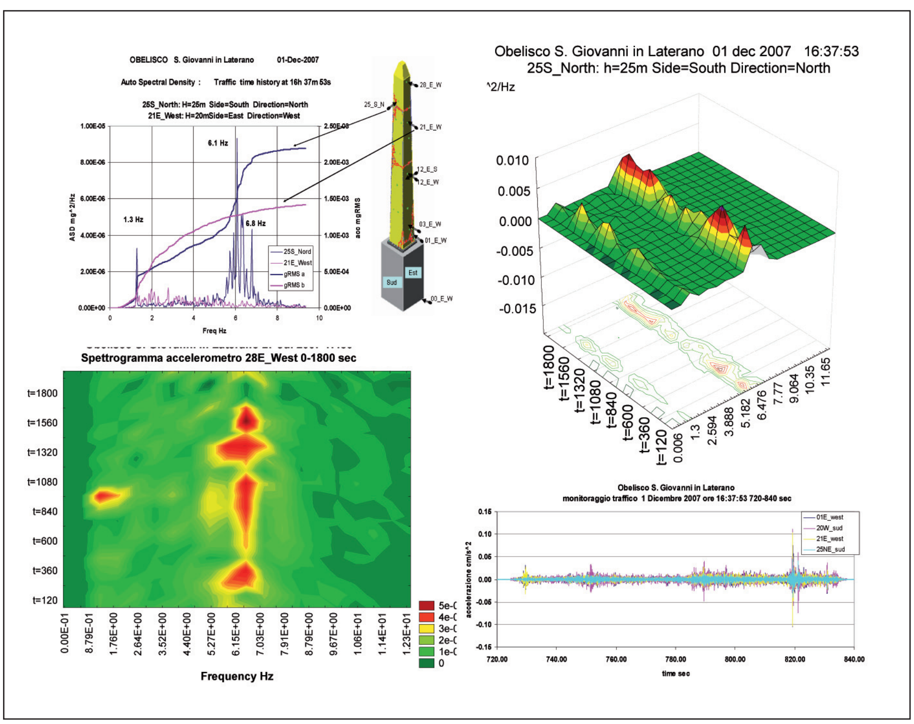


FIGURE 1 Power Spectral density and Frequency contribution to the RMS acceleration value (in cm/sec^2). Spectrograms and time history during the green phase of the traffic light
Source: ENEA

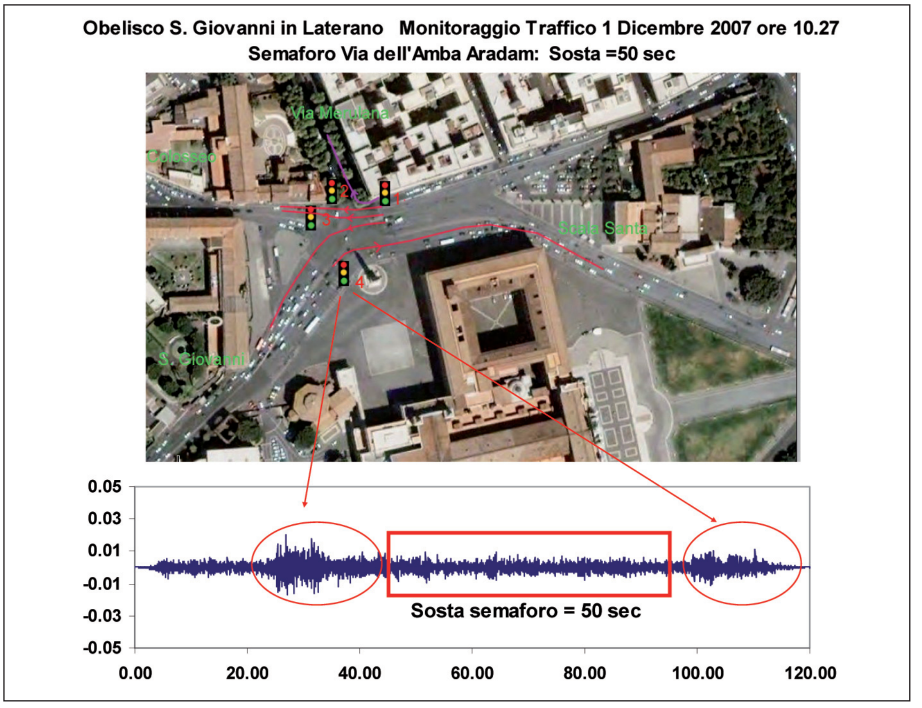


FIGURE 2 Accelerations due to the traffic from via dell'Amba Aradam to Piazza di porta S. Giovanni
Source: ENEA

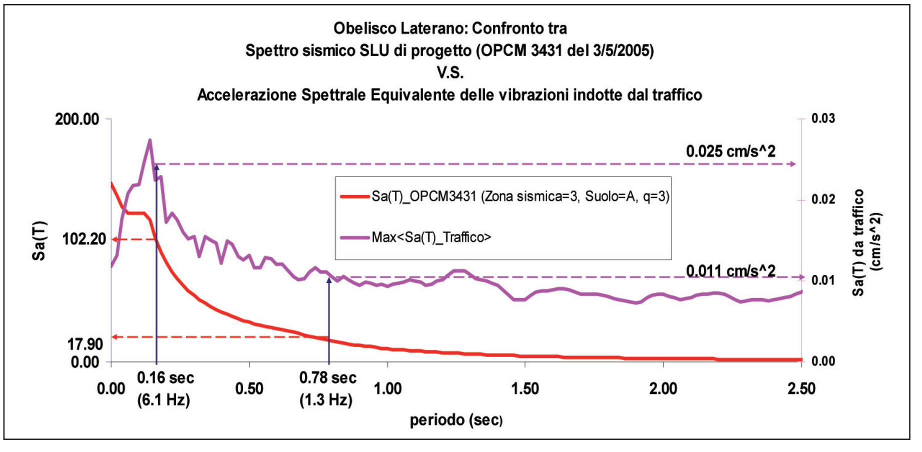


FIGURE 3 Confrontation between the maximum equivalent spectrum due to the traffic and the design earthquake spectrum of the site (OPCM 3431 the 2005-may-3th)
Source: ENEA

Mode No.	Hz	Sa(T)_traffic/ Sa(T)_site	Sa(T)_traffic/ Sa(T)_OPCM
1	1.3	0.013 %	0.600 %
2	6.1	0.040 %	0.024 %

TABLE 1 Ratio between traffic and site spectrum at the principal frequencies of the obelisk
Source: ENEA

Mode No.	Frequency Hz	Max<Sv(T)_Traffic>	Ratio Max<Sv(T)_Traffic>/ UNI9916
1	1.3	0.0034	1.36%
2	6.1	0.00057	0.22%

TABLE 2 Ratio between the maximum allowed ambient vibration and traffic equivalent velocity spectrum
Source: ENEA

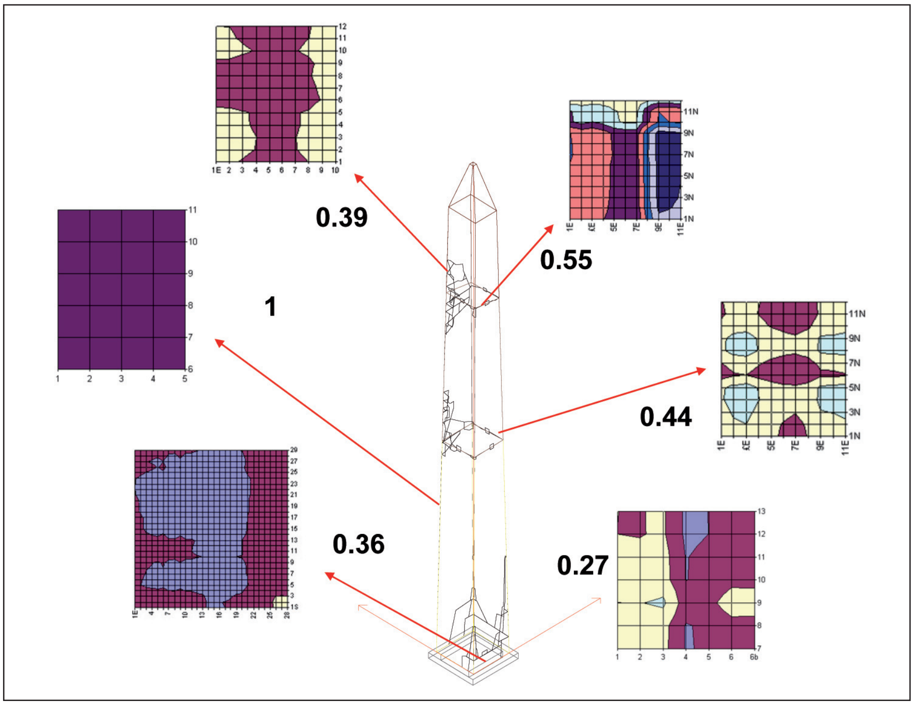


FIGURE 4 Sonic tomography at different levels of the obelisk
Source: ENEA

radar investigations have been performed to identify the geometry and characterize the mechanical properties. Knowing the differences between the mechanical characteristics of the representative zones of the obelisk it is possible to perform a parametric analysis of the dynamic response in terms of mechanical characteristics normalised with respect to the reference zone. Since the mechanical properties for the non-damaged zone are unknown, a parametric analysis have been performed and, for each parametric value, the properties for the other zones have been assessed according to the sonic and radar NDT experimental results. Figure 4 shows the sonic tomography results at different levels of the Obelisk. The sonic tomography allowed to verify the presence of iron staffs and bronze plates at the base of the Obelisk and also the presence of the joints with crux to avoid sliding between the three blocks.

The radar investigation of the Obelisk has been performed in order to evaluate the characteristics of the joints. The following results were achieved:

- The base of the Obelisk has non-homogeneous parallel blocks along the east, north and west sides.
- Inside each ring there are non-homogeneous materials.
- Metallic plates and rods in symmetric positions 50-50cm deep

Numerical Analysis

The numerical analysis of the Obelisk has been performed assuming the properties of the materials as resulting by the NDT investigations and referenced to the parametric properties of the granite in good conditions. A parametric evaluation has been performed assuming different values of the elasticity modulus within the value range of 12 GPa and 45 GPa:

$$\rho_{granito} = 2700\ Kg/m^3; \quad \nu = 0.14;$$
$$1.25\ E{+}10 < \mathbf{E\ [Pa]} < 4.5E{+}10$$

A static non linear analysis has been performed considering the following distribution of the seismic action:

- type-a seismic forces applied at the gravity center of the obelisk

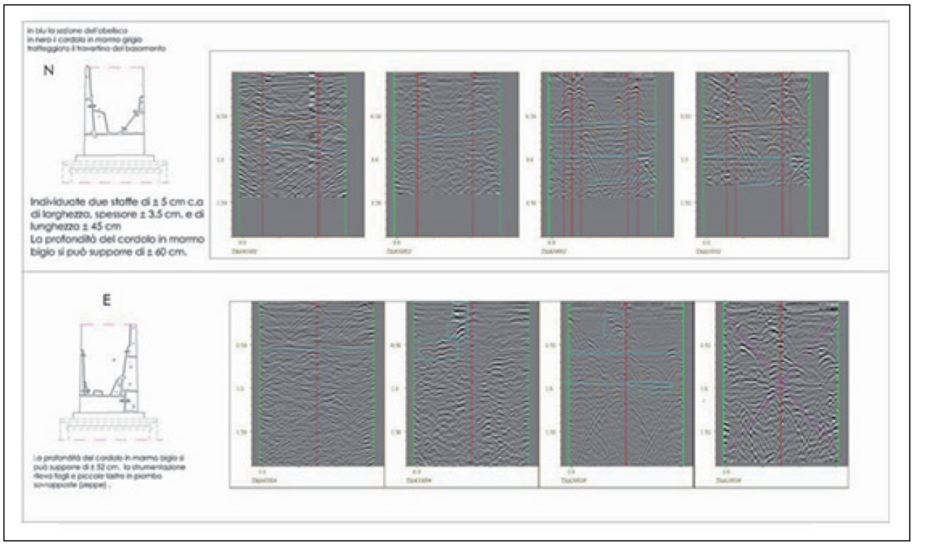


FIGURE 5 Radar echoes at the base of the Obelisk due to metallic bars and discontinuity between blocks
Source: ENEA

- type-b seismic forces distributed at the gravity centers of the blocks
- type-c seismic forces proportional to the first two modes

Table 3 summarizes the results of the numerical analysis with different seismic load distribution.

Conclusions

The identification of the dynamic response of the Egyptian Obelisk of Piazza San Giovanni in Laterano in Rome, Italy, has been performed by means of long-term monitoring of environmental loads due to traffic and/or microseisms. A series of non-destructive testing methods (sonic tomography and radar investigation) have been used to assess the material properties, the internal cracking and the hinges status. The numerical analysis of the obelisk has been performed knowing the differences between the mechanical characteristics of 4 representative zones by means of a parametric analysis with respect to the mechanical characteristics of the undamaged section.

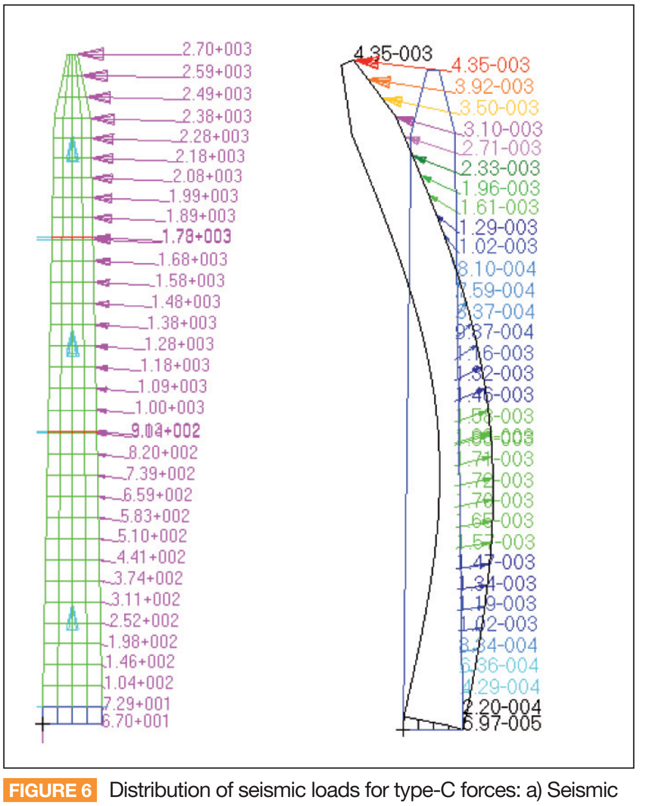


FIGURE 6 Distribution of seismic loads for type-C forces: a) Seismic load C_I, b) Seismic Load C_II
Source: ENEA

Seismic load:	Critical multiplier
a: Gravity + seismic action applied at the gravity center of the obelisk	11.25%
b: Gravity + seismic action distributed at the gravity centers of the blocks	12.0%
cI: Gravity + seismic action proportional to the first mode of the obelisk	12.5%
cI: Gravity + seismic action proportional to the second mode of the obelisk	15.0%

TABLE 3 Critical acceleration multiplier evaluated assuming different seismic load
Source: ENEA

References

[1] G. De Canio, *"Large Scale experimental facilities at ENEA for seismic tests on structural elements of the historical/monumental cultural Heritage"*, Proc. 9th Int. Congress on Deterioration and Conservation of Stone, Venice 19-24 June 2000.

[2] M. Mongelli: *"Analisi agli elementi finiti dell'Obelisco Lateranense di Piazza San Giovanni in Laterano a Roma"* doc. ENEA-RT-34-07G.

[3] G. De Canio, G. Fraraccio, M. Mongelli, N. Ranieri *"Monitoraggio delle vibrazioni naturali ed indotte dal traffico"*, Doc. ENEA RT-45/08.

[4] A. Tatì *"Indagine diagnostica tramite esame sonico e ricostruzione tomografica dell'Obelisco di San Giovanni in Laterano-Roma"*, Rapporto ENEA RT-35/07.

[5] P. Giaquinto: *"L'Obelisco Lateranense: Ricerche storico-critiche e cronologia degli avvicendamenti tecnologico-costruttivi"*, Rep. ENEA-RT-32-07.

[6] P. Giaquinto, A. Colucci: *"L'Obelisco Lateranense: Rilevazioni Georadar. Risultati preliminari"*, Rep ENEA-RT-36-07.

[7] G. Zingone, G. De Canio, G. Cavalieri, *"On the improvement of monumental structure safety: a case study"*, III European Conference on Computational Mechanics Solids, Structures and Coupled Problems in Engineering, Lisbon, Portugal, 5-8 June 2006 C.A. Mota Soares et al. (eds.).

Seismic Preservation of the Archeological Site of Pompeii. Preliminary Analyses

The seismic preservation of archaeological sites should certainly be targeted at the conservation of the historical and artistic values but cannot prevent these sites from being visited by a high number of tourists daily. A complete study should include the analysis of the seismic hazard in the area and of the seismic local response at each site, in addition to the analysis of the health status and the seismic vulnerability of structures. The site of Pompeii, recently interested by collapses, is probably the most interesting case in the world. The Soprintendenza Speciale per i Beni archeologici di Napoli e Pompei, in collaboration with ENEA, is organizing a study for the evaluation of the health status and the seismic vulnerability of some of the most diffused structural typologies in the archaeological site. The preliminary analysis pointed out the need for a detailed vulnerability analysis based on a comprehensive experimental investigation on both structure and site

Immacolata Bergamasco, Valerio Papaccio, Bruno Carpani, Paolo Clemente, Fernando Saitta

Introduction

The city of Pompeii was partially destroyed and buried under ash and pumice in the eruption of Vesuvius Volcano occurred in 79 A.D., and remained covered until its accidental rediscovery in 1749. The excavation has provided an extraordinarily detailed insight into the life of a city during the Roman period. Nowadays, Pompeii is a UNESCO World Heritage Site and one of the most popular tourist attractions in the world, with a very high number of visitors. Recently, it was affected by some collapses which brought to light the issue of safety of all the archaeological sites.

Due to the historical importance and to the daily presence of tourists, the seismic rehabilitation of archaeological sites is quite delicate, aiming at protecting both human life and cultural heritage.

The *Soprintendenza Speciale per i Beni archeologici di Napoli e Pompei*, in collaboration with ENEA, is organizing a study for the evaluation of the health status and the seismic vulnerability of some of the most diffused structural typologies in the archaeological site. Among these, the ruins of the colonnades of the Basilica and of the Forum, and the structures made of large blocks along *Via dell'Abbondanza* and *Via della Fortuna*, that are very representative of the most vulnerable situations. The scope of the analysis is to identify the

Immacolata Bergamasco, Valerio Papaccio
Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei
Bruno Carpani
ENEA, Unità Tecnica Ingegneria Sismica
Paolo Clemente, Fernando Saitta
ENEA, Unità Tecnica Caratterizzazione, Prevenzione e Risanamento Ambientale

seismic risk and formulate different hypotheses aimed at improving the seismic safety of these structures. These should pursue a suitable equilibrium between the two above-mentioned requirements, i.e. safety and conservation, so as to obtain a partial, yet effective seismic improvement, preserving the original cultural meaning and value.

The study is based, first of all, on the historical analysis of the structure and identification of the damage, including the seismic history of the site. Then, the characterization of materials and building techniques should be performed as well as the dynamic modelling of the structure and the evaluation of the seismic vulnerability. Finally the design of the intervention and the corresponding evaluation of the seismic improvement should be carried out.

In this paper some results of the preliminary analysis are shown.

Earthquakes in Pompeii

The strongest seismic event occurred in 62 A.D., only seventeen years before the catastrophic eruption. According to Seneca, who wrote about this event in the sixth book of his *Naturales Quaestiones*, Pompeii collapsed almost completely. The later excavations not only confirmed the occurrence of the earthquake but also shed light on an example, unique of a kind, of an ancient city during the post-quake reconstruction. On the basis of historical and archaeological data, the intensity at Pompeii was assessed as IX in the MCS scale. The earthquake was also reported by Tacitus with a brief note in his *Annales* (15.22.3). After the earthquake the reconstruction works proceeded somewhat slowly and in a disorganized way, so that at the time of the eruption they were not concluded yet. The examination of the methods employed by the ancient builders shows interventions revealing the clear-cut purpose of reinforcing structures against earthquakes [1, 2].

After the rediscovery of the site in 1749, the seismic catalogue reports two significant earthquakes, one in 1930 (VII MCS) and the other in 1980 (VI-VII MCS), both with epicentre in Irpinia (South Italy) [3]. Despite the long distance from the epicentre, the 1980 event caused widespread, moderate damage to the archaeological remains, with few cases of collapse (such as that of the columns of the Temple of Isis). According to the official report [4], the damaged structures were in a bad state of conservation, a factor that obviously affected their seismic vulnerability; in particular, the observed damage was mostly due to the

FIGURE 1 Wall in Regio VII (Insula 2, No. 1), (a) before and (b) after the collapse
Source: Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei

deteriorated condition of the mortar. However, for this event we lack a detailed damage survey, such as the outstanding one carried out by Maiuri on the 62 A.D. earthquake [1]. During the structural restoration works many concessions to modern construction technology were made, including the use of reinforced concrete top string-courses, injections of cement mortar and reinforcing ties in walls and vaults (iron bars inserted into drilled holes and grouted with cement). These interventions represent a matter of some concern because they were invasive and not mechanically consistent with ancient structures. Furthermore, the problem due to degradation of reinforced concrete elements is well known, in particular the carbonation process leading to the oxidation of iron bars.

Structural Types of Masonry

Two basic typologies of masonry structures are considered:

- walls made of small blocks, or concrete walls, where the loading capacity relies on the nucleus of *opus caementicium*, and therefore on the good quality of mortar, which plays an important role;
- structures made of great blocks and colonnades, where the role of mortar is negligible and structural safety essentially depends on the mechanical quality, size, shape and arrangement of the stone elements.

The Romans developed several methods for constructing concrete walls [5, 6]. They made use of stones (*opus incertum, opus reticolatum*), bricks (*opus testaceum*) or a mix of both (*opus mixtum*). All these types are found at Pompeii, but the opus incertum *"is the fundamental structure of the whole Pompeian building works"* [1]. These techniques essentially differ in the way the face walls are assembled and bonded to the inner core of opus caementicium. In the case of opus incertum, faces and nucleus were built in parallel with thin horizontal layers; the masons firstly set the elements of the outer faces using stones of polygonal shape, choosing the ones with the smoothest surface, then the core space were filled with rough stones (caementa) laid in a generous amount of fluid mortar [7].

Most of the structures, now exposed to various agents of degradation, were originally covered and plastered. The walls inside the housing units and made of two faces in opus incertum, are particularly degraded. In fact, even though the volcanic stones have quite good mechanical characteristics, mortar is poor. Besides, the mortar joints are sometimes more than 3 cm thick, and the masonry has no brick courses, nor brick bands that could make the texture regular and guarantee layers horizontality; these courses, when run through the full thickness of the wall, also perform as diatoni (bonding elements between masonry sheets), giving a monolithic behaviour to the wall [8, 9]. In this regard, it must be stressed that, although these structures were to some extent reinforced after the 62 A.D. earthquake, many walls (mostly belonged to private owners) were reconstructed without any anti-seismic reinforcement, employing salvaged materials and poor quality mortar.

Fig. 1 shows the walls of the Termopolio of P. Paquius Proculus, a commercial building excavated in 1943-1944. The partition wall that separated two adjacent workshops had a total thickness of 40 cm, a length of 5.0 m and a height of about 3.0 m, and the two opposite faces are N-W and S-E, respectively. Its collapse pointed out the absence of internal cohesion. In fact, the collapsed portion is completely disaggregated, the mortar is pulverized and the stones scattered on the ground look like those of a drywall.

Many other walls in the same area (*Regio VII*) are in the same condition, as pointed out during the survey of March 2009. Actually, the surface degradation observed in almost all masonry units examined is determined by chemical and mechanical degradation phenomena. These structures are subject to continuous cycles of wetting and drying. A recurring and widespread mechanism of decay was pointed out, in which the erosion of the mortar is particularly advanced in the mid-height of the walls. The mortar within joints is completely pulverized in these parts, probably because it is less wet both by the rainwater and by the water rising from the soil. Indeed, the faces on the South-East side are the most damaged (Figs. 2 and 3). The situation is often complex with overlapping causes and effects of degradation. Many of the walls are damaged or out of plumb. In such conditions even

FIGURE 2 Regio VII (Insula 2, No. 41 and 42)
Source: Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei

FIGURE 3 Regio VII (Insula 12, No. 34)
Source: Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei

FIGURE 4 The Forum area: free standing colonnades (in the back)
Source: Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei

FIGURE 5 Walls showing different structural behaviors and resultant damage
Source: Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei

small settlements could determine instability and collapse (Figs. 4 and 5).
Actually, the alternation of dissolution and crystallization of the salt deposits at the surface can lead to disintegration of mortars, and flaking of plaster, bricks, paints, etc. Once the mortar that holds the blocks together is consumed, the most degraded masonry becomes unstable and eventually the wall breaks. To avoid that, the mortar should be consolidated, the lacunae in the masonry faces reintegrated, and the walls protected.
It is worth noting that what said about the dynamics of the observed damage suggests the possibility of correlation between the weather and the progress of degradation processes. Therefore, further research requires reliable data on rainfall and environmental

FIGURE 6 Colonnade of the Basilica
Source: Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei

FIGURE 7 Blocks in grey tuff in Regio VIII (Insula 5, No. 19)
Source: Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei

conditions in the area, and also in different locations of the area. Further analyses would allow to identify timescales and procedures for proper maintenance, as well as the composition of mortar for masonry restoration.

Different types of vertical structures are present in the Pompeii excavations. Among these, the ruins of colonnades in the Forum area and the Basilica (Fig. 6) deserve particular attention. Besides, there are very common vertical structures in opus quadratum forming the jambs of the shops along the main roads. These are composed by the superposition of large blocks of gray tuff, having size of 100*70 *cm* and thickness equal to 40 *cm*. All these structures are very dangerous for visitors due to their position and size. Moreover, they show diffused cracks and significant degradation processes (Fig. 7). It is necessary an in-depth study of the stability of these structures, by carrying out the analysis and evaluation of mechanical characteristics of masonry, and understanding its texture and quality. Furthermore, foundation features and lying, as well as possible past structural interventions which could affect both static and dynamic behaviour should be investigated [10].

Several covering structures were built after the Second World War to protect wide areas, which are important also for their size and weight. They are made of reinforced concrete of uncertain quality, and span up to 11 *m*, with cross section 20-30 *cm* wide and up to 100 cm high, besides being supported by reconstructed masonry walls up to 10 *m* high. It is important to stress that these structures were built without earthquake-resistant design, therefore, according to the EM-98 scale they must be assigned to a low vulnerability class.

A Case Study

A case study related to the seismic reliability of the stacked blocks shown in Fig. 8 is analysed in detail. The blocks constituted the angular elements of the perimeter walls in a building ruin in Pompeii, largely collapsed.

The seismic action is defined according to the recent Italian code, assuming the highest return period of 2475 years, which corresponds to a peak ground acceleration of 0.224 g. Obviously, for such kind of structures, as largely recognized in the scientific literature, the motion under dynamic loads could be related mostly with the slipping along discontinuities and/or rocking motion of the blocks, whereas the deformability of the blocks could be negligible. It is well known that for a single block the rocking is possible if $\mu_s > b/h$ [11], where b and h are the length of half base and height, respectively; μ_s is the static friction coefficient. The damping is assured by friction forces. Thus, the

FIGURE 8 Stacked blocks of tuff for the case study
Source: Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei

classic response spectrum analysis cannot describe the behaviour of the system completely.
Due to the angular configuration of the structure, with indented joints between the two orthogonal wall pieces, a prevalent rocking motion of single parts seems not to be likely. Instead, sliding motion of single parts is possible. The friction at the horizontal interface between blocks is modelled as Coulomb type and the static and kinetic friction coefficients are assumed to be equal. The model has been defined in Ansys® software. The blocks are modelled by means of mass elements applied at the barycentre of each block, which allow the definition of inertial characteristics of the blocks. Fictitious, infinitely rigid beams have been considered to define the edges of each block and connect the mass element to the corners. At the contact points, elements capable of giving a Coulomb type friction in the horizontal plane have been introduced. Only horizontal motion of the blocks has been allowed. In this way, the nonlinear response to the base acceleration represented in Fig. 9 has been derived. The soil acceleration time history, assumed to act along the z principal axis (of the total system), has been simulated according to the code. Fig. 10a shows the displacement of the centers of mass along one horizontal direction, whereas the displaced system at time 2 sec is represented in Fig. 10b. The first figure shows that for a time close to 4 sec the displacements of some blocks become larger and larger, until the numerical integration cannot converge to solution. Thus, this first analysis indicates the possibility of a failure under an earthquake such as that used in the simulation, for sliding of the blocks.
A second model is based on the rocking behaviour of the whole structure, assumed to be a single rigid block. More complex models, involving several blocks are under study. The geometry of the structure suggests to resort to a complete three-dimensional analysis, unless strong simplifications are accepted. Assuming a density of the tuff $\rho = 2100$ Kg/m^3, the total mass of the block is $m = 7555.85$ Kg. The inertial characteristics

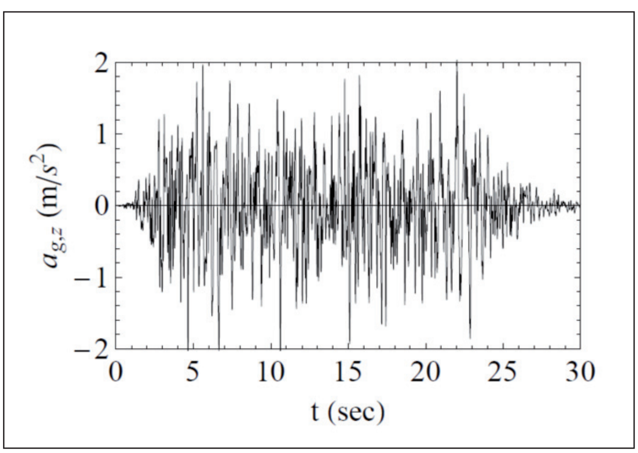


FIGURE 9 Acceleration time history for horizontal and vertical seismic component
Source: ENEA

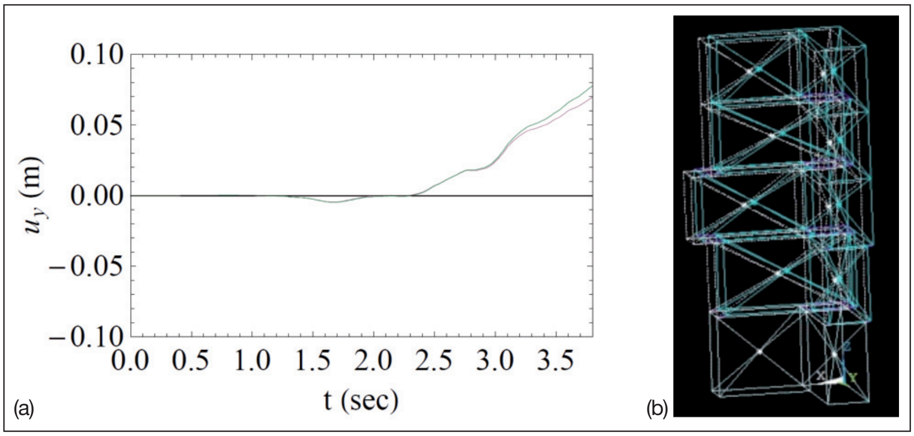


FIGURE 10 Displacement of the centre of gravity (a) and displaced system (b) at time 2 sec
Source: ENEA

of the whole system are: $I_x = 2372\ Kgm^2$, $I_y = 9068\ Kgm^2$, $I_z = 10295\ Kgm^2$. The equations of motion of the block can be written as follows [12]:

$$\mathbf{M}\ddot{\mathbf{x}} = \mathbf{F} + \mathbf{f} \qquad \mathbf{B_c}\,\ddot{\Phi} = \mathbf{Q} - \mathbf{A_F} + \mathbf{M_q}$$

where $\mathbf{M}$ is the mass matrix, $\mathbf{x} \equiv (x_c,y_c,z_c)^T$ and $\Phi\ (\phi,\psi,\theta)^T$ are the vectors of the Lagrangian coordinates, chosen as the three coordinates of the center of gravity and the three Euler angles, $\mathbf{A_F}$ - $\mathbf{M_q}$ - $\mathbf{B_c}$ are derived by means of Lagrange equations and are function of the Euler angles and the three inertia moments of the block, $\mathbf{F}$ and $\mathbf{Q}$ collect the contact forces and the related moments, $\mathbf{f}$ is the vector of external forces applied to center of mass. In the case of earthquake forces only f $= [mg - ma_{g,x}(t), -ma_{g,x}(t)]^T$. The axes are aligned with the principal reference system (Fig. 11).

The equations of motion can be cast in a single vector equation. Besides, it is convenient to use a state space form in order to apply numerical integration procedures. In this work, the Runge-Kutta scheme is adopted.

In [12] the soil is modelled alternatively by means of concentrated springs and dampers at the corners in contact with the ground, or by a Winkler model with distributed springs and dampers. The analysis of the impacts can also be treated by means of the conservation of angular momentum [13], even if in real cases the actual non complete rigidity of the impact zones should be taken into account. For the sake of this initial study, according to [12], the parameters are chosen in order to characterize a soil with elastic modulus of 1.0 GPa. For the friction coefficient the value 0.8 has been assumed. An exact estimation of parameters would require an experimental characterization of the soil. The results are presented in Fig. 12.

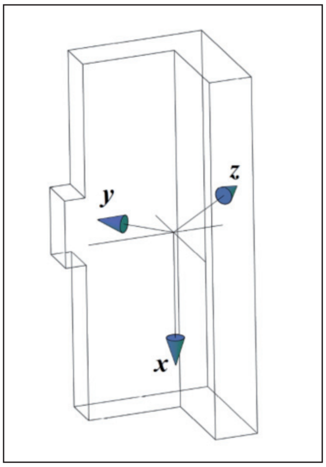


FIGURE 11 Rocking model and principal axes
Source: ENEA

In the first case (Fig. 12), the acceleration of Fig. 9 has been considered, whereas in the second one (Fig. 12) the acceleration has been amplified by a factor 4. In the former, the system is clearly stable, whereas displacements becomes relevant in the second case, even if the stability is maintained. Thus, a failure for rocking motion of the whole structure seems unlikely to occur, whereas the structure could be unsafe for sliding of some part.

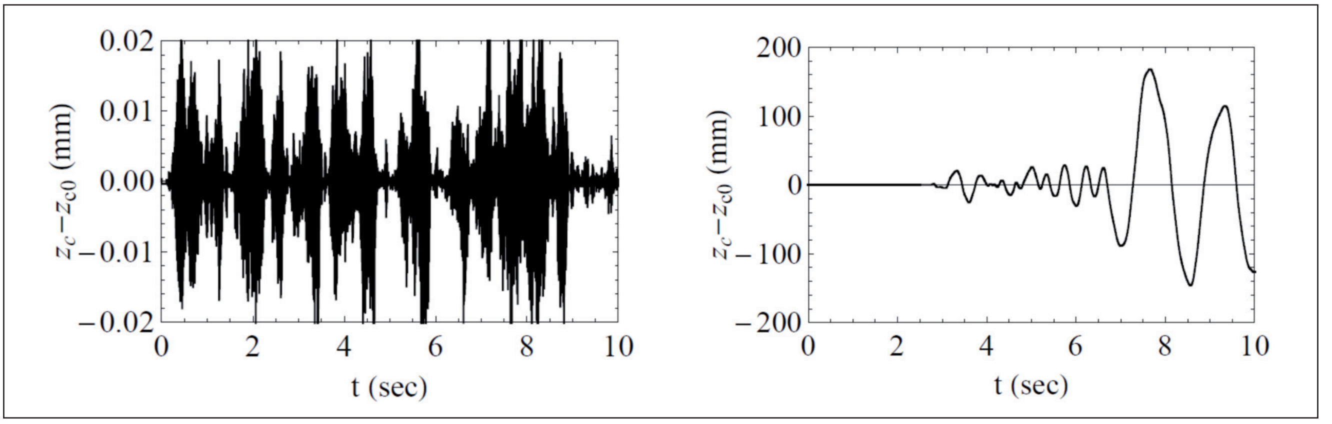


FIGURE 12 Horizontal displacement of the centre of gravity due to: a) Seismic acceleration following the Italian code; b) Seismic acceleration amplified by a factor 4
Source: ENEA

Conclusions

The first analysis of the Pompeii archaeological area, here reported, pointed out the high vulnerability of such kind of structures to seismic actions. In view of its historical importance and the daily massive influx of tourists, the seismic rehabilitation of the archaeological site of Pompeii is quite delicate, having to account for the protection of both human life and cultural heritage. For this reason, all these efforts should pursue a suitable equilibrium between the two essential requirements, i.e. safety and conservation, in order to obtain an effective seismic improvement, preserving the original cultural meaning and value.

References

[1] Maiuri A. (1942), *L'ultima fase edilizia di Pompei.* Istituto di Studi Romani, Roma.

[2] Adam J.P. (1989), *Osservazioni tecniche sugli effetti del terremoto di Pompei del 62 d.C.* In Guidoboni E. (Ed.) I terremoti prima del Mille in Italia e nell'area mediterranea. SGA,

[3] Locati M., Camassi R., Stucchi M. (Eds.) (2011), *DBMI11, the 2011 version of the Italian Macroseismic Database.* Milano, Bologna, http://emidius.mi.ingv.it/DBMI11.

[4] Proietti G. (Ed.) (1994), *Dopo la polvere – Rilevazione degli interventi di recupero post-sismico del patrimonio archeologico, architettonico e artistico delle regioni Campania e Basilicata danneggiato dal terremoto del 23 novembre 1980*, 1, Ministero per i Beni Culturali e Ambientali, Roma.

[5] Adam J.P. (1988), *L'arte di costruire presso i Romani: materiali e tecniche.* Longanesi, Milano.

[6] Lugli G. (1957), *La tecnica edilizia romana.* 2 Voll., Giovanni Bardi ed., Roma.

[7] Lancaster L. (2008), *Roman Engineering and Construction.* In Oleson J.P. (Ed.) The Oxford Handbook of Engineering and Technology in the Classical World, Oxford University Press.

[8] Giuffrè A. (1991a), *Letture sulla meccanica delle murature storiche.* Kappa ed., Roma.

[9] Giuffrè A. (1996), *A Mechanical Model for Statics and Dynamics of Historical Masonry Buildings.* In Petrini V., Save M. (Eds.) Protection of the Architectural Heritage against Earthquake. Wien, Springer.

[10] Bergamasco I., Carpani B., Clemente P., Papaccio V. (2012). *Seismic Preservation of archeological sites: the case of Pompeii.* Proc. 8th Int. Conf. on Structural Analysis of Historical Constructions, SAHC 2012 (Wroclaw, 15-17 Oct.).

[11] Shenton, H. (1996), *Criteria for initiation of slide, rock and slide-rock rigid-body modes.* Journal of Engineering Mechanics, 122(7), 690–693.

[12] Chatzis M.N., Smyth A.W. (2012), *Modeling of the 3D rocking problem.* International Journal of Non-Linear Mechanics, 47, 85-98.

[13] Zulli D., Contento A., Di Egidio A. (2012), *3D model of rigid block with a rectangular base subject to pulse-type excitation.* International Journal of Non-Linear Mechanics, 47, 679-687.

Anti-Seismic Marble Basements for High Vulnerable Statues in Italy: Bronzes of Riace, Annunciazione by Francesco Mochi, San Michele Arcangelo by Matteo di Ugolino

New anti-seismic basements made of marble and granite have been developed by ENEA for earthquake protection of the *Bronzes of Riace* at the Archeological Museum of Reggio Calabria, the *Annunciazione* by Francesco Mochi and the *St. Michele Arcangelo* by Matteo di Ugolino at the Opera del Duomo Museum of Orvieto, Italy. These basements are also useful for the preventive conservation of other high vulnerable statues with analogous reduced support at the base, such as the *David by Micheangelo* in Florence

Gerardo De Canio, Simonetta Bonomi, Alessandra Cannistrà

Introduction

This paper describes the new anti-seismic basements made of marble for earthquake protection of high vulnerable statues of primary importance in Italy:

- two *Bronzes of Riace* at the Archeological Museum of Reggio Calabria,
- three statues at the Opera del Duomo Museum (MODO) of Orvieto, namely: the two marble statues of the *Annunciazione* made by Francesco Mochi, and the bronze statue of *S. Michele Arcangelo* made by Matteo di Ugolino da Bologna.

The new basements are also useful for other high vulnerable statues standing on their legs, e.g., the David by Michelangelo in Florence. The design approach of the basements was to confer the seismic isolation property to the geometry of the surfaces, according to the following design targets: maximum seismic isolation, low stiffness and low dissipation; reversibility; full compatibility of the materials; easy maintenance.

Gerardo De Canio
ENEA, Unità Tecnica Tecnologie dei Materiali
Simonetta Bonomi
Soprintendente per i Beni Archeologici della Calabria
Alessandra Cannistrà
Curatore Museo OPSM - Opera del Duomo di Orvieto

Anti-Seismic Basements for the Bronzes of Riace

The two statues, *"Bronze A the young"* and *"Bronze B the old"*, were previously located at the ground level of the museum and provided with laminated rubber anti seismic devices. Moving the statues from the ground

level to the new exposition room on the first floor of the museum required the upgrading of the basements according to the new seismic classification of the site and the change in the maximum hazard spectra. The previous devices inserted in the old basement provided a seismic isolation coefficient value of 2.5-3 and, to avoid overturning, the statues where anchored with strengthening forces of 1800N applied to each shoulder by means of steel cables inserted in the cave legs (ref. [1]). The need to reduce the strengthening anchoring forces, together with the new expected seismic demand due to the new seismic classification, induced to re-design the anti-seismic basements to increase the isolation coefficient, reducing the risk of exceeding the seismic capacity of the two statues.
The design results are, for each statue, a basement made of two blocks of marble type *Carrara*, showed in Fig. 1, and the surfaces of the blocks modelled as an ellipsoid of revolution, where 4 spheres made of the same material of the blocks are located. In short, the basement is made of the following elements: *BI= marble lower block, S= marble spheres, DO= Horizontal*

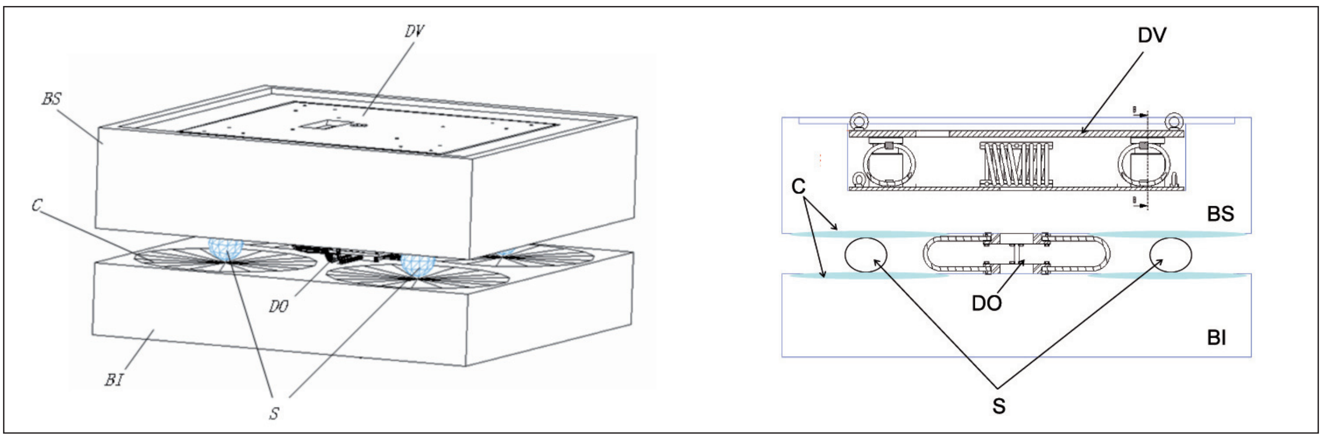


FIGURE 1 Marble anti-seismic basement for the Bronzes of Riace
Source: ENEA

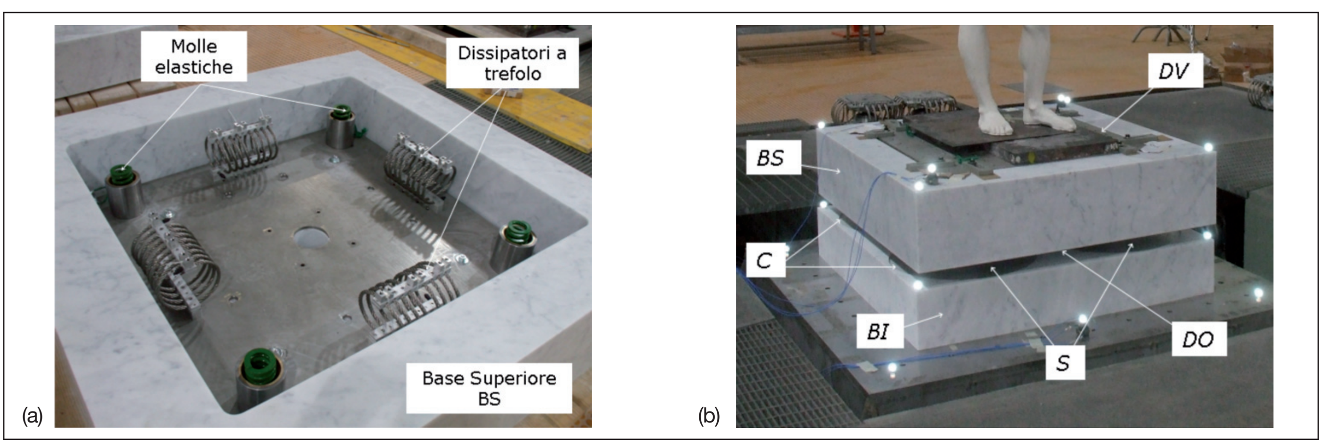


FIGURE 2 Marble basement for the Bronzes of Riace: a) Details of the vertical isolation device inserted into the upper block, b) Basement ready for the shaking table tests
Source: ENEA

displacement limitation and *re-centering device, BS= marble upper block, DV=vertical isolation device* inserted in the BS upper block.

However, stiffness and principal frequency of the basement are not constant, due to the elliptical geometry of the rolling surfaces, the principal frequencies are ranging from 0.015Hz to 0.025 Hz depending on the position along the surface, with zero value at the centre, where the re-centering function is demanded to the element *DO*. The vertical isolation is provided by two stainless steel plates connected by four shock absorbers made of dissipative cables plus four springs inserted in piston guides confining and de-coupling the vertical and the horizontal motions, therefore the horizontal isolation is demanded to the basement geometry and the vertical isolation is demanded to the shock absorbers inserted in the upper basement.

Shaking Table Tests

The shaking table tests on the basements have been performed at the Qualification of Materials

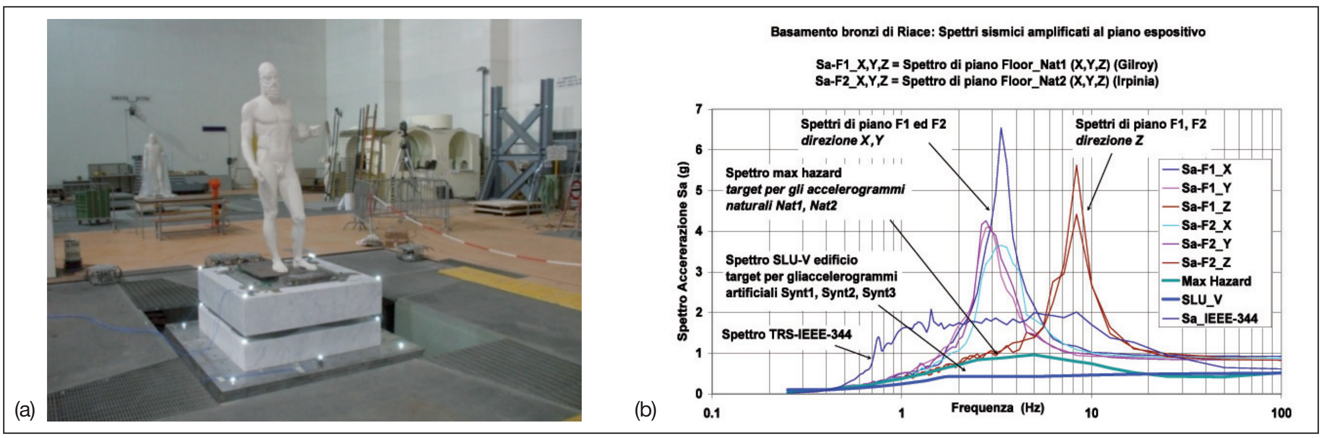


FIGURE 3 Shaking table tests of the marble anti-seismic basements for the Bronzes of Riace (ref. [2]): a) test set-up, b) test acceleration spectra at the base table
Source: ENEA

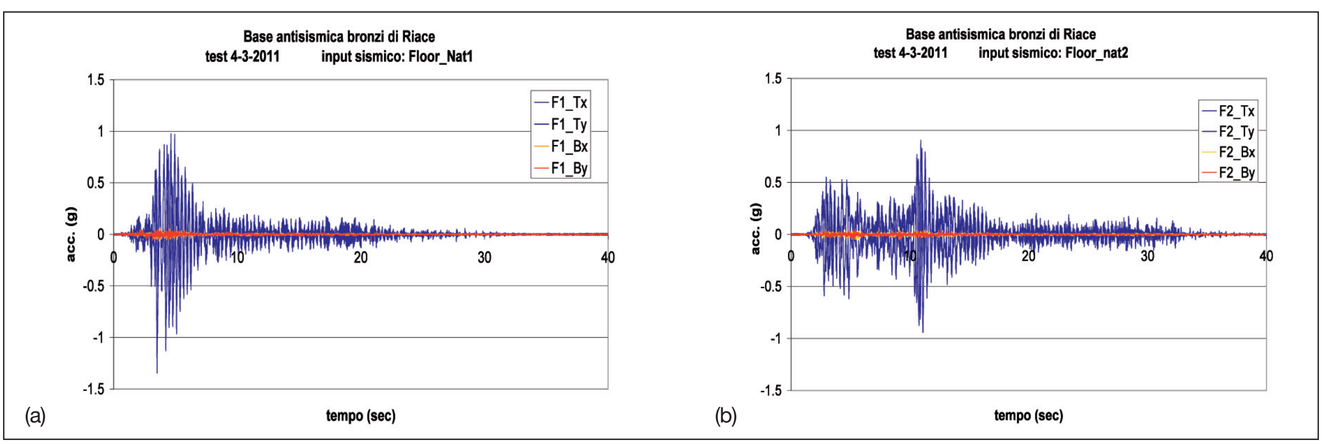


FIGURE 4 a) Floor-Nat1, F1_Tx,y= base table, F1_Bx,y= basement. Isolation Coeff.= 22; b) shaking table test Floor-Nat2, isolation Coeff.= 20
Source: ENEA

and Components Laboratory of the ENEA Casaccia Research Centre, Rome (Italy); test set-up and details of the basements are showed in Fig. 3.
The input time histories were natural accelerograms rescaled to the max hazard of Reggio Calabria, return period of 2475 years, amplified on the first floor of the museum. Also three artificial accelerograms were applied, compatible to the Ultimate Limit State of the museum amplified on the first floor at different damage conditions of the building. At the end of the test campaign were three X,Y,Z accelerograms also applied, compatible with the RRS (Required Response Spectrum) for NPP (Nuclear Power Plant) class 1-E equipment (essential for safety) in compliance with the IEEE-344 specifications. All tests reached the reduction coefficients of 15-20 for the horizontal accelerations and 2.5-3 for the vertical accelerations; the overall maximum acceleration measured on the basement in all the tests was 0.08g.
During the tests with natural earthquake, the max acceleration peak on the basement was 0.062g. In the vertical direction, with Peak Floor Acceleration PFA=2g, with isolation coefficient 2.4 and max basement vertical acceleration 0.86g.

The two forces of 1800N at each leg to prevent overturning are not yet necessary and have been reduced to 600N and 300N in the new basement, just to replace the weights of the shield on the left arm and the lance on the right arm.

Anti-Seismic Basements at the Opera del Duomo Museum, Orvieto, Italy

In this chapter the anti seismic basements for the two marble statues of the Annunciazione by Francesco Mochi, and the bronze statue of *S. Michele Arcangelo* at the Opera del Duomo Museum of Orvieto in Italy are described, as well as the design of the basements for the 12 statues of the St. Apostles, either if the 12 statues will be repositioned in the Cathedral or in the annexed Museum.

Annunciazione by Francesco Mochi

Devices of the same family as those for the Bronzes of Riace have been developed for the Annunciazione by Francesco Mochi at the Cathedral of Orvieto (Fig. 5)
The devices, made of black granite, will be positioned

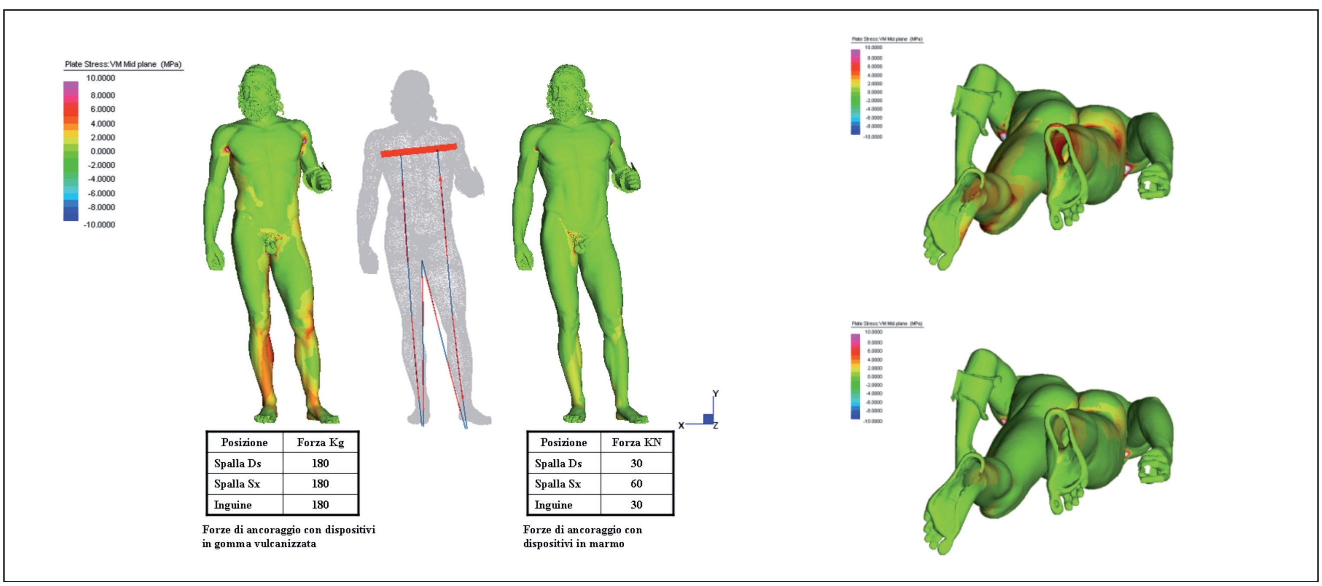


FIGURE 5 Bronze A: comparison of the stress fields by the old and new strengthening forces
Source: ENEA

FIGURE 6 The Cathedral of Orvieto (Italy) and the two statues of “The Annunciazione” by Francesco Mochi
Source: ENEA

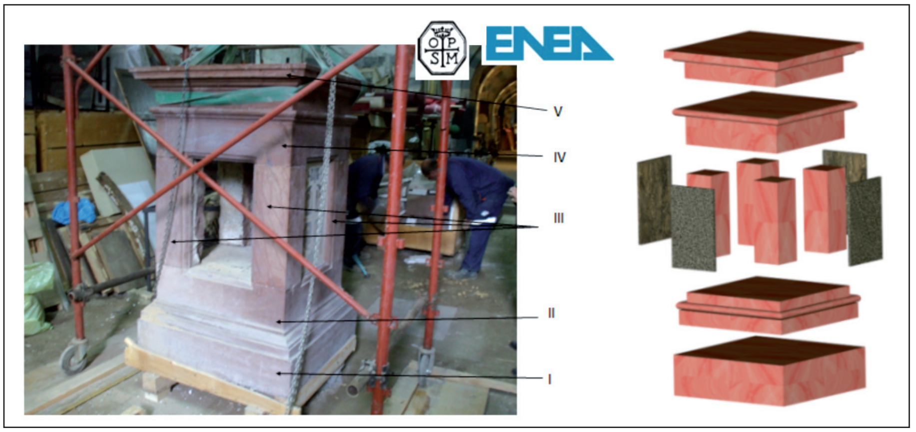


FIGURE 7 Original basement composed of several blocks
Source: ENEA

FIGURE 8 The anti-seismic basement for The Annunciazione by Francesco Mochi
Source: ENEA

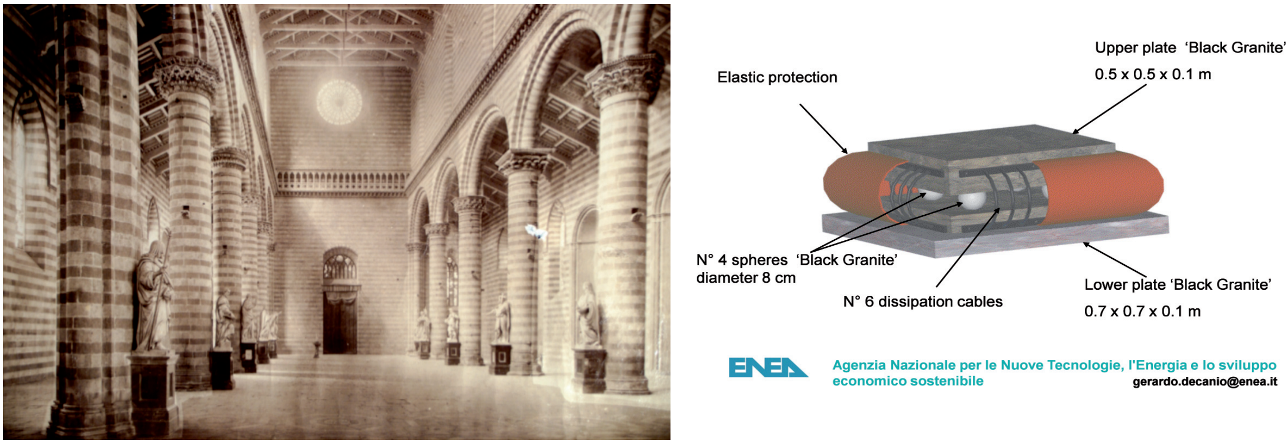


FIGURE 9 Image rendering of the repositioned statues of the 12 Apostles in the Orvieto Cathedral (ref. [3]) and the Black Granite anti-seismic device
Source: ENEA

on the original basement and covered with the same stone.

The two statues representing *The Annunciazione*, together with other 12 statues representing the St. Apostles were removed from the Cathedral of Orvieto in the XIX century. The rendering in Fig. 9 show the statues of the 12 Apostles as they will look if repositioned in the Cathedral. In the figure the design of the anti-seismic device for the 12 statues is also represented, either if they will be repositioned in the nave of the cathedral or in the Museum.

S. Michele Arcangelo by Matteo di Ugolino

Figure 10 represents the bronze statue of S. Michele Arcangelo on the façade of the Cathedral and the design of the new basement with the granite anti-seismic device.

This statue was heavily deteriorated by severe weather conditions and large oscillations due to inadequate strengthening forces, therefore the statue was removed from the façade and then moved into the museum, at the end of its restoration.

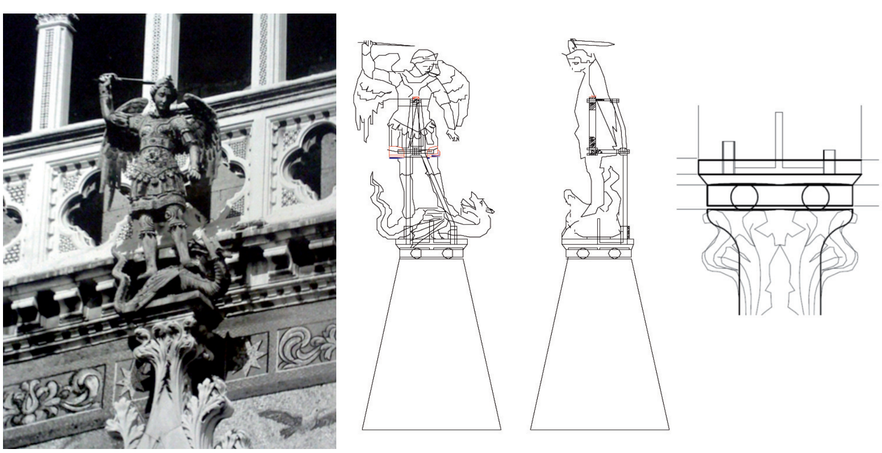


FIGURE 10 *S. Michele Arcangelo* on the façade of the Cathedral and design of the basement for the museum exposition
Source: ENEA

Marble Basement for High Vulnerable Statues: Proposal *for the David* by Michelangelo

The ***David by Michelangelo*** in Florence, Italy, one of the statues of the absolute importance ever acknowledged by humankind, is highly vulnerable to earthquakes because it is standing directly on its feet and because the legs are seriously cracked. Therefore, the same type of basement can be useful to protect this statue from earthquake-induced overturning and shear stress. In this case, due to the mass of the actual basement and statue, a marble basement of 2m x 2m with 25 spheres as shown in Fig. 2, are needed.

Conclusions

New anti-seismic basements made of marble have been developed for high vulnerable statues in Italy. For the ***Bronzes of Riace***, the very low acceleration at the base of the statues allows to reduce the strengthening forces to the values equivalent to the shield on the left arm and the lance on the right hand. Basements of the same family have been used for the two statues of the ***Annunciazione*** by Francesco Mochi, and the ***St. Michele Arcangelo*** by Matteo di Ugolino at the Opera del Duomo Museum of Orvieto, Italy. Analogous basements have been designed for the statues of the ***12 Apostles*** to be positioned either in the Orvieto Cathedral or in the annexed museum.
The results allow to propose the same type of basement for the ***David by Michelangelo*** in Florence, Italy.

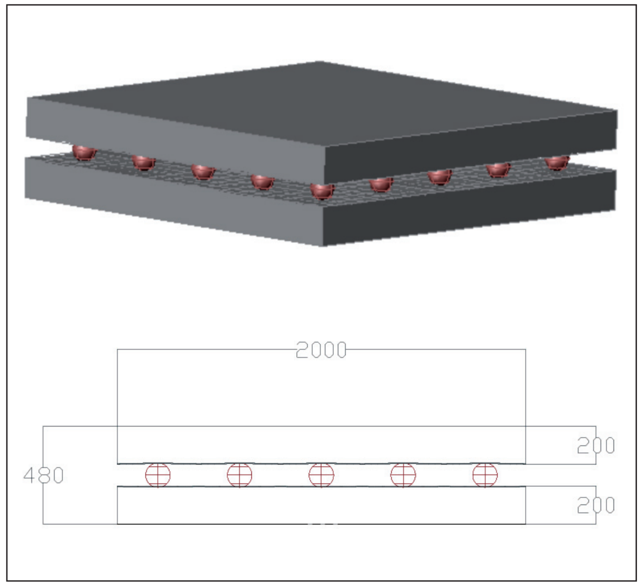


FIGURE 11 Proposal for the base isolation for the *David by Michelangelo*
Source: ENEA

Acknowledgements

The authors wish to thank Roberto Ciabattoni and Paola Donati of ISCR, restorators of the Bronzes of Riace and the S. Michele Arcangelo; the ISCR Director, Dr. Gisella Capponi, for the supports to better configure the basements of the Bronzes of Riace; Elisabetta Andreani of OPSM for the studies of the Orvieto Cathedral; the ENEA researchers Alessandro Colucci and Francesco Di Biagio for shaking table tests and data acquisition, Ivan Roselli for 3DVision data acquisition, Marialuisa Mongelli for Numerical Analysis and Model validation, Angelo Tatì for the NDT investigations, Massimiliano Baldini, Stefano Bonifazi and Alessandro Picca for test set-up and laboratory experiments.

References

[1] A.M. Vaccaro, G. De Palma, 2003: *I bronzi di Riace, Restauro come Conoscenza.* Artemide Edizioni, ISBN 88-86291-73-6.
[2] G. De Canio (2012). Marble devices for the Base isolation of the two Bronzes of Riace a proposal for the anti seismic basement for the David of Michelangelo. *The 15th World Conference on Earthquake Engineering*, September 22-29, 2012, Lisbona, Portugal.
[3] A. Cannistrà (2006): *Da Simone Martini a Francesco Mochi* - Verso il nuovo museo dell'Opera del Duomo di Orvieto. Silvana Editoriale S.p.A. ISBN 88-366-0704-7.

Experimental Dynamic Analysis and Seismic Rehabilitation of Palazzo Margherita in L'Aquila

The studies carried out for the retrofit of Palazzo Margherita, the City Hall in L'Aquila, seriously damaged by the 2009 earthquake, are shown. The building and the tower were first analyzed by means of ambient vibration tests, in order to find out the dynamic characteristics of the structure even in a damaged situation. On the basis of the results obtained and of the microzoning analysis results, the base isolation was proposed as the most suitable solution for the seismic retrofit of the structure, because it allows to obtain a good structural result without altering the architectural features of the superstructure. The new isolation system is based on the realization of an isolated platform under the building foundation without any intervention on the building itself. The system can be used for single buildings but also for complex structures, typical of the Italian historical centres

Giacomo Buffarini, Paolo Clemente, Sandro Serafini, Alessandro De Stefano, Roberta Olivieri, Antonello Salvatori

Introduction

Historical structures have been built without accounting for the seismic actions and are vulnerable even to moderate events but, due to their historical importance and to the daily presence of tourists, their seismic rehabilitation is quite delicate, aiming at the protection of both human life and cultural heritage. Seismic preservation should be based on a good knowledge of the dynamic characteristics of the structure and a suitable choice of the intervention, if necessary.

Giacomo Buffarini, Paolo Clemente, Sandro Serafini
ENEA, Unità Tecnica Caratterizzazione, Prevenzione e Risanamento Ambientale

Alessandro De Stefano
Politecnico di Torino

Roberta Olivieri, Antonello Salvatori
Università degli Studi dell'Aquila

The first step is very important in order to assess, also by means of a suitable numerical model, the possible dynamic behaviour of the structure during strong events. But it is not easy for several reasons: the structural size of the various elements (walls, floors, etc.) cannot be evaluated with the needed accuracy; the material characteristics, such as the tension-strain relationship, the strength, etc., are not known; structure and materials often exhibit inelastic behaviour; horizontal structures are not effective in joining the vertical ones; the depth of the foundations is often variable as well as their geometry and material properties, including the soil characteristics; buildings are often connected to other constructions, so that their behaviour is very complicated. For such kind of structures the experimental analysis is often the only way to improve our understanding about their dynamic behaviour [1, 2, 3, 4, 5].

Sp

Speaking of interventions, it is worth noting that traditional techniques are not suitable for the seismic rehabilitation of cultural heritage buildings. In fact, these are based on the increasing in strength and ductility, and so are often not reversible, making use of materials different and incompatible with the original ones, and can determine changes in the original structural conception. Furthermore, under high-intensity earthquakes, traditional techniques can just guarantee against the collapse, but cannot avoid heavy damage both to structural and non-structural elements. Therefore, base isolation could be a suitable solution for the seismic rehabilitation of historical structures. It aims to reduce seismic actions, thus avoiding significant damage to the structure and its contents even under strong earthquakes, and presents very low interference with the structure itself.
In this paper the study carried out on Palazzo Margherita in L'Aquila is shown. First of all an experimental campaign was carried out in order to find out the dynamic characteristics of the structure. Then a conventional improvement intervention was defined, which allowed the structure to be able to support minimum horizontal actions. On the basis of the effective earthquake resistance of the restored structure and of the actual seismic input at the site, a suitable solution for the base isolation system was designed.

Palazzo Margherita: History and Characteristics

The erection of the City Hall in L'Aquila started in 1294. A first important restoration was completed in 1541 (Fig. 1). Important works were done since 1573, when the building became the house of Margherita d'Austria, and most of the original characteristics were lost. At the beginning of the XX century another restoration intervention was made to realize a concrete ring beam under the roofing. The palace has three levels and a rectangular plan of about 40*60 m, with an internal court. The vertical structure is made of stone and brick masonry with good mortar. The horizontal structures are made of masonry vaults, some of them with chains, and steel decks.

FIGURE 1 Palazzo Margherita: main façade and courtyard
Source: ENEA

The Civic Tower, built from 1254 and 1374 at the N-E corner of the building, was seriously damaged by the 1703 earthquake and then rebuilt with lower height. In 1937 it was consolidated by inserting iron T-beams at the floors. It has an almost square cross-section of about 6.30 m size. The thickness of the walls is about 2.0 m at the basement.
The building suffered heavy damage during L'Aquila earthquake of April 6th, 2009. Several cracks were apparent and local collapse mechanisms were activated. In more details the seismic events caused the disconnection between the orthogonal walls, the out-of-plane collapse of some masonry walls, the formation of large cracks, the collapse of some floors and important damage to the stairs.

Dynamic Characterization of the Building

As already said, an experimental campaign was carried out, in order to find out the dynamic characteristics of the structure. Fifteen velocimeter sensors were

Freq. (Hz)	Building Description	Freq. (Hz)	Tower Description
2.24	Transversal	1.46	Transversal
2.74	Transversal + Tors.	1.46	Longitudinal
3.32	Longitudinal	2.83	Transversal
3.71	Torsional	3.22	Longitudinal

TABLE 1 First resonance frequencies of the building and of the tower
Source: ENEA

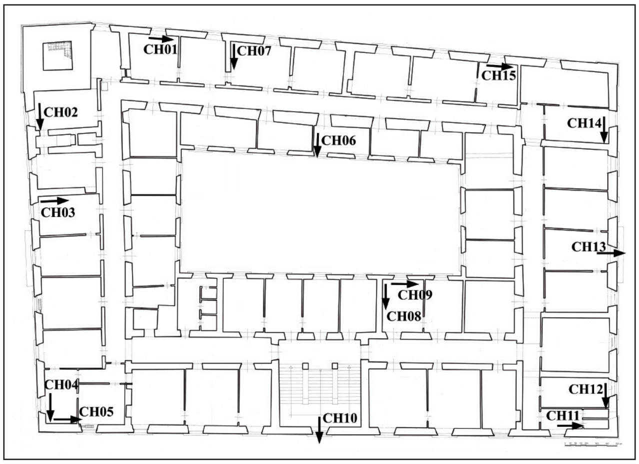


FIGURE 2 Second floor: sensor deployment in the first configuration
Source: ENEA

deployed in two different configurations. In the first one, the sensors were deployed in the building, in order to point out the global and local resonance frequencies (Fig. 2). In the second configuration, the sensors were deployed at different levels of the tower. For each configuretion three tests of about 300 sec were carried out, with a sample rate of 200 *point/sec* using ambient noise only as source of vibrations. With this low level of excitation the building showed a quasi-linear behaviour, and a spectral analysis was performed. As well known, peaks in the power spectral densities (PSD) could be associated to structural frequencies, while the same peaks in the cross spectral densities (CSD), with significant values of phase factor and coherence function, could confirm this statement and give some indications about the modal shape associated to each structural resonance [6, 7, 8, 9].

In Fig. 3, the PSDs and the CDS relating to sensors CH11 and CH13 in the longitudinal direction are plotted. The PSDs and the CDS relating to sensors CH04 and CH14 in the transversal direction are plotted in Fig. 4. The experimental analysis pointed out the resonance frequencies of the building and of the tower listed in Table 1 [10].

Design and Application of Seismic Isolation in Existing Buildings

Seismic isolation has already been used for the retrofit of historical buildings [11], among these:

- the Saint Francisco City Hall, whose retrofit was completed in 1998. The foundations were first reinforced with new beams and a new deck was realized above the isolation interface. Then, the structural elements were shored up and the foundations were cut at their top. Hydraulic jacks

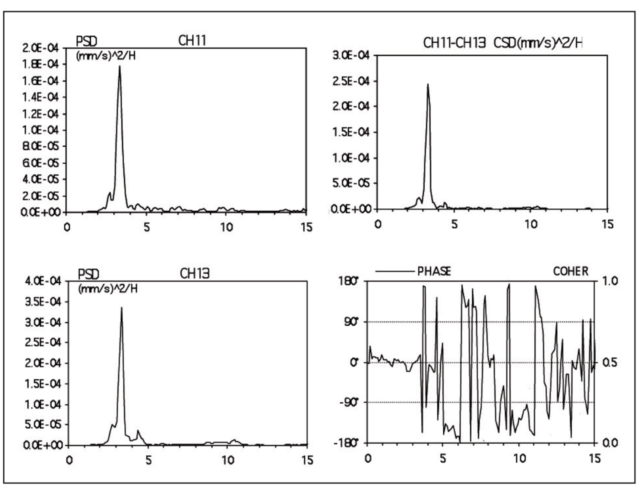


FIGURE 3 PSD and CSD of longitudinal sensors CH_{11} and CH_{13}
Source: ENEA

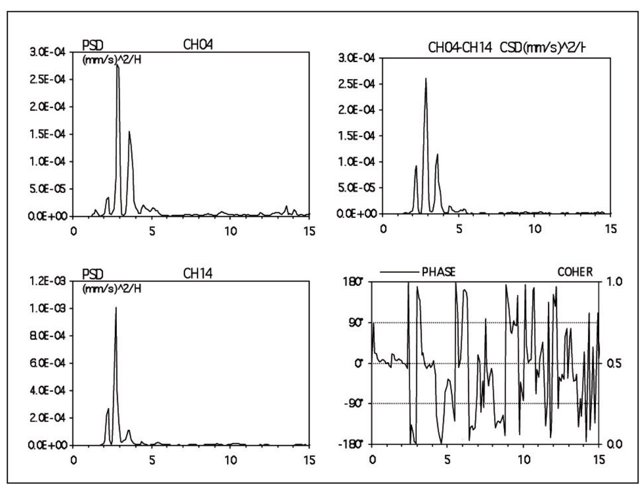


FIGURE 4 PSD and CSD of transversal sensors CH_{04} and CH_{14}
Source: ENEA

were used as temporary supports for steel columns and brick walls to install the lead rubber bearings under each column;

- the City Hall of Oakland, where 112 devices were installed and the superstructure was strengthened by means of reinforced concrete shear walls. Structural details were studied to protect the structure from earthquakes during the works, and the construction phases guaranteed the symmetry. The works were completed in 1995.
- the City and County Building in Salt Lake City, a massive unreinforced masonry structure completed in 1894. The isolation system is composed of 443 lead-rubber bearings, installed underneath the building on top of existing foundations.
- a masonry school building in Vanadzor, Armenia, after the 1988 earthquake; the construction phases are shown in Fig. 5.

Among the proposals, not realized at the moment, it is worth reminding the seismic retrofit of the Iran Bastan Museum in Tehran [12] and the seismic retrofit of a residential building in Belluno, Italy.

The isolation system must be designed in order to reduce the seismic action in the superstructure to the value that the restored building will be able to support in the elastic range. More in detail, the first period of vibration of the isolated building should be chosen as the one corresponding, in the elastic spectrum relating to the superstructure, to the acceleration value that the superstructure is able to bear. Then the corresponding displacement values in the elastic spectra relating to the isolation system, are evaluated.

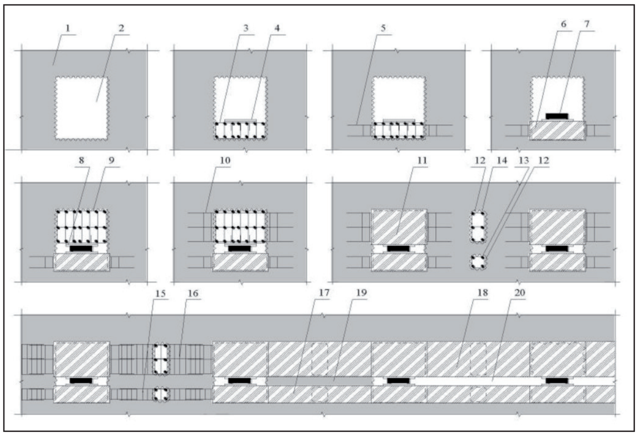


FIGURE 5 Construction phases for the isolation system in the school in Vanadzor
Source: M. Melkumyan

In the case study, a preliminary analysis allowed to fix 0.10g as the maximum spectral acceleration tolerable by the superstructure and the corresponding period was tentatively assumed as period of vibration of the isolated building. This value was first compared with those obtained during the experimental analysis. In fact, a suitable decoupling between the motion of the building and the motion of the soil is obtained only if the frequency of the isolated building is lower enough with reference to the frequency of the superstructure assumed as fixed at its base. Besides, it is important reminding that the seismic microzoning, carried out by the Italian National Civil Protection Department, pointed out the presence of seismic amplifications in the range 0.4÷0.6 *Hz* in a wide area, which also

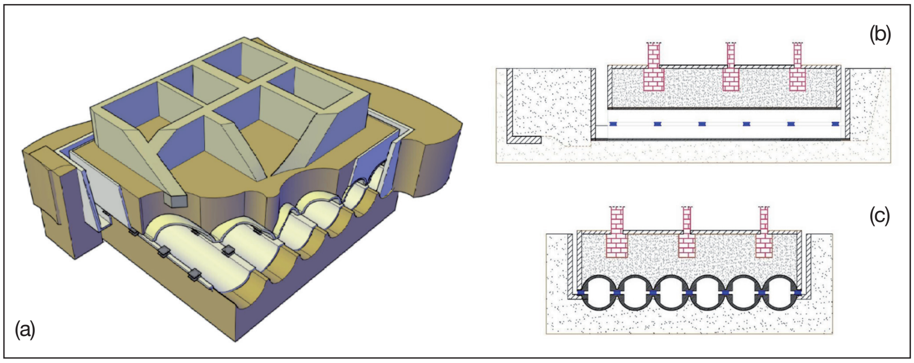


FIGURE 6 The new isolation system: (a) view, (b) longitudinal and (c) transversal sections
Source: ENEA

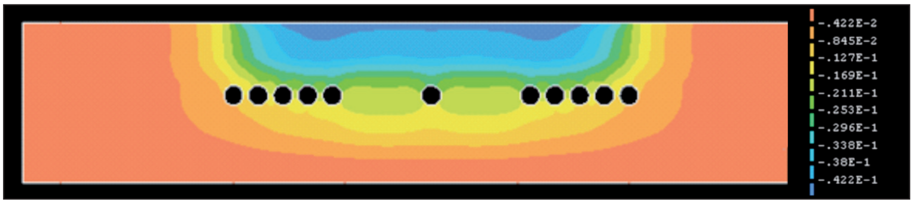


FIGURE 7 Filling the layer of pipes (strategy 1)
Source: ENEA

included the site of Palazzo Margherita. So the main resonance frequencies of the isolated structure should be lower than the minimum value of this range. Taking into account all these considerations, a period of the isolated building equal to 3.0 s was fixed. At this period, the spectral acceleration and displacements were S_e=0.07g and S_{De}=0.30 m, respectively.

A New Isolation System

An innovative solution has been proposed for Palazzo Margherita, which consists in the realization of an isolated platform under the foundations of the building, without touching the building itself (Fig. 6). A discontinuity between the foundations and the soil is created by inserting horizontal pipes, by means of auger boring or micro-tunnelling technique, the positioning of isolation devices at their horizontal diametric plane and the realization of a double system of vertical walls around the building. The pipe diameter should be ≥ 2 *m*, in order to allow the inspection and the substitution of the devices. The pieces of pipe have a particular shape, composed of a lower and an upper sector, connected by means of removable elements. The removable elements, placed in correspondence of the isolator locations are first removed, and the isolation devices are positioned also joining each pipe with the two adjacent ones by means of reinforced concrete elements. Then, also the other connection elements along the pipe are removed, other reinforced concrete elements are casted to connect adjacent pipes, so the lower sectors are definitely separated from the upper ones. Finally, vertical walls are built along the four sides of the building [13, 14].
The structure is seismically isolated but not affected by any interventions that could modify its architectural characteristics, which is very important for historical buildings. Even underground level are not modified but can be part of the seismically protected building. The system also allows the realization of a tunnel for pedestrians or vehicles.
During the micro-tunnelling operation two problems can arise: the soil settlement and the vibration induced at the surface level [15]. Analogue experiences suggest that minor threats should be expected from induced vibrations, but theoretical and experimental in-depth studies are needed. More serious problems can arise by settlements [16]. A FE 2-D model was set up and then exploited in a *Diana 2* environment. The vertical edges of the model are kept far enough from the perturbed zone, to reduce their influence as much as possible. The nodes belonging to those edges are restrained by means of springs and dampers able to cut-off the wave reflection. In the model the soil is described as a layered continuum indefinitely extended, supported by the bedrock at 17 m depth. The building imposes a load of 3000 kN/m uniformly distributed along its base width. That load induces a local settlement. Then micro-tunnels, later named simply "pipes", are included in the model, following two different alternative strategies: i) strategy 1: one central pipe, then the two most external ones and all the others filling the layer from the external pipes to the centre (Fig. 7); ii) strategy 2: one central pipe, then the two most external ones; other pipes are then inserted in intermediate positions, regularly spaced, gradually filling the layer.
The settlement due to the insertion of pipes, originated by a stress release process, was computed as the difference between the settlement due to the weight of the building and the insertion of the pipes and the settlement due to the weight of the building alone. The three-dimensional mechanism of the stress release during micro-tunnelling was described by a

plane-strain two-dimensional model by means of a conventional hole-boundary force reduction approach known as "β-value method", or Convergence-confinement method using the stress-release factor λ, varying inside the 0-1 range. For the case of $\lambda = 0.4$ and $H/D = 3.5$, where H is the depth of the pipe axis and D is the diameter of the pipe, the final computed value of the settlement is about 6.8 *mm* for the strategy 1, and about 5.6 *mm* for the strategy 2. Increasing the stress release factor λ to 0.6 the settlement values increase of about 1.2. A larger H/D ratio reduces the problem but increases the cost of the trenches. Technologies to contrast the settlements exist and are consolidated but, of course, they push the cost up.

Conclusions

For the seismic retrofit of Palazzo Margherita, the City Hall in L'Aquila, seriously damaged by the 2009 earthquake, an isolation system has been proposed. It is based on the realization of an isolated platform under the building foundation without any intervention on the building itself and can be used not only for single buildings but also for complex structures, typical of the Italian historical centres. The structure was first studied by means of the dynamic experimental analysis, the results of which were determinant for the design of the isolation system as well as the seismic response at the site.

References

[1] De Stefano A., Clemente P. (2009). *"Structural health monitoring of historic buildings"*. In Karbhari V.M. and Ansari F. (Eds) Structural Health Monitoring of Civil Infrastructure Systems, Woodhead Publishing Ltd.

[2] Clemente P., Rinaldis D. (2005). *"Design of temporary and permanent arrays to assess dynamic parameters in historical and monumental buildings"*. In Ansari F. (ed), Sensing Issues in Civil Structural Health Monitoring (Proc., North American Euro-Pacific Workshop, CSHM, Honolulu, 10-13 November 2004, invited paper), Springer, 107-116.

[3] Rinaldis D., De Stefano A., Clemente P. (2005). *"Design of seismic arrays for structural systems"*. In Ou J.P., Li H. & Duan Z.D. (eds), Structural Health Monitoring of Intelligent Infrastructure (Proc., 2nd International Conference SHMII-2, Shenzhen, Nov.16-18, 2005), Vol. 2, 1447-1453, Taylor & Francis/Balkema, Leiden, The Netherlands.

[4] De Stefano A., Clemente P. (2005). *"S.H.M. on historical heritage. Robust methods to face large uncertainties"*. Proc., 1st International Conference on Structural Condition Assessment, Monitoring and Improvement, (12-14 Dec. 2005, Perth, W. Australia), 09-22, CI-Premier Conference Organisation, Singapore.

[5] Clemente P., Buffarini G. (2009). *"Dynamic Response of Buildings of the Cultural Heritage"*. In Boller C., Chang F.K., Fujino Y. (eds), Enciclopedia of Structural Health Monitoring, John Wiley & Sons Ltd, Chichester, UK, 2243-2252.

[6] Buffarini G., Clemente P., Rinaldis D. (2009). *"Experimental Dynamic Analysis of Cultural Heritage Buildings"*. Proc., Int. Operational Modal Analysis Conference, IOMAC 2009 (Portonovo, May 4-6), 459-466.

[7] Clemente P., Rinaldis D., Buffarini G. (2007). *"Experimental seismic analysis of a historical building"*. Journal of Intelligent Material Systems and Structures, Vol. 18, No. 8, 777-784, 07 SAGE Publications.

[8] Rinaldis D., Clemente P., Buffarini G. (2010). *"Dynamic Behavior of a Historical Building"*. In Advanced Materials Research Vols. 133-134 (2010), Proc. 7th International Conference on Structural Analysis of Historic Constructions, pp 659-664, © (2010) Trans Tech Publications, Switzerland.

[9] Buffarini G., Clemente P., Paciello A., Rinaldis D. (2008). *"Vibration Analysis of the Lateran Obelisk"*. Proc., 14th World Conference on Earthquake Engineering (Beijing, 12-17 October), Paper S11-055, IAEE & CAEE, Mira Digital Publishing, Saint Louis.

[10] Buffarini G., Cimellaro G., Clemente P., De Stefano A. (2011). *"Experimental dynamic analysis of Palazzo Margherita after the April 6th, 2009, earthquake"*. Proc. 4th Int. Conf. on Experimental Analysis for Civil Engineering Structures, EVACES 2011, (Oct. 3-5, Varenna, Italy), 247-254.

[11] Clemente P., Bontempi F, De Stefano A. (2012). *"Application of seismic isolation in masonry buildings"*. Proc. 5th European Conference on Structural Control – EACS 2012 (Genoa, Italy, 18-20 June), Paper No. 117.

[12] Clemente P., Santini A., Ashtiany M. Ghafory (2009). *"The proposed isolation system for the Iran Bastan Museum"*. In Mazzolani F.M. (ed), Protection of Historical Buildings, PROHITECH 09 (Proc., Int. Conf. on Protection of Historical Buildings, Rome, Italy, 21-24 June 2009), Vol. 1, 575-682, Taylor & Francis Group, London.

[13] Clemente P., De Stefano A. (2012). *"Seismic isolation in existing complex structures"*. 15th World Conf. on Earth. Eng. (15WCEE), Lisbon, 24-28 Sept. 2012, Paper No. 0712.

[14] Clemente P., De Stefano A., Zago R. (2012). *"Seismic retrofit of historical buildings with seismic isolation"*. 8th Int. Conf. on Struct. Analysis of Historical Constr. (SAHC), Wroclaw, 15-17 Oct. 2012, Paper No. 196.

[15] Clemente P., De Stefano A. (2011). *"Application of seismic isolation in the retrofit of historical buildings"* In Brebbia C.A.& Maugeri M. (eds) Earthquake Resistant Engineering Structures (Proc., ERES 2011, Sept. 7-9, Chianciano, Italy), 41-52, WIT Transactions on The Built Environment, Vol. 120.

[16] Clemente P., De Stefano A., Renna S. (2011). *"Isolation system for existing buildings"*. Proc., 12th World Conf. on Seismic Isolation, Energy Dissipation and Active Control of Structures – 12 WCSI (Sept. 20-23, Sochi, Russia), ASSISi.

Microbe-Based Technology for a Novel Approach to Conservation and Restoration

Changes both in the human perception of the environment and in conservation thinking, that have evolved following the Venice Charter (1964), require changes in the approach to scientific and technological research for cultural heritage. Bio-based methods are meeting those needs, presenting some advantages over the traditional chemical-physical methods: low environmental impact, absence of toxic effects for operators, selectivity for the weathered material, safety for the artwork and economical costs. Ongoing activities at ENEA in microbe-based technology address problems still lacking solution or needing improvement with respect to costs, feasibility and safety, both for operators and artworks; among them, the removal of shellac and adhesives from different materials composing artworks or historical documents. An overview of diagnostic and bio-restoration activities is presented

Nicoletta Barbabietola, Flavia Tasso, Michela Grimaldi, Chiara Alisi, Salvatore Chiavarini, Paola Marconi, Brunella Perito and Anna Rosa Sprocati

Introduction

In recognition of the fragile nature of our cultural heritage and its invaluable legacy, which is integral to our future, European policy has sought to identify the best, most sustainable means of conserving our artworks. The Venice Charter (1964) identified a number of key conservation principles relating to minimum intervention, reversibility, repeatability and retreatability, providing, in this way, a framework for deciding on acceptable and unacceptable conservation interventions. These conservation principles are not static, but have evolved over time, as a consequence of both the internal development of conservation as a profession and the changes in the human perception of the world, and of the environment in particular. From the middle of the last century, a widespread opinion in unlimited progress and prosperity led to believe in the principle of human universality. Fifty years on, our perspective has changed to one in which we recognize the complexity and dynamism of the world and the variety of species and cultures it contains. So perspective has changed to a global rather than a universal one, diversity is now a key issue, whether cultural or ecological, and sustainability has become a social, economic and political force. This perspective

Chiara Alisi, Salvatore Chiavarini, Paola Marconi, Anna Rosa Sprocati, Flavia Tasso
ENEA, Unità Tecnica Caratterizzazione, Prevenzione e Risanamento Ambientale

Nicoletta Barbabietola, Michela Grimaldi, Brunella Perito
Università degli Studi di Firenze, Dipartimento di Biologia Evoluzionistica

accepts not only the complexity of life, but also that it is impossible to control everything (European Parliament; Directorate-general for research - 2001).
Through all these changes, the principles of conservation activity have been reinterpreted. So, whilst in the past we would have expected to achieve the total control of the environment, we are now prepared to accept the principle of minimum intervention, the notion of the life-cycle of materials, including heritage materials, and the development of the concept of ''acceptable levels of damage''. The principles of reversibility and/or repeatability have been openly discussed and have been replaced by the principles of compatibility and retreatability, which represent a more sustainable conservation strategy. Compatibility requires that treatment materials do not have negative consequences, and retreatability requires that the present conservation treatment will not preclude or impede future treatments. These principles are considered more sustainable because they are more realistic and enable future treatments to take advantage of progress in scientific knowledge, whereas preventive conservation is closely associated with environmental sustainability.
These changes in conservation thinking require changes in the approach to scientific and technological research for cultural heritage (European Parliament; Directorate-general for research - 2001). In the last decade, chemistry, physics and material science played an important role in many aspects of cultural heritage conservation, but today the scene is dominated by biotechnology and applied microbiology, which contribute to the development of new methods, both for a correct biodeterioration diagnosis of weathered historic artworks (Fernandes 2006) and for the development of bio-based restoration techniques for cleaning and consolidation applications (Palla et al. 2006). The development of bio-based techniques took a great advantage from the scientific knowledge gained through research projects funded by the European Community in the Fifth Framework program (2011 EUR 24490 Directorate-General for Research and Innovation Environment). The application of biotechnology for improving the conditions of deteriorated artworks has been recently developing (Webster & May 2006). The biocleaning of frescoes (Ranalli et al. 2005), the removal of black crusts and salts from stone (Heselmeyer et al. 1991, Cappitelli et al. 2007), the bio-consolidation of carbonatic materials (Tiano et al. 1999, Rodriguez-Navarro et al. 2003, Sprocati et al. 2007) represent examples of where microbial technology may contribute to the innovation of conservation.

Ongoing Activities at ENEA: Microbial Technology for Open Issues

The application of physical and chemical techniques to the field of Cultural Heritage has a long history inside ENEA, whereas the application of microbial biotechnology is recent. Our research addresses problems still lacking solution or needing improvement with respect to costs, feasibility and safety both for operators and artworks. Biotechnologies present advantages over the traditional chemical-physical restoration methods: low environmental impact, absence of toxic effects for operators and human health, selectivity for the weathered material, safety for the artwork and economical costs (Webster & May 2006). The activities started in collaboration with the Superintendency for Southern Etruria, on the occasion of the restoration of the Etruscan hypogeum of Mercareccia, located in Tarquinia necropolis of Monterozzi, declared World Heritage in 2004 by UNESCO. The work involved the characterization of large deteriorated areas of the tomb walls, once decorated with reliefs and paintings and now almost entirely disappeared. Microbial characterization, carried out using both classical cultivation and molecular techniques, allows understanding which microorganisms are naturally able to colonise that monument in the course of time, providing a reasonable base for the development of monitoring protocols for the prevention of the biodeterioration over time. At the same time, it allows isolating microbial strains, that can be studied and used for bio-restoration applications. Activities continued on bio-restoration, identifying some critical problems still open, such as the removal of shellac, which is a serious problem for valuable mural paintings, and the removal of adhesives from paper documents.

Microorganisms play a dual role, as a single function can be harmful or beneficial, depending on the circumstances. They can be responsible for the destruction of cultural heritage assets, but this "destructive" action can be used for the biological removal of deteriorated superficial patinas, or even converted in a 'constructive' action, able to induce the precipitation of calcium carbonate deposits on carbonatic materials. Beneficial use of microorganisms for cultural heritage applies both to bio-cleaning and to bio-consolidation, which represent the main bio-restoration application fields.
Metabolic capabilities of our interest in bio-restoration are the ability to precipitate calcite and, conversely, to dissolve carbonate patinas; the capacity to biodegrade resins and glues; the ability to produce biomolecules with surfactant or emulsifying properties. Preferably, the strains should be non-spore-forming, to be sure not to leave latent forms after treatment, and non-pathogenic. The about 120 strains isolated from the tomb walls are now part of the laboratory strains collection "ENEA-Lilith", containing numerous bacterial strains of different environmental origin, suitable for applications of bio-consolidation and/or bio-cleaning. The activities are briefly illustrated in the following; scientific details are exposed in published papers (Sprocati et al. 2007, Sprocati et al. 2008). Detailed information and a historical excursus on studies carried out on the addressed restoration problems may be examined in depth in the doctoral dissertation of Barbabietola (2012).

Bio-Consolidation

The research into a new approach which uses bio-carbonates, more similar to the nature of the stones treated, derives from the necessity to get over some of the drawbacks of the traditional consolidation treatments: incompatibility between the stone and the material applied, low penetration, scant solubility and high degradation, in particular for organic products.
All this has motivated several research groups to carry out numerous experiments, which have led to the development of two patents (Adolphe et al. 1990, Castanier at al. 1995) and to the European project BIOREINFORCE. The first applications of a bio-mediated consolidation were based on the use of Organic Matrix Macromolecules (OMMs) extracted from the shell of a mollusc (Mytilus californianus) (Tiano 2005). Recently, Jroundi F. et al. (2010) demonstrated that the application of an appropriate nutritional medium to non-sterilised porous limestone (calcarenite) in the sixteenth century San Jeronimo Monastery in Granada, Spain, led to the formation of a coherent cement of bacterial calcium carbonate within the stone pores, highly efficient for the consolidation of carbonate stones like calcarenite, due to the presence of native calcinogenic bacteria.
From the Etruscan tomb of Mercareccia we isolated several bacterial strains capable of precipitating calcium carbonates (bio-mineralizers), allowing for the establishment of a collection of strains producing crystals of different colours and sizes, that may be useful for applications to different colour gradation stones (Fig. 1). Some of them have not so far been described for calcinogenic ability. On the basis of the rate of crystals formation on colonies grown on agar medium, as well as of a visual assessment of the amount of crystals purified from it, a few strains have been chosen for a trial of bio-consolidation on the Pietra di Lecce, by in vivo application. The strain TSND 13 (genus Rhodoccoccus) has performed best, considering the reduction of water absorption by capillary action (about 20% vs. control), the alterations in the colour of the stone, the type of biofilm formation and the type and amount of precipitated crystals. This bacterial genus had not been studied for similar applications yet and, compared to the strains usually used in these studies, it has the advantage of being non spore-forming and so easy to eliminate at the end of treatment.

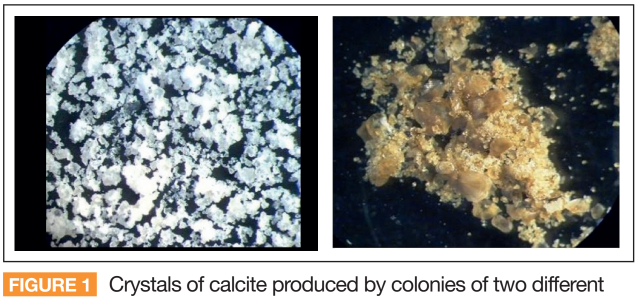


FIGURE 1 Crystals of calcite produced by colonies of two different bacterial strains (stereomicroscope 50x)
Source: Sprocati el al, 2008

Bio-Cleaning

Removal of Shellac Films from Mural Paintings

Shellac is a natural resin of animal origin, produced from the glandular secretion of an Indian scale insect, Kerria lacca, which lives on numerous trees from the East Indies. On the molecular level, shellac is a complex mixture made of mono- and polyesters of hydroxy aliphatic and sesquiterpenoid acids (Colombini et al. 2003). The use of shellac as a fixative for mural paintings was very widespread in India, being used for the restoration of paintings kept in the caves of Ajanta, Ellora, Bagh or Kancheepuram (Bridgland, 2008, Sharma et al. 1980).

The Ajanta caves had been forgotten and, after re-discovering in 1819, they were further subjected to erosion and human vandalism. In 1920-1922, serious restoration work was initiated by an Italian Conservator L. Cecconi and his associates, applying the white quality of shellac diluted in alcohol or turpentine oil as a preservative coat to protect the paintings (Sharma et al. 1980). Around 1970-1980, the work was continued by the staff of Hyderabad state, who repeatedly and liberally applied shellac, probably with the aim of brightening the paintings (Mora and Philippot, 1984).

Although shellac showed good penetration features, adhesive properties and resistance to biological attacks, the resin had a tendency to yellowing and darkening, becoming hard, brittle and insoluble, because of polyesterification reactions accelerated by high temperatures (Fig. 2). Therefore, cleaning operations were necessary to re-establish the visual perception of the paintings. In the last thirty years different cleaning procedures, which have involved the use of various solvents, have been carried out. Colour loss, white crusts and surfacing of soluble salts appeared after each treatment. Recently, an investigation into Cave 17 highlighted the fragility of the paint layers and the worsening of lacunae over time. Moreover, general phenomena of abrasion of the pictorial film, ascribable to cleaning operations using over-abrasive methods, are evident in specific areas on the different walls (Giovagnoli et al. 2008).

From the cited example, it is evident that, even where a procedure of solubilisation of the resin could be set up, further deterioration processes might occur. The result is an extreme difficulty in the removal of the resin and the impossibility of carrying on successive restoration procedures, compromising the artwork conservation. Moreover, the use of chemical solvents in confined spaces, such as caves, can have harmful effects for conservationists.

Shellac Biodegradation

To our knowledge from the literature, there are no previous studies on the ability of microorganisms to use shellac as a carbon source, degrading it into less complex molecules.

Following a screening, performed on numerous strains of laboratory collection "ENEA-Lilith", using the Biolog systemTM, we selected three bacterial strains, CONC 11 (genus Pseudomonas), CONC 18 (genus Achromobacter), and LAM 21 (genus Acinetobacter), capable to grow over three orders of magnitude higher than the concentration of bacterial inoculum

FIGURE 2 Images of an Ajanta painting (a) and of a detail (b), showing the worst conservation conditions
Source: http://www.saigan.com/heritage/painting/ajanta/ajanta.html

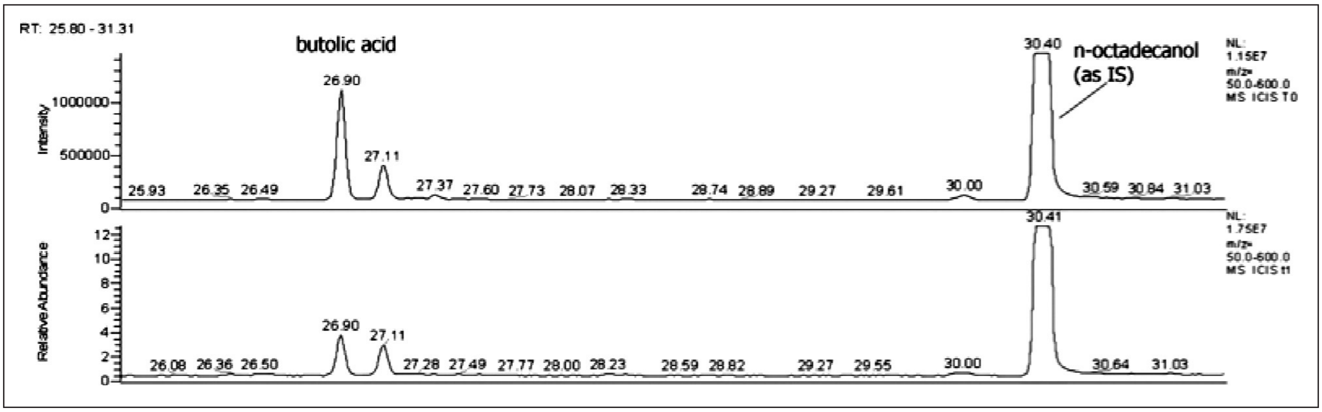


FIGURE 3 Gas Mass analysis of Shellac composition at baseline and after 72 hours (top-down) of growth of the strain CONC 18
Source: Doctoral thesis Barbabietola, 2012

within 24 hours, using shellac as sole carbon source. The rate of use is a key parameter in such a case, as an application over an extended period of time may pose a risk to the integrity of the artwork. In our batch experiments a partial degradation of fresh shellac was observed. Thanks to gas-mass analysis and the novel extraction procedure we developed, it has been shown that the bacterial growth was supported by the butolic acid, the more hydrosoluble fraction of shellac, reduced by 80% after 72 hours (Fig. 3). Given the macromolecular nature of shellac, work is in progress to increase the degradation action, by developing a microbial formula with a higher degradative power, thanks to the metabolic networks individually provided by the different strains. Pending the development of the microbial formula, specimens of mural paintings, partly coated with a thin film of a shellac solution, were purposely prepared for in vivo testing that will be carried out. The specimens are now under artificial weathering, at environmental conditions of 34 °C and 90% R.H, which simulate the annual average climate of the Ajanta caves.

Removal of Animal Glues from Paper Materials

Animal glues are natural polymers derived from the bones, skins, tendons and cartilage of mammalians or fishes. These glues may exhibit varied physical, chemical and mechanical properties, depending on their origin and method of preparation. Animal glues are mainly made up of collagen, which is an insoluble fibrous protein consisting of long molecules composed of naturally occurring amino acids that are linked in a specific sequence by covalent peptide bonds. Collagen is insoluble in cold water and is transformed into soluble gelatine by denaturation in hot water, a process of critical importance for the performance of the resulting glue. Animal glues were historically used both in paper manufacturing, during the sizing process, and in conservation as adhesive for the lining of prints or graphics and for the creation of passe-partout. Animal glue films are highly hygroscopic and go through degradation by ageing. The development of internal stresses will affect the glue's elasticity, strength and physical stability and may lead to significant damage to the substrate. Humidity, temperature, UV radiation and pollutants can induce deterioration phenomena, such as protein cross-linking, hydrolysis of peptic bonds, oxidation, while the presence of microorganisms can lead to the production of acid metabolites and pigmented spots, which cause a strong optical-chromatic alteration. So the removal of glue staining and the detachment of prints from the aged support become an essential step in the restoration and conservation of paper artworks. For centuries, cleaning was the most common, indeed the sole form of paper restoration, as the large number of methods, products and 'formulae', handed down to us, testifies. The choice of a cleaning method depends

on the degree and extent of dirt and stains, each requiring specific treatment. Mistaken diagnoses can increase damage through the prescription of the wrong cure (Crespo et al. 1984). These methods, together with more recent recipes, can be divided into four groups: 1) Mechanical methods, 2) Cleaning with non aqueous solvents, 3) Bleaching, 4) Washing enhanced with the use of specific substances, such as detergents, colloidal agents or enzymes.
Each method shows drawbacks. To date, the use of enzymes is the only bio-based method. The need for skilled operators, together with the optimal application conditions required (high temperature, stable pH conditions, favourable saline concentrations), and the high costs have created difficulties in mastering the enzyme use so far. Moreover, the successful enzyme applications described in the literature are mainly directed at the removal of starch paste (Schwarz et al. 2003).
These considerations have led us to develop a method for the removal of animal glues from paper, which combines efficacy of treatment with ease and feasibility. For this purpose, we use bacterial cells that do not require restrictive operating conditions.
Cervione glue and rabbit skin glue were chosen to carry out degradation trials because they were the most used in cultural heritage conservation. Following a screening, five strains were selected from the laboratory strains collection "ENEA-Lilith", able to grow on glue/ glues as sole carbon source. None of the selected strains had cellulolytic activity, which would render them unsuitable for application on paper material.
Original paper samples, kindly supplied by the National Institute for Graphics, representing the back supports of ancient prints from a historical volume of prints from the collection of the Institute, have been treated with bacteria. The strain TSNRS 15 of the genus Ochrobactrum, deriving from an Etruscan hypogeum, was selected as a good candidate, because it was able to grow on both glues within 24 hours. This research applied for the first time this bacterial genus in a process of paper bio-cleaning. The vulnerability of the support (paper) requires much care in developing a gentle procedure; the bio-cleaning treatment was thus performed with bacteria immobilized in an agar gel. The treatment showed its efficacy already after 4 hours of incubation, allowing the complete removal of the thick layer of glue from the surface of the paper specimen. The colorimetric measurements allowed to assess the whitening of the specimens, by the increase in the L* and the decrease in the b* coordinates. SEM

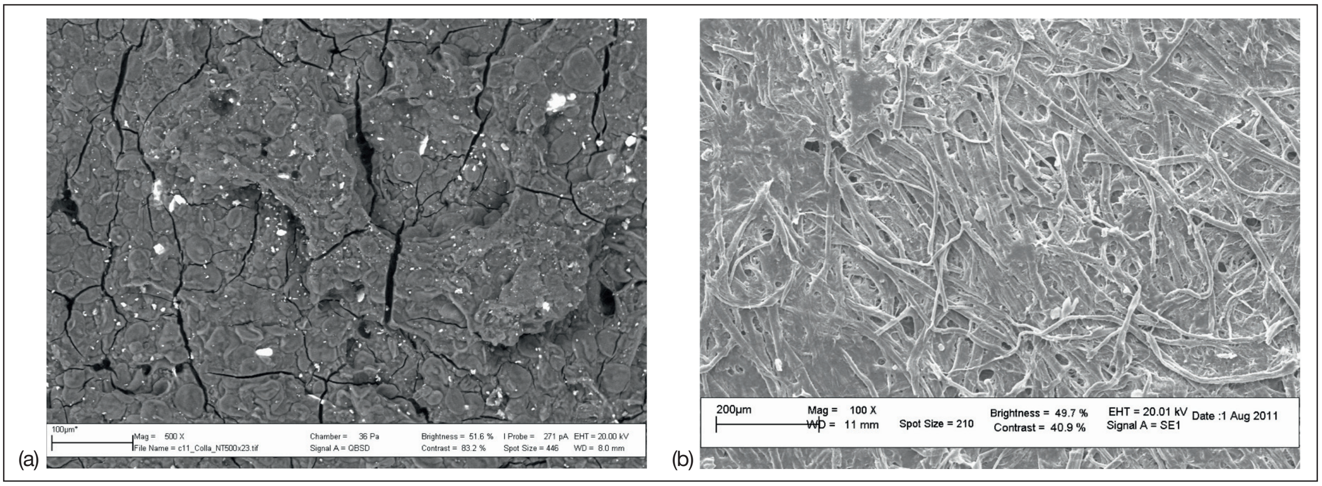


FIGURE 4 Images (SEM 500x) of a paper specimen before treatment, where the glue layer is evident (a), and after 4-hour treatment with the strain TSNRS 15 immobilised in agar gel, where the cellulose fibres are disclosed (b)
Source: Doctoral thesis Barbabietola, 2012. SEM analysis was kindly performed by ICRPAL laboratory

observations, performed after 4 hours of treatment, showed cellulose fibres appearing from the compact paste layer, demonstrating the disappearance of the adhesive layer consumed by bacteria as a carbon source (Fig. 4). Conversely, the observation of the samples treated with the sole agar gel, bacteria-free, shows significant glue residues, characterized by globular clusters, clearly visible on the surface. The final stage of the procedure is designed to check out that no undesirable residues are left over after the treatment, in order to avoid both the continuation of undesired metabolic processes and possible secondary colonisation due to the remains of the organic gel carrier. Actually, both streaking a swab after the treatment and SEM observation demonstrated that no residual bacteria or gel fragments were detectable.
The advantage of the developed procedure, based on living bacteria, over the current methods of glue removal, based on enzymes, lies in the metabolic versatility of microorganisms, that can adjust their action according to the changing conditions.

Partnerships

In partnership with the University of Florence two doctoral theses, awarded by the University, have been carried out at ENEA leading to scientific knowledge on shellac biodegradation; establishing a bio-cleaning procedure of original specimens of ancient paper kindly provided by the National Institute for Graphics, and exploring the application of biomolecules with surfactant properties (SACs), produced by selected microbial strains, for the removal of deposits or coatings from artworks. On the latter topic cooperation with the Department of Biomedical Sciences of the University of Cagliari is in progress.
With the Biology laboratory of the Central Institute for Restoration of the Book Heritage (ICRPAL), collaboration is underway on a diagnostic investigation of a biodeteriorated ancient parchment. Recently, collaboration has been extended to the University of Arizona.
A multidisciplinary study of an ancient Roman fresco fragments from the archaeological site Casa di Augusto at the Palatino is underway, in collaboration with the Special Superintendency for Archaeological Heritage of Rome, the Architectural Conservation and Restoration of University of Lund (Sweden), the Chemical Engineering Department of the University of Rome "Sapienza" and the Applied Physics Institute-National Research Council, Florence.
In collaboration with Small Restoration Enterprises, operating with different Institutions and especially with the Special Superintendencies for Archaeological Heritage of Rome and of Southern Etruria, preliminary trials are successfully in progress on frescoes in the Lodge of Casina Farnese, at the Palatino site, for the removal of hardened layers of casein and deposits from urban pollution.
Regarding activities on stone bioconsolidation, we thank the laboratory of magnetic resonance "Annalaura Segre", of CNR of Rome 1, for the kind willingness to cooperate with us.

Concluding Remarks and Perspectives

Biotechnology applied to restoration is an area still under development. In perspective, optimal restoration solutions require strong interaction among bio-based methods and physical- and chemical-based methods, as well as a better understanding and dialogue between the scientific-technological world and the art-restorers world.
Within this framework the research presented in this paper has led to advancement in the state of the art, both in terms of knowledge and potential applications. The research on shellac biodegradation represents the first attempt for its removal through a biological approach and has provided knowledge to develop a microbial formula for the removal of shellac without using toxic products. A successful procedure for the bioremoval of glues from ancient paper has been established, using for the first time immobilised living bacteria, instead of enzymes, expensive and of difficult application. All the bacteria used in this research have been tested for the first time for these purposes and have been specifically selected among numerous environmental strains of the ENEA laboratory collection, isolated and characterised for biotechnological application. All strains r-DNA 16S sequences are deposited at the GeneBank.

Thanks to the skilled partnerships, scientists as well as conservationists, we have the opportunity of expanding and deepening our investigations and the chance of testing our original products (microorganisms and bio-molecules arising from them) on real specimens. In perspective, this point is of great help to develop specific procedures for bio-restoration.

Acknowledgements

Authors thanks dr. Giovanna Pasquariello of the National Institute for Graphics, Rome, Italy, for providing paper specimens of historical importance; dr. Flavia Pinzari of the Central Institute for Restoration of the Book Heritage (ICRPAL, Rome, Italy) for sharing the research on parchment specimens and Livia Martinelli, degree student of the University of Rome "Sapienza" for her contribution in the experimental work.

References

[1] Adolphe J.M., Loubière J.F., Paradas J. and Soleilhavoup F., 1990. Procédé de traitement biologique d'une surface artificielle. European patent 90400G97.0 (after French patent 8903517, 1989).

[2] Barbabietola N., 2012. Innovative microbe-based technology for Conservation and Restoration. PhD dissertation in Science for Conservation of Cultural Heritage, University of Florence, Faculty of Mathematical, Physical and Natural Sciences.

[3] Cappitelli F., Toniolo L., Sansonetti A., Gulotta D., Ranalli G., Zanardini E., Sorlini C., 2007. Advantages of using microbial technology over traditional chemical technology in removal of black crusts from stone surfaces of historical monuments. In: Applied and environmental microbiology, Vol. 73, No. 17: 5671–5675.

[4] Castanier S., Le Métayer-Levrel, G. and Loubière, J.F., 1995. Nouvelles compositions pour mortier biologique, procédé de recouvrement d´une surface ou de comblement d´une cavité à l'aide des compositions. French Patent n. 9505861.

[5] Colombini M.P., Bonaduce, I., Gautier, G., 2003. Molecular pattern recognition of fresh and aged shellac, Chromatographia 58, n.5/6: 357-364.

[6] Crespo C., Vinas V., 1984. The preservation and restoration of paper records and books: a ramp study with guidelines. Paris, France: Programme général d'information et UNISIST,vi, 117 p. ; 30 cm.

[7] European Parliament, Directorate-General for research, 2001. Technological requirements for solutions in the conservation and protection of historic monuments and archaeological remains. European Parliament, Working paper for the STOA Unit.

[8] European Commission. Survey and outcomes of cultural heritage research projects supported in the context of EU environmental research programmes. 2011 EUR 24490

[9] Fernandes P., 2006. Applied microbiology and biotechnology in the conservation of stone cultural heritage materials. In Applied microbiology and biotechnology, Vol. 73: 291-296.

[10] Giovagnoli A.,Capanna F., Ioele M., Marcone A.M.,Ozino-Caligaris E., Risotto L., Singh M., 2008. The mural paintings of the Ajanta caves part I: documentation on execution techniques and conservation condition. In: Art 2008- Non-destructive investigations and microanalysis for the diagnostics and conservation of cultural and environmental heritage, Jerusalem, Israel.

[11] Heselmeyer, K. et al., 1991. Application of Desulfovibrio vulgaris for the bioconservation of rock gypsum crusts into calcite. BIOforum 1, 89.

[12] Jroundi F., Fernández-Vivas A., Rodriguez-Navarro C., & Bedmar E.J. and González-Muñoz M.T., 2010. Bioconservation of Deteriorated Monumental Calcarenite Stone and Identification of Bacteria with Carbonatogenic Activity, Microbial Ecology, No. 60: 39-54.

[13] Mora, P., Philippot P.,1984. Conservation of wall paintings, pp. 165-296.

[14] Palla F., 2006. Le biotecnologie molecolari per la caratterizzazione e la valutazione del ruolo dei microrganismi nei processi di degrado di manufatti di interesse storico artistico. Quaderni di scienza della conservazione: 183-194.

[15] Ranalli G., Alfano G., Belli C., Lustrato G., Colombini M.P., Bonaduce I., Zanardini E., Abbruscato P., Cappitelli F., Sorlini C., 2005. Biotechnology applied to cultural heritage: biorestoration of frescoes using viable bacterial cells and enzymes. Journal of applied microbiology, 98: 73-83.

[16] Rodriguez-Navarro C., Rodriguez-Gallego M., Ben Chekroun K., Gonzalez-Muñoz M.T., 2003. Conservation of Ornamental Stone by Myxococcus xanthus-Induced Carbonate Biomineralization. Applied and Environmental Microbiology, Vol. 69, No. 4: 2182-2193.

[17] Schwarz I., Bluher A., Banic G., Thobois E., Maurer K.H, 2003. Lo sviluppo di un impacco pronto all'uso per la rimozione localizzata di pasta d'Amido attraverso l'azione enzimatica. In: Nuove metodologie nel restauro del materiale cartaceo. Collana I talenti, Il Prato (ed.), p:89-106.

[18] Sharma, R. K., Yenkateswaran, N.S., Singh, S.K., 1980. Solvent used for the removal of shellac and other accretionary deposits. In Symposium on mural paintings under the aegis of Indo-US sub-commission on culture, held in Ajanta in April 1980/Dehra Dun: Archeological survey of India.

[19] Sprocati A.R., Alisi C., Tasso F., Vedovato E Barbabietola N., 2007. Esplorazione della tomba della Mercareccia (Tarquinia) per un'analisi descrittiva dei microorganismi colonizzatori e selezione di ceppi di interesse biotecnologico per la conservazione ed il restauro. In: Atti del Convegno Lo stato dell'Arte 5, IGIIC – gruppo Italiano - the International Institute for Conservation. Cremona (Italy),11-13 ottobre.

[20] Sprocati A.R., Alisi C., Tasso F., Vedovato E., Barbabietola N. and Cremisini C., 2008. A microbiological survey of the Etruscan Mercareccia tomb (Italy): contribution of microorganisms to deterioration and restoration, In: Art 2008 - Non-destructive investigations and microanalysis for the diagnostics and conservation of cultural and environmental heritage, Jerusalem, Israel.

[21] Tiano P., Biagiotti, L., Mastromei, G., 1999. Bacterial bio-mediated calcite precipitation for monumental stones conservation: methods of evaluation. Journal of microbiological methods, 36: 139-145.

[22] Tiano P., Cantisani E., 2005. Precipitazione bioindotta di calcite per la conservazione delle pietre monumentali, Progetto Bioreinforce – (EVK4–2000-00037).

[23] Webster A. and May E., 2006. Bioremediation of weathered-building stone surfaces, TRENDS in Biotechnology Vol.24 No.6: 256-260.

Performance of Nanomaterials for the Conservation of Artistic Stones

In the last few years nanocomposites have been frequently applied for restoration and conservation of artworks. In fact, it has been demonstrated that inorganic oxide nanoparticles, such as silica and titania, may improve the performance of materials used in the conservation field. The experience in the synthesis and characterization of nanoparticles within UTTMAT at ENEA, combined with the experience in conservation materials in terms of durability of the conservative products, fostered a research investigation on nanocomposites applied to cultural heritage. In this study, performances of nanocomposites composed by an acrylic resin and a polyalkylsiloxane with nanosilica and nanotitania will be comparatively presented. Artificial aging to verify the positive effects of nanoparticles were carried out on stone specimens treated with nanocomposites

Franca Persia, Rosaria D'Amato, Franco Padella, Luciano Pilloni, Antonio Rinaldi, Angelo Tatì

In the last few years, nanoparticles and nanostructured materials have been frequently applied to restoration and conservation of artworks [1,2]. In fact all cultural heritage undergoes aging processes with final degradation effects, due to their intrinsic material properties and deterioration phenomena, which are influenced by environmental conditions such as climate, pollution, biological agents, and mechanical stresses. In order to slow down these degradation processes it is necessary to carry out conservative interventions, consisting in restoration and preventive treatments. So far, conservation science focused on chemical compounds, in general polymers and copolymers, able to consolidate and protect the artistic substrate (e.g. coating, adhesive, water repellent and biocide materials). Nowadays the application of nanomaterials and nanotechnology is enabling new functionalities that promise to improve the properties of traditional commercial products.

Inorganic nanoparticles (such as Ag, SiO_2, TiO_2, ZnO_2, ferrites and other metal oxides) due to their unique physico-chemical characteristics, such as cohesive forces arising from high surface area, photocatalytic effect, colour tone modification, good optical properties, higher penetration depth, thermal expansion coefficient, etc., exhibit improved performance over traditional chemical compounds for the conservation field [3,4]. The modulation of physical chemical properties of a protective coating (such as polymer based paints) can be obtained by a proper blending of the coating material with suitably chosen nanoparticles. This way, the developed nanocomposite can be accurately tailored to the different purposes required from the considered application [5].

The Technical Unit for Materials Technologies (UTTMAT) at ENEA possesses a consolidated knowledge in

Franco Padella, Franca Persia, Luciano Pilloni, Antonio Rinaldi, Angelo Tatì
ENEA, Unità Tecnica Tecnologie dei Materiali
Rosaria D'Amato
ENEA, Unità Tecnica Sviluppo di Applicazioni delle Radiazioni

Sp

nanomaterials synthesis and characterization. The ENEA Technical Unit Materials Technologies (UTTMAT) possesses a consolidated knowledge in nanomaterials synthesis and characterization. In the Unit advanced diagnostic expertise and instrumentation [Scanning Electronic Microscopy (SEM), Transmission Electronic Microscopy (TEM), Optical Microscopy (OM), X Ray Diffraction (XRD), Fourier Transform Infrared Spectroscopy (FT-IR), X Ray Fluorescence (XRF), Ultra Sound (US), Termogravimetry (TG), Differential Thermal Analyses (TDA), Raman spectroscopy, light scattering and N_2 adsorption at 77K to explore nanomaterials surface characteristics, zeta potential to measure nanofluid stability] are conjugated with nanopowder synthesis capabilities. Nanosized powders are obtained by conventional and unconventional methods, such as by precipitation from water, organic and micellar solutions or by laser pyrolysis from liquid precursors. Nanoparticles are usually obtained by mechanochemistry, inducing near-room-temperature solid state reactions by Ball Milling[1]. Furthermore, since 1984 diagnostic evaluations and in situ interventions on more than 1300 artworks have been performed by UTTMAT researchers. Paintings of Michelangelo, Raffaello, Leonardo, Antonello da Messina, Beato Angelico, Piero della Francesca, Tiziano, Tibetan thangkas, frescoes, wall paintings, mosaics, bronzes, mortars and stones have been characterized [6,7,8]. In order to evaluate the compatibility and durability of conservation materials and methodologies, we have conducted diagnostic analyses on cultural materials, studies on nanoparticles and nanocomposites appropriate for the cultural heritage field, and comparisons of methodologies and materials according to different environmental parameters (temperature, humidity, solar light and simulated aerosols).

In this technical report, the results from a study about polymer-based nanocomposites and about their efficiency in protecting stones frequently found in cultural heritage are reported.

White marble (statuary and veined Carrara, Proconnesio and Pentelic), travertine and biocalcarenite samples were considered as substrates on which the nanocomposites were tested. Before treatment, all specimens were aged with natural and/or artificial weathering. Two different commercial products: Paraloid B72, an acrylic resin (methylmethacrylate/ethylmethacrylate copolymer MA/EMA 30/70 w/w%) (sold by SINOPIA) and Rhodorsil RC80, a polyethysiloxane (produced by Rhodia Silicones), were chosen as polymers for this research. As nanoparticles, SiO_2, TiO_2 and their mixture were applied; they were synthesised by CO_2 laser pyrolysis of two liquid precursors, $Si(OEt)_4$ and $Ti(i\text{-}OPr)_4$, respectively, delivering on average a mean size around 15 nm with low polydispersity [9]. In general, the synthesis of nanocomposites to obtain a final homogenous dispersion is a tricky step, depending on the type of: chosen preparation method, solvent, and particles concentrations. In our case, several preliminary laboratory tests were carried out to obtain a homogenous dispersion, without formation of protruded aggregates. SEM micrographs were used to check the results with nanoparticles at different concentration (fig.1) and the selected dispersions are shown in Table 1.

To simulate a treatment, as it happens in a real situation, the obtained suspensions were applied on the surface of the stones by brushing until visible refusal and repeating the treatment after 4 hours [10].

The nanocomposite performance was tested after submitting all the specimens to accelerated weathering by artificial sunlight and freeze-thaw cycles. This step is very delicate due to the lack of specific standard practice or regulations (national or international) ruling the tests to assess the durability of the consolidant/protective materials. Only few regulations exist and for artificial solar irradiation, the NORMA UNI 10925-2011 – which concerns the methodology for artificial solar light test applied on natural and artificial stones – was applied. Following this standard method, a climatic chamber (SOLARBOX 1550 E) equipped with a xenon arc light source, 1500 W, with spectral range from 280 to 800 nm, was used and samples underwent constant irradiation at $1000 W/m^2$ for 556 hours. The irradiation time was sufficient to ensure 2000 MJ/m^2, the specific irradiation conditions required by the above standard norm. For freeze-thaw resistance, due to the lack of any specific standard, the UNI EN 539–2 issued for tiles was applied. Tests were performed in

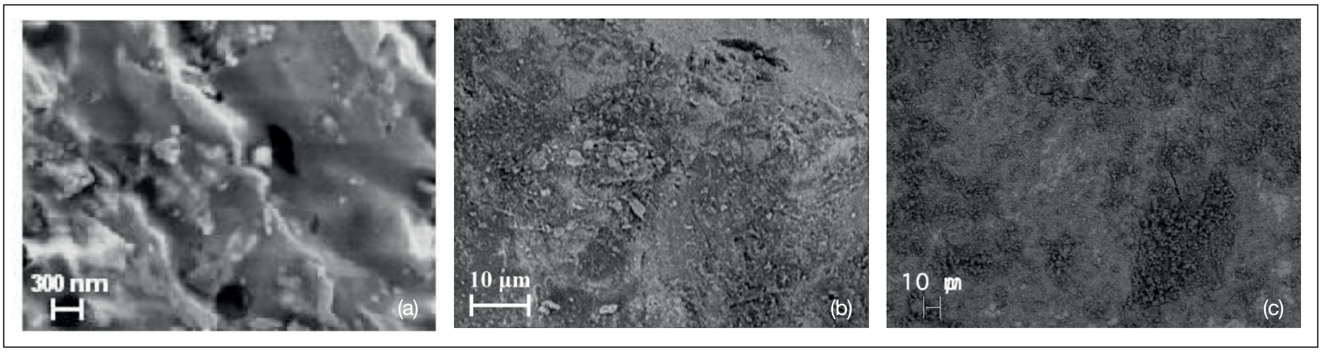


FIGURE 1 SEM images of statuary Carrara marble treated with Rhodorsil RC80 and 0.2% (a), 1% (b), 2% (c) w/v silica nanoparticles
Source: ENEA

an Angelantoni climatic chamber and samples were first immersed in water for 7 days until complete imbibition of water. About the artificial aging step, it is also possible to carry out other kinds of weathering processes simulating, for instance, the marine aerosol effect (hazard for outdoor stones), the temperature (T) and the relative humidity (RH) effects. In fact the aging processes to different environmental parameters (T, RH, sun, spray marine) must be done when a new chemical compound is commercialized. In particular, these kinds of qualifications are fundamental when considering works of art, where compatibility is a very important concept [11].

The consolidant and protective nanocomposite behaviour was tested checking some properties before and after the accelerated aging. With SEM micrographs it was possible to investigate the nanoparticle composite film morphologies and to evaluate the influence of nanoparticles on the integrity of surface coatings after the aging processes. The microstructural investigations were performed with a FEG-SEM LEO 1530 (Zeiss, Obercoken-Germany) equipped with

Polymer	Nanoparticles Concentration
RC80 and Paraloid B72	SiO_2: 1%
	TiO_2: 0,2%
	SiO_2 (0,2%) - TiO_2 (0,2%)
	SiO_2 (1%) - TiO_2 (0,1%)

TABLE 1 Final concentrations used to prepare the nanocomposites
Source: ENEA

In-lens secondary electron detector, conventional secondary electron detector and scintillation detector for backscattered electrons (Centaurus), and the higher magnification SEM image revealed that the nanoparticle aggregate morphology induces a micro- and nano-scale roughness at the surface of the films.

The wettability properties of the nanocomposite coatings were assessed by static water contact angle measurements to evaluate the local water repellence of the surface. The measurements were carried out through a home-made apparatus, in compliance with standard UNI EN 15802 – 2010 (Conservation of cultural property - Test methods - Determination of static contact angle). The measurements showed the increase in static water contact angle (θs) as a function of SiO_2 particle concentration for Rhodorsil and Paraloid B72 composite films. Fig. 2 shows the image of a water drop on a treated marble sample. The addition of both titania nanoparticles and silica and titania mixture gave comparable positive results for both kinds of investigated polymer coatings. These data suggest that nanoparticles induce a significant enhancement in hydrophobicity and impart highly water repellent properties to protective films. In particular, Paraloid B72 protective layers change their character from hydrophilic ($\theta s<90°$) to hydrophobic ($\theta s>90°$) surface [12].

The capability to protect stone materials was verified also by measurements of water absorption by total immersion. The absorption curve and the relative Imbibing Capacity (I.C.) was measured for each sample by means of the gravimetric method. These results were used to calculate the protection ratio percentages, P.R.%, defined as the percentage variation between the imbibing capacity of untreated and coated stone, according to UNI Document 10921 (Natural and artificial stones – Water repellents – Application on samples and determination of their properties in laboratory). For both RC80 and Paraloid, the water absorption data have demonstrated the enhanced efficiency of nanoparticles for marble and travertine protection.

Ultrasound method (US), a non-destructive technique that measures the velocity of elastic waves through a solid medium, stones in our case, was also carried out to provide information concerning the effect of treatments on the mechanical properties (integrity and cohesion of the protective film on the stone surface) of the specimens. A portable instrument, a Krautkramer USM 23 with low frequency using a probe of 50 KHz through transmission method, was used and no sample preparation was necessary. Ultrasonic wave velocity was measured in all specimens in the three directions X, Y, and Z. For each direction, four values were recorded and the average was calculated. A thin layer of water was used as acoustic coupling medium between the stone and the transducer. The obtained measurements were processed by a home-made software, operating in Windows XP system and able to measure the propagation time in the tested sample. This time corresponds to the interval between the initial ultrasonic pulse and the instant at which the signal exceeds a threshold in amplitude. After the consolidation treatments all the samples showed an increase of ultrasonic velocity with respect to the untreated specimens due to the improvement of structural cohesion and mechanical resistance of marble and travertine substrates.

The US results for both marbles and travertines show a significant variation with siloxane treatment, while Paraloid B72 increase reached only 5% (Fig. 3). This effect can be attributed to the low penetration capacity of the acrylic resin, partially ascribed to its high macromolecular dimensions. For Rhodorsil RC80 dispersions, the best performances were recorded with the addition of the silica and titania mixture at

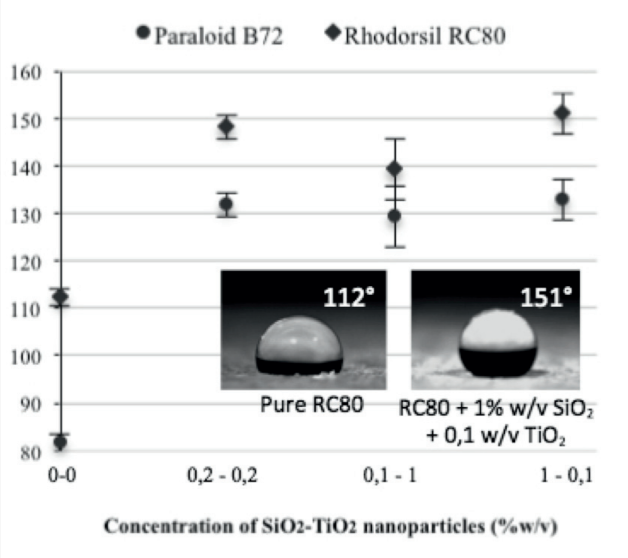


FIGURE 2 Static contact angle vs. concentration of SiO_2 and TiO_2 nanomixture
Source: ENEA

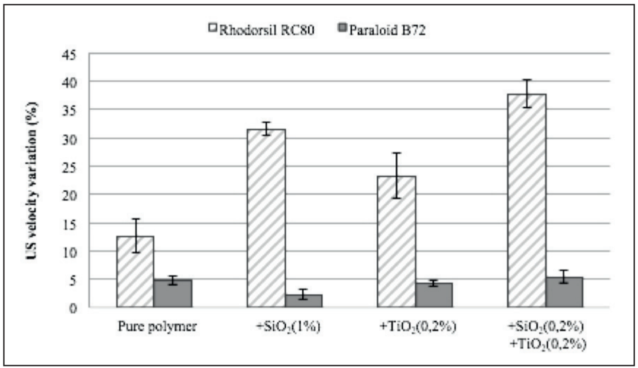


FIGURE 3 Ultrasonic velocity variation (%) in marble samples after the consolidation treatment
Source: ENEA

the same nanoparticle concentration of 0.2% w/v (an ultrasonic velocity variation of more than 25% with respect to the pure siloxane application).

Finally, colorimetric measurements were executed to calculate colour changes induced by photochemical and photothermal degradation of nanocomposites. Colour values, reported in the CIEL*a*b* space, were obtained with a Minolta CM-

525i Spectrophotometer using a D65 illuminant. The colorimetric variations, measured before and after the accelerated aging processes, revealed that the optical surface alterations remain acceptable (ΔE value is always under 5).

The results show that some properties of conservation materials can be improved with the presence of nanomaterials. Research must be continued, mainly with respect to the reversibility and compatibility of the new products. Nanotechnology can be also applied to other kinds of cultural heritage materials, such as - for instance - the restoration of wall paintings, wood and paper [1].

Note

1. Mechanochemical technique allows, in particular, a low cost production of ferrites, coloured mixed metal oxides. Starting from the particle dimensions (≈ 5nm) of as synthesized material, nanoparticles size can be modulated by simple heating up to 100 nm and above, thus obtaining a color tone modulation.

References

[1] P. Baglioni, R. Giorgi, (2006) "Soft and hard nanomaterials for restoration and conservation of cultural heritage" Soft Matter, 2, 293-303.
[2] M.J. Mosquera, D.M. De los Santos, A. Montes et al. (2008) "New Nanomaterials for Consolidating Stone" Langmuir, 24, 2772-277.
[3] P.N. Manoudis, I. Karapanagiotis, A. Tsakalof et al. (2009) "Superhydrophobic films for the protection of outdoor cultural heritage assets" Surface & Coatings Technology, 203, 1322–1328.
[4] L. Toniolo, T. Poli, V. Castelvetro, A. Manariti, O. Chiantore, M. Lazzari (2002) "Tailoring new fluorinated acrylic copolymers as protective coatings for marble" Journal of Cultural Heritage 3, 309-316.
[5] C. Miliani, M.L. Velo-Simpson, G.W. Scherer (2007) "Particle-modified consolidants: A study on the effect of particles on sol-gel properties and consolidation effectiveness" Journal of Cultural Heritage 8, 1-6.
[6] M. Diana, F. Cavallini, M. Ferretti, G.F. Guidi, M. Massimi, A. Matteja, A. Melchiorri, P. Moioli, F. Persia, A. Sargenti, R. Scafé, C. Seccaroni (1995) L'Attività dell'ENEA per i Beni Culturali. 1983-1994, Editrice Il Torchio, Firenze.
[7] E. Borsella, R. D'Amato, F. Fabbri, M. Falconieri, G. Terranova, (2011) "Synthesis of nanoparticles by laser pyrolysis: from research to applications", Energia, Ambiente e Innovazione, Vol. 4-5/2011, 54-64.
[8] P. Ferreira Pinto, J. Delgado Rodrigues (2008) Stone consolidation: The role of treatment procedures Journal of Cultural Heritage 9, 38-53.
[9] F. Persia (2008) "Problematiche relative agli invecchiamenti artificiali" Kermes, Anno XXI – Numero 72, 57-59.
[10] H.M. Shang, Y. Wang, S.J. Limmer, T.P. Chou, K. Takahashi, G.Z. Cao (2005) "Optically transparent superhydrophobic silica-based films" Thin Solid Films 472, 37-43.

ENEA Contributions to Safeguarding Material and Immaterial Knowledge from Ancient Mesopotamia

Thanks to the "Duplicazione e Rinascita" (Duplication and Rebirth) Project, funded by the Ministry of Foreign Affairs and aimed at supporting the Baghdad Museum, since the beginning of the year 2000 studies have begun in ENEA, with the purpose of protecting material goods and the great deal of knowledge of the ancient civilizations flourished in the ancient Mesopotamia, now Iraq. Although the studies, projects and activities carried out share the use of data processing in the broadest sense, they focus on three different lines of research, which have faced and are still facing the problem of preservation of ancient artifacts or – equally important – maintenance and dissemination of ancient knowledge from different standpoints. The three technologies at issue are, respectively: the Reverse Engineering and Rapid Prototyping; the integration of Language Technologies (Multilingual Text Mining) and GRID Technologies in the ENEA-GRID infrastructure, for the analysis of ancient texts in Assyriology; the use of ICT technologies for the collection, use and dissemination of cultural resources

Paola Negri, Sergio Petronilli, Giovanni Ponti, Daniela Alderuccio, Giorgio Mencuccini, Alessio Rocchi, Flavio Fontana

Introduction

Among the many archaeological objects, a special place is occupied by clay tablets written in cuneiform writing and coming from the Ancient Near East (the so-called Fertile Crescent). Beyond the purely assyriological problems, there are many issues crucial to the conservation and use of these ancient documents. In the last decade, three classes of problems have been identified, for which solutions could be found thanks to the technologies employed within ENEA in a framework of interdisciplinary cooperation.

Millions of texts were written in ancient times, and though only hundreds of thousands of those tablets are preserved, it is nevertheless an extremely important amount, often difficult to be mastered by scholars.

Whilst clay is one of the strongest writing materials employed by the man, it is not free from damage, that may result from chemical factors, such as the crystallization of the salt content in the clay, or by mechanical factors, such as fragmentation and breakage. Moreover, in ancient times tablets were not always baked – an expensive procedure reserved

Paola Negri
ENEA, Unità Tecnica Tecnologie dei Materiali

Sergio Petronilli
ENEA, Unità Trasferimento Tecnologico

Daniela Alderuccio, Giorgio Mencuccini, Giovanni Ponti, Alessio Rocchi
ENEA, Unità Tecnica Sviluppo Sistemi per l'Informatica e l'ICT

Flavio Fontana
ENEA, Unità Tecnica Modellistica Energetica Ambientale

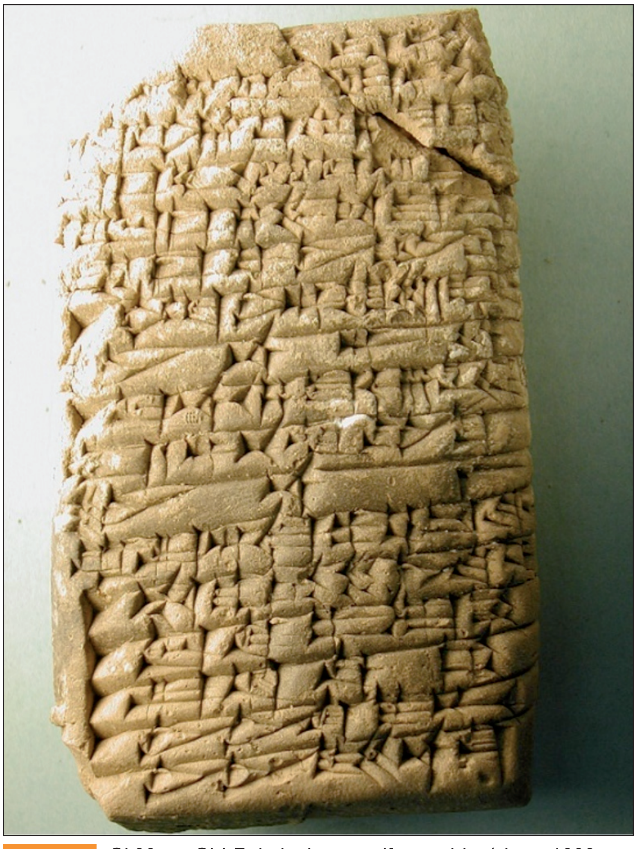


FIGURE 1 Oj 32, an Old-Babylonian cuneiform tablet (about 1800 B.C.) from Isin related to a sale of real estate
Source: ENEA / Centro Studi Diyala

for the most valuable documents destined to last – whereas the other ones, more ephemeral, were only sun dried and therefore are more subject to damage. Moreover, scholars necessarily handle the tablets to study the texts and this can damage them, although conservation treatments and methods have been developed since many years.

In addition, for study, teaching or exhibition purposes, often in modern times copies are made from casts, with procedures that may damage the tablet, because plastic substances come into direct contact with the tablet itself. So often fragments of the surface material are removed by contact with disastrous results for the conservation of the tablet itself. To solve the problem, the proposed technology is the Reverse Engineering and Rapid Prototyping, which is well developed here in ENEA.

Furthermore, in order to enhance access to text knowledge extracted from the cuneiform tablets, the integration of Language Technologies (Multilingual Text Mining) and GRID Technologies in the ENEA-GRID infrastructure offers a new perspective in the analysis of ancient texts in Assyriology, supporting scholars in mastering a large number of texts from the linguistic point of view and in managing the complexity of grammar.

Still a third class of problems arises from the number of the texts, so that for years in the field of Assyriology many different types of databases have been prepared separately by a variety of institutions. This type of information does not allow fast access, consistent and complete documentation. ICT applied to this particular type of cultural heritage can be an important response to this problem.

So, applying existing ENEA resources to an extremely complex field can both refine the techniques in our possession and provide high-value tools for a better use of cultural heritage.

Reverse Engineering and Rapid Prototyping

The term RAPID PROTOTYPING actually indicates a group of related technologies that are in use to make objects directly from CAD data sources. This methodology builds objects adding and bonding materials in layers. It is a fast and suitable solution for solving fabrication problems of objects with any geometric complexity or intricacy, that are difficult to make by a material subtraction manufacturing.

For this reason it is widely employed in several fields; in ENEA, the PROTOCENTER Laboratory employs this complex methodology in support of SMEs and handicraft, like fashion houses and jeweller's art, offering not only technological support, but also knowledge dissemination to enterprises.

In the Nineties it was observed that works of art and archaeological objects are also reproduced with this technology, and therefore in ENEA some experiments were made: as a result of these experiments some

Sp

objects have been replicated, the most relevant of which is the *Situla della Certosa*, in the Museum of Bologna.

In 2000, after that experience, a new type of archeological objects was taken into consideration, for the first time in the world: cuneiform tablets, and a preliminary attempt of applying RP to them was carried on in ENEA by a multidisciplinary team including S. Petronilli e P. Negri. Subject of the test was the cast of a XV century B.C. tablet. Testing that technology on a cast and not on a real tablet ensured that the tablet did not run any risk.

Main problems in this experiment were: 1) to obtain a readable cuneiform text; 2) to match questions concerning the form of the tablets, that are usually convex, with the text covering not only obverse and reverse, but also the four edges.

The preliminary model was built by scanning the cast of the tablet by a laser triangulation scanner. The resulting points were used as a reference for assembling the resulting "clouds of points" obtained by a high-resolution piezoelectric system. Therefore, the flexibility of a laser in reassembling "clouds of points" and the very high resolution of a piezoelectric system were mixed together.

In this preliminary experience six laser scanning and two piezoelectric scanning were performed in order to acquire all the surfaces of the tablet.

The resulting file fed an RP machine working with a multi jet modelling technology, and a model of the cast was made by adding and bonding a thermoplastic material in layers. The results encouraged the team to go on with experiment, in order to improve the use of the technology. An RP process for replicating cuneiform tablets was then established, which is similar to that usually employed for other materials, but takes into consideration the specificities of the tablets.

Based on that previous experience, in ENEA Laboratories another Project started, the *kima labirišu* Project – which means "like its original Project" – aimed at co-operating with Institutions and Museums to safeguard the cuneiform clay tablets. That Project was developed on the occasion of a special Project in support of the Baghdad Museum, the "Duplicazione e Rinascita" Project, funded by the Ministry for Foreign Affairs (MAE).

On that occasion 89, badly damaged tablets belonging to a private art dealer were scanned and replied. The *kima labirišu* Project aims not only at making copies or casts of tablets without touching them and reducing their handling to the minimum, but also at experimenting the creation of 3D images so precise that they could be used by students to read, analyze, study and publish texts.

In the three-dimensional scanning of the tablets, two different systems have been employed to obtain a high resolution acquisition: a laser triangulation system and a structured light system. For each tablet about 30 scannings have been processed, to a 400 p./mm2 resolution. The aim is to acquire a complete geometry of the cuneiform signs. This means to obtain and manage a file of 300Mb.

Starting from the 3D models, replicas of the tablets have been created through the technology of the 3DP (Three Dimensional Printing) Rapid Proto-typing. By applying the texture of the original tablet it is possible to obtain a coloured copy of the tablet, sending the machinery a virtual model of the tablet on which it has been applied.

The case of these 89 tablets has been emblematic: 1) thanks to either virtual models and real copies, very fragile exemplars are at the disposal of the scholars who can handle, study, analyse them without any problem for their safeguard and conservation; 2) although they belong to a private collection, and are therefore not freely available to the scientific community, thanks to the copies and 3D images obtained with permission by the collection owner they can be studied and the information drawn from them can be used into the wider system of knowledge. 3) Moreover, as a result of the *kima labirišu* Project, data concerning the 89 tablets have become available to the Iraq Museum, together with the results of the "Duplicazione e Ricerca" Project.

This Project has not come into being without a successor: as a further activity the group of the scholars of the "Duplicazione e Ricerca" Project, of which P. Negri is also part, is publishing the texts just starting from the 3D images. From a preliminary examination, it results that these tablets offer some new information on the environment of the Southern Mesopotamia in the II millennium B.C. and add new knowledge on forms of contracts, chronology (new dates of kings) and scribal system.

For its part, the PROTOCENTER Laboratory is going on with activities concerning cultural heritage, as the Horemheb Project with the Museum of Cairo demonstrates. The aim of the Horemheb Project is to make copies of some stone reliefs so as to bring the tomb of the pharaoh Horemheb, located in Egypt in the necropolis of Saqqara and currently incomplete, to its original condition. The copies of the reliefs will be made starting from 3D models performed by the ENEA PROTOCENTER Laboratory by techniques of high resolution laser scanning, so as to avoid any contact with the originals and then the copies in stone material similar to the original will be produced through a system of 3-axis milling.

ENEA-GRID and e-Assyriology

With its fast and secure access to software and hardware resources, ENEA-GRID allows to share computing resources across collaborative projects, attracting, engaging and supporting a wide range of users and researchers from science and industry communities. For these reasons, ENEA-GRID facilities can be used in several contexts and fields of interest, such as weather forecasting, fluid dynamics, 3D applications, etc.

In this contribution, we want to show our activities and research on the integration of language technologies (e.g., text mining) in the ENEA-GRID infrastructure to provide a novel approach for studying and analyzing cuneiform corpora. In the domain of Assyriology, ENEA-GRID offers a digital collaborative environment, to share knowledge and digital resources with the integration of Multilingual Text Mining Software, Lexical Resources and Data Visualization tools for Network Analysis. The GRID enables researchers to perform quantitative and comparative studies on transliterated cuneiform texts, providing access to computational resources for the storage and processing of large textual corpora.

For this purpose, the TIGRIS Project (**T**oward **I**ntegration of e-tools in **GR**id infrastructure for e-a**S**syriology) started in 2008, and preliminary studies by P. Negri and D. Alderuccio [Negri-Alderuccio, 2009 and 2011] provided the basis for the activity for integrating and analyzing assyriological texts.

A first experimental application of new technologies to a corpora of Babylonian texts has been carried out using Multilingual Text Mining in ancient languages, in the prospective of an integration into the digital environment in ENEA-GRID. The main goal here consists in offering an innovative approach for the study of cuneiform corpora, from which software developments and collaborative working could coexist to match the specific needs of scholar communities.

The first case-study is referred to the texts of the town of Nuzi [Negri-Alderuccio et al., 2011], belonging to the small Kingdom of Arrapkha and located East of the Tigris River (XV-XIV centuries B.C.). Among the whole corpus of Nuzi texts, the best preserved texts belonging to the scribal family of Šeršiia (with his son Hupita and his grandson Muš-teššup) has been analyzed, in order to highlight innovative and conservative stylistic elements in the redaction of texts (administrative texts and contracts) through three generations. Documents have been tagged in order to put graphic and graphemic, grammatical, and prosopographical data into light. The small dimension of the corpus allows for an exhaustive control of the results in the application of the software. Preliminary results invite to continue with the application of these methodologies also to the whole corpus of the Nuzi texts.

Recently, we started from the past experience on assyriological texts and proposed a new strategy to analyze such data. In particular, our latest study consists in exploiting data mining algorithms tuned on assyriological transliterated corpora from cuneiform tablets. Such an approach has been developed by G. Ponti (UTICT) [Ponti et al., 2012] and supports document clustering of assyriological e-texts.

Clustering analysis is an unsupervised technique that allows correlating data and grouping them to highlight hidden relations and relevant patterns. Such information is particularly precious for the works of assyriologists, who may exploit such a data reorganization to discover new interesting relations and considerations for their studies.

In our study, we used as a case study a corpus of 50 letters from old-Babylonian Kingdom of Eshnunna, flourished

Sp

(XXI-XVIII centuries B.C) along the Diyala River, an affluent of the Tigris River. In particular, in an ambitious attempt of reconstructing the grammar of that local form of old-Babylonian language (XVIII century B.C), we resorted to letters, instead of administrative texts or contracts, because their language is more varied, thanks to the different, widely ranging arguments, whilst standard, repetitive formulas are prevailing in the contracts; for these reasons, letters are particularly suitable for text analysis. Cuneiform texts have been preprocessed (as we will describe in the following paragraph), and then clustering algorithms have been executed. We employed the well-known K-means clustering algorithm, which partitions the corpus into groups (i.e., clusters) according to the number chosen by the analyst. K-means typically assumes that texts are represented by means of the Vector Space Model, where a document is seen as a vector of its terms and each term relevance depends on the statistical/correlation measure employed. A two-stage analysis has been performed: a quantitative analysis accessed the quality of the clustering task exploiting quality-based indexes known in literature, whereas a qualitative analysis aimed at describing data relations and affinities discovered by the clustering algorithm involving assyriologists.

Both cases of study require a preprocessing phase, connected with the graphemic and linguistic characteristics of the documents. Text Mining and Lexical Analysis Software require adaptation in order to deal with problems related to cuneiform texts, such as graphemic ambiguities and inconsistencies, the use of more than a language in the same text, questions connected with printing fonts and the use of particular characters, and other peculiarities like the lack of punctuation and/or space and carriage return (the only separators of graphic forms). The preprocessing task on Eshnunna corpus consisted in two main steps, that are the transliteration phase, in which cuneiform texts have been transcribed in Latin alphabet, and the lemmatization phase, where nouns, adjectives, and verbs have been brought back to the base standard form.

The research is still in progress, but some aspects and preliminary results can be underlined: in particular, the analysis of the extracted forms aims at best evaluating either the completeness of the extracted data and their typology. At the moment attention is focused on the declension of the nouns and the conjugation of the triradical stark verbs, with a particular care to the D forms, in view of a future phase in which semantic aspects will be taken into account.

Data collected until now in both case-studies are very interesting and encourage ENEA researchers to carry on. Next steps will be to extend the analyses to the whole corpora and to open an international co-operation, thanks to the HPC systems of the GRID and the opportunities offered by the GRID Virtual Lab TIGRIS (www.afs.enea.it/project/tigris). ENEA-TIGRIS is a Virtual Lab in e-Humanities, based on the integration of e-tools in GRID infrastructure for e-Assyriology.

TIGRIS Virtual Lab is the digital environment where the Assyriologists and research teams can meet and collaboratively work together, exchanging research results, best practices, fonts, software, e-text collection, lexical resources (dictionaries, grammars, ontologies, genealogies and name dictionaries, etc), images, etc.

At present, integrating e-tools in the GRID virtual environment enables ENEA-GRID for e-Humanities.

ICT and H-DATA (Historical Documents on Ancient Technologies and Artifacts)

From many years in ENEA, attention is devoted to a sector of the cultural heritage: the documents on ancient technologies and on the way in which artifacts and works of art were created in ancient times. The reconstruction of ancient technologies can concern academic purposes, like history of the science and history of art, or conservative purposes, in particular restoration, and also other fields, like social and economic history. In the last decades, interest in these documents long considered not particularly significant has been shown, as many activities in the world widely demonstrate: one for all, the recent experiences made by the Fraunhofer Institut in the German National Vitruvius Project, where analyses of ancient technologies are linked with the Latin text and with the experimental reconstruction of roman decorative wall painting techniques.

This branch of knowledge is part of the immense cultural and scientific legacy of thought and knowledge passed on from ancient times to the present time Europe, to ensure the conservation of which great attention is paid. Safeguarding either the immaterial aspects, such ideas and knowledge, and material supports, such as books and written documents in general, is presently one of the scholars' tasks. The great amount of these cultural resources makes it often difficult to ensure their conservation and accessibility.

The study of ancient materials extends in large span of time incompatible with the short project times, and scientists are facing and defining more and more complex data. In the past this kind of work was carried on exclusively in a restricted way, without any cooperative network approach and integration. The applications, for which medium-sized personal databases are used, generally have limited functionality. In fact, two solutions to these problems were possible: 1) a unique standard, static, relational database, limited in data domains, 2) several different, heterogeneous databases, more complex to manage. Moreover, multiple standard technologies, sometimes not specifically dedicated to their requirements, have been often employed. They require an ICT expert support because of their complexity in being managed. Moreover, if any modification to the databases is necessary, realizing it is very difficult and requires a co-presence of the technical staff, with high costs in terms of time and money. The existence of strictly thematic data bases, which interact with great difficulty, makes it often impossible to match the data and information loaded in different supports without a particularly complex intervention of technology experts. So, for example, a text record cannot be linked with an archaeological record containing relevant information, unless this link has been projected in advance; a later planning should cost more and more time and money. Therefore, a project facilitating the access to different areas of cultural heritage through a wide range of technical formats, which can enable the efficient use of digitized cultural resources, seems particularly important, as it allows promoting active research and new knowledge, easier access to the documentation, included that out of reach and from less known sectors, and also the development of new products in creative industries.

In consideration of the presence and importance of ICTs in everyday life, which can offer innovative solutions to a wide range of problems, included those concerning cultural heritage, P. Negri and F. Fontana are engaged from some time in an ICT project that can connect written data on ancient technologies with archaeological and archaeometric data.

Preceded by moments of experimentation and preparation particularly useful to fine-tune a few factors, the project strategy regards the implementation of innovative intelligent systems finalized to collect different types of documents and historical materials, with autonomous software agents and standard procedures, to catalogue them with innovative ways that reduce the specific experts' manual work. To perform this activity, experts could define the selection criteria to the platform in a previous task, simply using their knowledge to define the characteristics and parameters for the classification and selection phases to the system. Then, the system will select the information and knowledge of H-DATA interest autonomously.

In the H-DATA project, the design and implementation of a portal (H-DATA Meta Portal - MP) are planned, together with an advanced communication system (H-DATA Meta Multi Platform - MMP), that can interface with other present and operational e-learning platforms and databases. The MP is finalized to the functional aspects of the H-DATA Project, and manages and retrieves information and multimedia data. The platform will also be used for the following activities:

1) Information about the textual, historical documents will be refined and integrated with audio, video and textual contributes;
2) The data structure could be dynamically modified in relation to the type of documents and their specific characteristics;
3) This platform will be dynamic and include applications suitable for reducing divergence of technical approaches, in order to improve the usability of the system;
4) The platform will be integrated with an innovative meta search engine, to offer new perspectives and possibilities to end users;

5) With a parallel and independent development, the platform can integrate also a meta e-learning platform based on different resources and 3D objects;
6) Links and connections with other existing Databases and systems can allow the integration among other scattered materials.

This way, the H-DATA platform can offer an answer to particular requirements in the cultural heritage and the possibility for final users of accessing freely and easily to interdisciplinary materials and data. There is still another aspect of great importance: loading data is often a very complex burden, because of the number and complexity of data and the many possibilities of error. A system that can reduce problems in loading data, without reducing quality, is certainly welcome. The H-DATA platform offers a revolutionary solution to all these problems and also opens to further unexpected developments, because it goes beyond the system of data base, with innovative devices based on a new approach to problems.

At present, as the first case-study, texts taken into account are those related to building techniques, glass and metals, in Greek, Latin and also in Assyro-Babylonian (languages of ancient Mesopotamia): the latter are very interesting, difficult to be found by non-specialists, and considered the antecedents of the classic cultures and important comparison elements. Mesopotamian receipts for making glasses offer data on the beginning of a technology, while documents spanning from the Mesopotamian handicraftsmen to the Roman *vitrarii* offer information on the development into a workers' category. Tablets on brick manufacturing (costs for materials and workers, working days, etc.) can be paralleled with Greek epigraphs on the construction costs and times of the Parthenon. Apart is the sector of metallurgy, and of documents on metals, leagues and handicraftsmen. And examples could be innumerous.

In any case, thanks to the integrated knowledge that the platform could allow, further data and information can be retrieved in order to offer information to a very large audience and to different types of users.

Conclusions

In this framework, it is interesting to take also into consideration what S. Ross observed already in his 2004 paper, where the importance of the cultural and scientific heritage of Europe as a source of raw materials for economic, intellectual, social, and cultural development in the 21st century is put into light; in particular not only does Ross stress that the value of these raw materials multiplies when they are available in digital form, but also that these materials contribute to improvements in the quality of life, enabling education, supporting life-long learning, underpinning the development of new products by creative industries.

References

[1] S. Ross, 2004, "Progress from National Initiatives towards European Strategies for Digitisation" in Towards a Continuum of Digital Heritage: Strategies for a European Area of Digital Cultural Resources, European Conference, (Den Haag: Dutch Ministry of Education, Culture and Science), pp 88-98.

[2] F. Fontana, M. Moscarini (2004), An Advanced e-Learning Platform to Manage Virtual Courses and Multimedia: MATRIX 3, ENEA, University of Rome, Italy, ED-MEDIA 2004, Lugano, Switzerland.

[3] F. Fontana, E. Cosimi, G. Ponzo, ENEA Usability Lab, Department of Computer Science, An Advanced Web 3D Mobile e-Learning System to Manage Virtual Courses and Multimedia, University of Rome, Italy, E-LEARN 2010, Orlando, Florida, USA.

[4] P. Negri Scafa, D. Alderuccio, (2009), ENEA, "A new experimental approach to text computer analysis applied to the Nuzi texts", 55th RAI 2009, "Family in the Ancient Near East: Realities, Symbolisms, and Images", Paris, France, July 6th-9th 2009.

[5] P. Negri Scafa, D. Alderuccio (2011), Giovanni Bracco, Silvio Migliori, ENEA "A preliminary analysis of a Nuzi scribal family in view of an application in the ENEA-GRID", 57th RAI 2011; "Tradition and Innovation in the Ancient Near East", Rome, Italy, July 4th-8th 2011.

[6] G. Ponti, P. Negri Scafa, D. Alderuccio, G. Mencuccini, A. Rocchi, G. Bracco, S. Migliori, (2012) ENEA, "Toward the integration of informatic tools and GRID Infrastructure for Assyriology Text Analysis" 58th RAI 2012; "Private and State (Privat und Staat) in the Ancient Near East", Leiden, The Netherlands, July 16th-20th 2012.

[7] ENEA PROTOCENTER: www.protocenter.enea.it

[8] ENEA GRID: www.eneagrid.enea.it

[9] GRID Virtual Lab TIGRIS: www.afs.enea.it/project/tigris

[10] ICT_H-DATA: odl.casaccia.enea.it

[11] www.desire-net.enea.it

The Conservation of the Shroud of Turin: Optical Studies

The ancient linen cloth of the Shroud of Turin is one of the archaeological objects most studied in history, mainly because of the unexplained nature of its image. We have recently irradiated linen fabrics by excimer laser pulses obtaining a Shroud-like coloration, and have recognized photo-chemical processes that may have played a role in the formation of the image embedded into the Shroud. Our results suggest some actions aimed at a long-term conservation of the Shroud and its image

Paolo Di Lazzaro, Daniele Murra, Antonino Santoni, Enrico Nichelatti

Introduction

The detailed studies of the front and back images of a scourged man embedded onto the Shroud of Turin (see Fig. 1) show such a microscopic complexity that nobody has been able to reproduce an image identical in all its details [1–9].

The most important in-depth experimental analysis of the Shroud was carried out in 1978 by the multidisciplinary team of the Shroud of Turin Research Project, Inc. (STURP). They used the most advanced instruments available at the time. The Shroud was examined by ultraviolet, visible and infrared spectrometry, X-ray fluorescence spectrometry, microscopy, thermography, pyrolysis-mass-spectrometry, laser-microprobe Raman analyses, microchemical testing [1-2]. After years of study and data evaluation, the STURP team achieved the following results:

a) X-ray, fluorescence and microchemistry tests on the fibers preclude the possibility of paint being used as a method for creating the image. Ultraviolet and infrared evaluations confirm these studies. The Shroud image was not painted, nor printed.

b) Both kinetics studies and fluorescence measurements support the hypothesis that the image was formed by a low-temperature process. The temperature was not high enough to change cellulose, and no char was produced. Thus, the Shroud image was not made by pressing the cloth on a heated bas-relief.

c) The Shroud's image is superficial as the color resides on the outer surface of the fibers that make up the threads of the cloth. Recent measurements on image-fibers of the Shroud [3] confirmed that the coloration depth is extremely thin, about 200 nm.

d) The shallow coloration of the Shroud image is due to an unknown process that caused oxidation, dehydration and conjugation of polysaccharide structure of fibers, to produce a conjugated carbonyl group as the chromophore.

e) The image seen at the macroscopic level is an areal density image. This means that shading is not due to a change of color, but to a change in the number of colored fibers per unit area at the microscopic level.

f) The image fading has three-dimensional information of the body encoded in it.

Paolo Di Lazzaro, Daniele Murra, Antonino Santoni

ENEA, Unità Tecnica Sviluppo di Applicazioni delle Radiazioni

Enrico Nichelatti

ENEA, Unità Tecnica Tecnologie dei Materiali

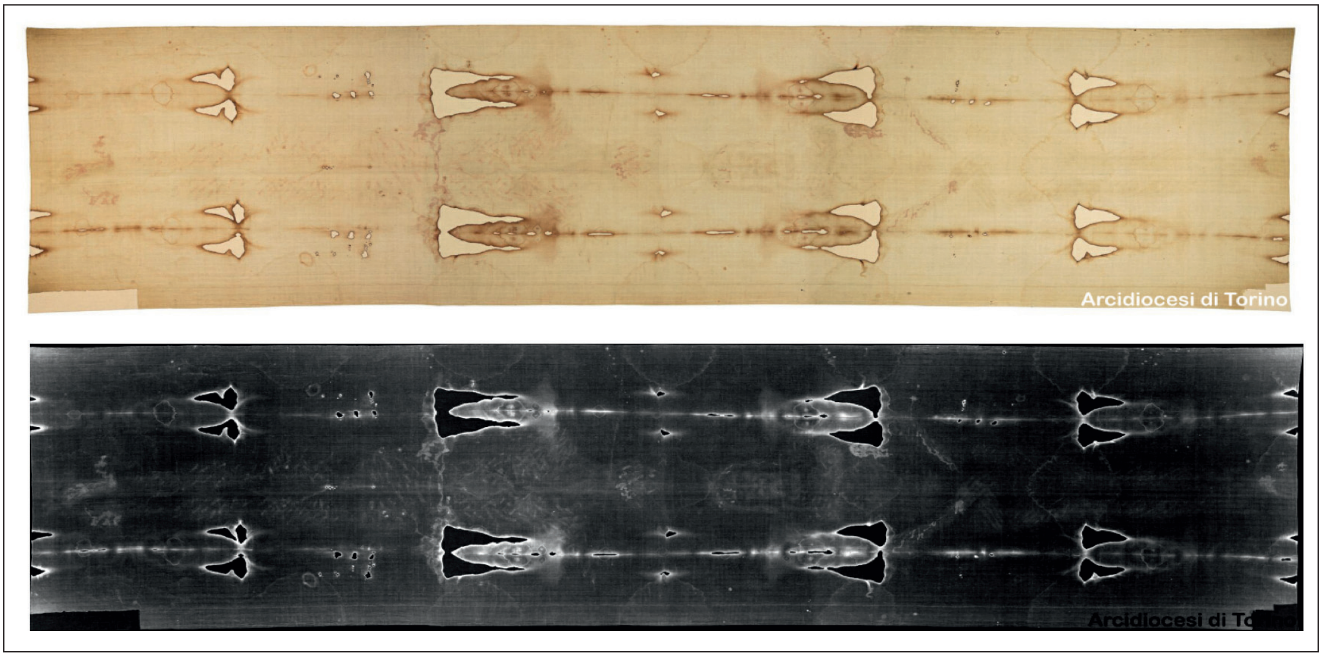


FIGURE 1 Photograph of the Shroud of Turin (top) and its negative (bottom). The image is clearly a negative, not a positive. The Shroud is a linen cloth of about 441 cm in length and 113 cm in width
Source: www.sindone.org

g) The blood stains tested positive for human blood, and there is no image beneath the blood. This means the image must have occurred after the blood flowed onto the cloth. As a consequence, the image was formed after the deposition of the corpse.

h) On the Shroud there are no signs of putrefactions, which occur at the orifices about 40 hours after death. This means that the image does not depend on the gases of putrefaction and the corpse was wrapped in the Shroud no longer than two days.

i) There is a perfect anatomical consistency of blood and serum versus wounds, including the presence of birilubin, which is invisible at the naked eye. These subliminal features require knowledge of anatomy and of forensic medicine not available before the XIX century.

According to the above results, the Shroud poses a scientific puzzle, independently of the middle age dating [5,6]. In this paper we summarize the main results of experiments carried out at the ENEA Frascati Centre, aimed at identifying the physical and chemical processes able to generate a Shroud-like coloration. The identification of these processes suggests actions aimed at a long-term conservation of this ancient relic.

Experimental Results by UV and VUV Laser Irradiations

In principle, ultraviolet (UV) or vacuum ultraviolet (VUV) electromagnetic energy incident on a linen could reproduce the main characteristics of the Shroud image, such as the absence of pigments, the shallowness of the coloration, the image in areas not in contact with the body, the gradient of the color, and the absence of image under the blood stains. To have an experimental check, we used two excimer lasers, emitting ns-pulsewidth radiation pulses at $\lambda = 308$ nm (XeCl) and $\lambda = 193$ nm (ArF), that were focused by a lens onto a linen fabric fixed on a frame.

In summary [7–9] we obtained a superficial and

Shroud-like linen coloration in a very narrow range of laser parameters. The hue of the color was brown and yellow after XeCl and ArF laser irradiations, respectively, see Fig. 2.

Aging can be a concause of linen coloration, after laser irradiations that at first do not generate any visible effect. We cut half of the laser spot on linen irradiated below the intensity threshold for coloration. As a consequence, the irradiated linen did not appear colored. We then heated one of the two parts with an iron at a temperature of 190±10 °C for 10 seconds, and coloration appeared immediately after heating. Figure 3 shows that the heating process, which simulates aging, colors only the surface irradiated below threshold, and does not color the non-irradiated area.

We also obtained a latent coloration similar to that of Fig. 3, which appeared after a natural aging of more than one year, maintaining the linen at room temperature in a dark environment [7].

We made additional experiments which gave the following results:

- When illuminated with a UV lamp, irradiated linen fabrics show a partial inhibition of fluorescence, exactly like the Shroud image [8].
- The measured absolute spectral reflectance of our linen shows a perfect overlap with the Shroud in the UV and VUV spectral region. Thus, when irradiated by UV and VUV light our linen behaves like the linen of the Shroud [8, 9].
- Using a petrographic microscope, we have observed some defects induced by UV radiation in the structure of irradiated linen fibers, see Fig. 4, similarly to very old linen fabrics. We can infer that short and high-intensity UV pulses change the crystalline structure of cellulose in a similar manner as aging and low-intensity radiation (Radon, natural radioactivity, secondary particles from cosmic rays) accumulated in a long term period do [7].
- Using an infrared camera we measured the surface temperature of our linen during irradiation with uncertainty of ±0.2 °C. The thermal heating associated with UV and VUV radiation is within a few degrees centigrade and therefore irrelevant for the purpose of coloring linens by scorching. As a consequence, excimer laser coloration is due to a photochemical process that does not involve significant thermal effects [9].

Chemistry of the Photochemical Coloration

We obtained a linen coloration (see Fig. 2) that approaches many of the characteristics of the image on the Shroud.

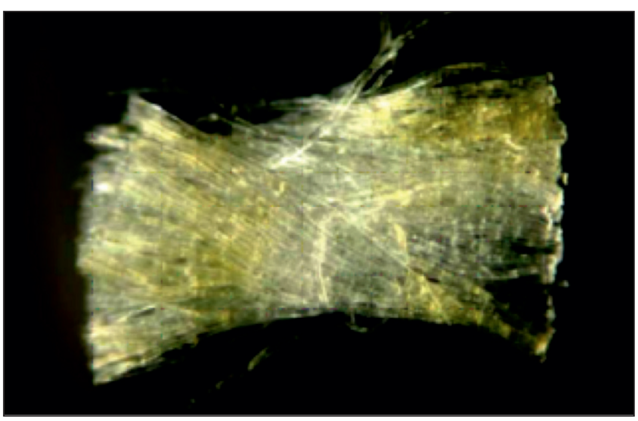


FIGURE 2 Photomicrograph of a warp thread of flax irradiated with ArF laser pulses. The thread was crushed with forceps to separate the fibers and highlight their yellow color. At the center of the thread there is an uncolored zone due to a weft thread that shadowed the laser radiation
Source: [9]

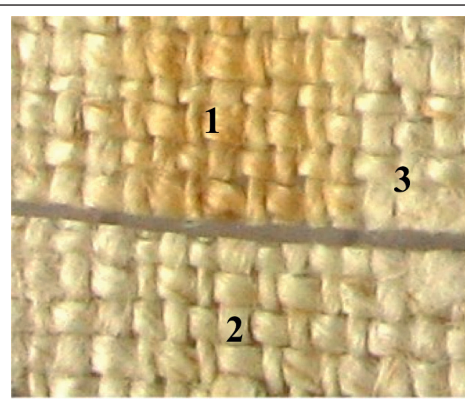


FIGURE 3 Linen fabric cut after irradiation below-threshold for coloration. 1) Irradiated area after heating. 2) Irradiated area not heated. 3) Non-irradiated area. Latent coloration of the linen area irradiated below threshold appears only after artificial aging of the upper part of irradiated linen
Source: [8]

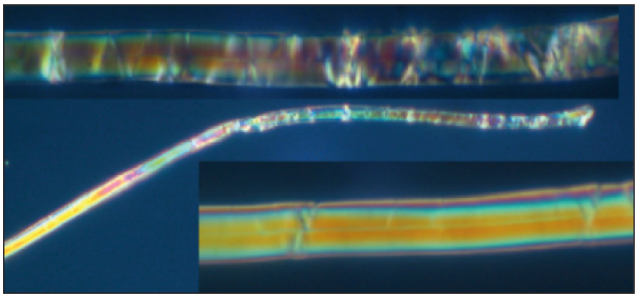


FIGURE 4 Microscope observation of a linen fiber. In the middle there is a fiber of linen between crossed polarizers to detect stress characteristics. The left part of the fiber is the non-irradiated region, which is enlarged in the inset below. On the right is the region irradiated by XeCl laser, enlarged in the inset above
Source: [7]

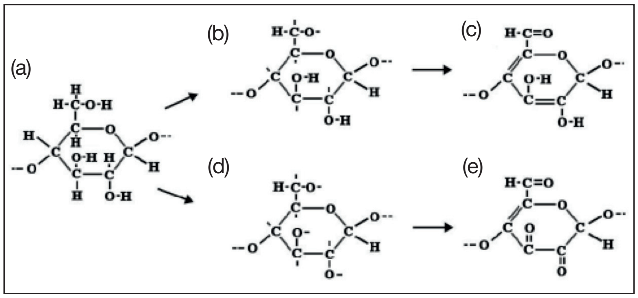


FIGURE 5 a) Main molecular structure of both cellulose and hemicellulose. There are two possible transitions (a) → (b) → (c) and (a) → (d) → (e) that generate chromophores after oxidation and dehydration. The C=C and C=O double bonds in (c) and (e) act as the chromophore and are responsible for the yellow color of the fibers of the image on the Shroud of Turin
Source: [9]

We also achieved a latent coloration that appears after a relatively long period (one year) or at once by an accelerated aging, following a laser irradiation that at first does not generate any visible image (see Fig. 3). We showed that the UV laser light produces fragility and stress of the irradiated fibers equivalent to an accelerated aging of the fabric (see Fig. 4). Finally, we have shown that the coloration is not due to a thermal effect, in analogy with the features of the Shroud image. So, the intimate chemical processes triggered by our laser irradiation may have something in common with the processes that generated the body image on the Shroud. Let us look at the details of these processes.
The STURP studies suggest the image chromophore is a conjugated carbonyl produced in the polysaccharide structure of fibers by a dehydrative oxidation process [1-2]. The color of the Shroud image is the result of an accelerated aging process of the linen, similar to the paper yellowing of ancient books [10]. Figure 5 shows two different chemical paths possibly involved in the formation of the image on the Shroud.
In our irradiations, a key-role is played by the VUV absorption band below 200 nm of alkene groups (-C=C-) [11] typically present in degraded cellulose and in organic impurities of the primary cell wall of linen fibers. The VUV absorption of these groups may trigger a reaction chain which leads to photo-oxidation (ageing) and to new alkenes and carbonyl groups. After a proper irradiation dose, new conjugated C=C and C=O groups are formed, increasing delocalization and thus shifting the absorption band to longer wavelengths, in the blue-green spectral region, to finally produce the yellowish Shroud-like coloration shown in Fig. 2.
In this frame, the formation of latent images (Fig. 3) can be explained by the oxidation and dehydration of cellulose (caused by heat or by natural aging), amending the new chemical bonds induced by laser irradiation, thus facilitating the formation of conjugated unsaturated structures that are essential part of the chemical transitions in Fig. 5. The synergy between heat and UV light is detailed in [12], showing how the process initiated by exposure to UV radiation is accelerated and reinforced by heat.

Conservation Issue: Physical, Chemical and Biological Parameters

Our experimental results show the photochemical reactions able to replicate many of the Shroud image characteristics. This can shed light on the chemical nature of the image, whose knowledge is essential to plan the long-term conservation of both the relic and the image.

Conservation of the Linen Cloth

The main component of linen is cellulose (see Fig. 5). The most important decomposition process of cellulose is dehydration. Linen adsorbs and absorbs water from air depending on both relative humidity RH and temperature T. For the sake of conservation, everything must be kept in equilibrium, as cellulose fibers will stretch and shrink when their degree of hydration changes. Thus, cellulose is well conserved if kept out of direct light, in a moderately dry atmosphere and at a constant T. These actions are necessary but not sufficient: kink bands and defects, shown in Fig. 4, can be limited only by shielding the Shroud from natural radiation such as Radon, natural radioactivity, secondary particles from cosmic rays. At sea level, secondary particles from cosmic rays can be neglected, and the main source of natural radiation is Radon, an invisible, odorless, radioactive gas formed by the disintegration of Thorium and Radium, the latter being a decay product of Uranium. Radon emits alpha particles and produces several solid radioactive products called radon-daughters. In this framework, the Shroud should be conserved in a building made by Radon-free materials (tuffaceous rocks, porphyry, basalt, syenite and granite must be strictly avoided) and built on a low Radon-emission soil. Putting the Shroud in a metal box guarantees a dark environment (absence of visible and UV-VUV light) and in addition, a few millimeters thick Aluminum (Al) stops the low-intensity beta particles emitted by radon-daughters, which are usually attached to airborne particles waving in the building atmosphere that may settle on the box.

Conservation of the Image Contrast and Visibility

Our experiments show that VUV light promotes photochemical processes leading to dehydrative oxidation of linen and formation of chromophores (Fig. 4). Smaller doses of VUV light, when coupled with heating (which simulates aging) produce latent coloration (Fig. 3). However, all these reactions require the presence of molecular oxygen O_2 to form chromophores. As a consequence, the gas in contact with the Shroud should be O_2-free in order to slow down the yellowing of non-image linen fibers that reduces the contrast of the image. An inert gas is recommended. Among inert gases, Helium is difficult to be sealed, while Krypton and Xenon are very expensive. Commercially available Argon (Ar) or Neon (Ne) with purity greater than 99,8% could be a good solution. However, a pure gas is too dry and may shrink linen, as mentioned previously. It is necessary to add some humidity, that is, water vapor. In addition, a 100% O_2-free environment favors the increment of anaerobic organisms on the Shroud. One must find a compromise between the requirements of a moderately dry environment to avoid shrinking of fibers, a low content of O_2 in contact with the Shroud to limit oxidation and the growth of anaerobic organisms. When seeking the compromise, one should consider that both dehydration and oxidation are responsible of the formation of chromophores, that is, of the linen yellowing. A compromise is RH ≈ 40%, like that of the most dry month in Jerusalem region, which corresponds to 9 mbar water vapor at T = 20°C added to the inert gas [13], and of a 0,4% O_2, which is enough to limit the growth of most anaerobic bacteria. A thorough microbiological study to assess the presence and nature of microorganisms on the Shroud should be undertaken, in order to assess the optimum value of O_2.

	Gases and pressure	Relative humidity, temperature	Box: material and thickness	Radon issue
Our suggestions	99.6% Ne or Ar, 0.4% O_2, 9 mbar water vapor P = 1,05 bar	RH ≈ 40% T = 20 °C	Al or Al-based alloy t ≥ 5 mm	Building materials and objects around must be Radon-free
Present reliquary [15]	99.5% Ar, 0.5% O_2 P equalized to the atmospheric pressure	RH = 50% T = 19-20 °C	Aeronautical alloy, t not available	Information not available

TABLE 1 Our suggestions of the optimum physical and chemical parameters and conservation measures of the Shroud, compared with the available characteristics of the reliquary made by Thales Alenia Space, where the Shroud is presently conserved
Source: Authors elaboration

Summary

In this paper we have briefly summarized the current state of knowledge on the Shroud image, and explained the reasons of the difficulty to create an image that matches its peculiar superficiality and chemistry at the microscopic level. We have demonstrated that short VUV light pulses generate a Shroud-like coloration on linen that matches many characteristics of the Shroud image. We have also identified the photochemical reactions triggered by VUV radiation that generate the Shroud-like coloration.

These results are interesting for the search of image formation mechanisms, and they also offer hints for long-term conservation measures. According to the arguments discussed above, the Shroud should be conserved in a few millimeter-thick Al (or Al-based alloy) box, filled with a proper mixture of high-purity Ne or Ar gas, O_2 and water vapor, in order to set an equilibrium between the dehydration and oxidation of linen fibers able to maintain the image contrast and visibility, while avoiding the growth of anaerobic organisms. The total pressure P should be just above the atmospheric pressure to prevent air and dust from entering inside the box. A constant T = 20°C eliminates any risk of autocatalysis-like processes from the acidic structures produced by previous oxidative activity [14]. The Al box containing the Shroud should be put in a building made of Radon-free materials, possibly in a room not on the ground floor, and every object, treasure, furnishing, floor, wall made of tuffaceous rocks, porphyry, basalt, gneiss, syenite or granite must be removed from around the box. The amount of Radon in the room should be monitored routinely.

Table 1 compares our proposals with the available characteristics of the reliquary made by Thales Alenia Space [15], where the Shroud is presently conserved.

Acknowledgements

Authors wish to thank Prof. B. Barberis, Director of the International Center on Sindonology, for making available unpublished technical details of the reliquary where the Shroud is conserved.

References

[1] L.A. Schwalbe, R.N. Rogers: *"Physics and chemistry of the Shroud of Turin, a summary of the 1978 investigation"*, Analytica Chimica Acta 135, 3-49 (1982).

[2] E.J. Jumper, A.D. Adler, J.P. Jackson, S.F. Pellicori, J.H. Heller, and J.R. Druzik, *"A comprehensive examination of the various stains and images on the Shroud of Turin"*, Archaeological Chemistry III: ACS Advances in Chemistry 205 (American Chemical Society, Washington, 1984), pp. 447-476.

[3] G. Fanti, J. Botella, P. Di Lazzaro, R. Schneider, N. Svensson: *"Microscopic and macroscopic characteristics of the Shroud of Turin image superficiality"*, J. Imaging Sci. Technol. 54, 040201-040201(8) (2010).

[4] L. Garlaschelli: *"Life-size Reproduction of the Shroud of Turin and its Image"*, J. Imaging Sci. Technol. 54, 040301-040301(14) (2010). See also: T. Heimburger, G. Fanti: "A scientific comparison between the Turin Shroud and the first handmade whole copy", Proc. IWSAI, P. Di Lazzaro ed. (ENEA 2010) pp. 19-28. ISBN 9788882862329. www.acheiropoietos.info/proceedings/proceedings.php

[5] P.E. Damon, et al.: *"Radiocarbon dating of the Shroud of Turin"*, Nature 337, 611-615 (1989).

[6] R. Van Haelst: *"A critical review of the radiocarbon dating of the Shroud of Turin"*, Proc. IWSAI, P. Di Lazzaro ed. (ENEA 2010) pp. 267-273. ISBN 9788882862329.

[7] www.acheiropoietos.info/proceedings/proceedings.php

[8] G. Baldacchini, P. Di Lazzaro, D. Murra, G. Fanti: *"Coloring linens with excimer lasers to simulate the body image of the Turin Shroud"*, Appl. Opt. 47, 1278-1285 (2008).

[9] P. Di Lazzaro, D. Murra, A. Santoni, G. Fanti, E. Nichelatti, G. Baldacchini: *"Deep Ultraviolet radiation simulates the Turin Shroud image"*, J. Imaging Sci. Technol. 54, 040302-040302(06) (2010).

[10] P. Di Lazzaro, D. Murra, A. Santoni, E. Nichelatti, G. Baldacchini: *"Colorazione simil-sindonica di tessuti di lino tramite radiazione nel lontano ultravioletto"*, RT/2011/14/ENEA. http://opac.bologna.enea.it:8991/RT/2011/2011_14_ENEA.pdf

[11] A. Mosca Conte, O. Pulci, A. Knapik, J. Bagniuk, et al.: *"Role of Cellulose Oxidation in the Yellowing of Ancient Paper"*, Phys. Rev. Lett. 108, 158301-5 (2012).

[12] A. Bos: *"The UV spectra of cellulose and some model compounds",* J. Appl. Polymer Science 16, 2567-2576 (1972).

[13] M. Yatagai, S.H. Zeronian: "Effect of ultraviolet light and heat on the properties of cotton cellulose", Cellulose 1, 205-214 (1994).

[14] 13 A. Buck: *"New equation for computing vapor pressure and enhancement factor"*, J. Appl. Meteorol. 20, 1527–1532 (1981).

[15] R.N. Rogers: *"A chemist's perspective on the Shroud of Turin"* J. Rogers & B. Schwortz editors, (Lulu, 2008) ISBN 9780615239286. Chapter XIII.

[16] http://www.sindone.org/santa_sindone/la_sindone/00024252_La_teca.html See also: http://www.sindone.info/TESI-ITA.PDF

Effects of Air Pollution on Materials, Including Historic and Cultural Heritage Monuments

The Int. Co-operative Programme on Effects on Materials, including Historic and Cultural Monuments (ICP Materials) started in 1985. It was initiated in order to provide a scientific basis for new protocols developed within the Convention on Long-range Transboundary Air Pollution. The main aim is to perform a quantitative evaluation of the effects of multi-pollutants and climate parameters on the atmospheric corrosion of materials, including Cultural Heritage. The primary objective is to evaluate dose/response functions and trend effects and use the results for mapping areas with increased risk of corrosion, and for calculating the costs of damage caused by the deterioration of materials. Here we present the study of two UNESCO CH sites: the Parthenon in Athens (Greece), and the building façades in the city centre of Paris (France)

Stefan Doytchinov, Augusto Screpanti, Giovanni Leggeri

Introduction

Air pollutants, together with climatic parameters, are of major importance for the deterioration of many materials used in cultural monuments. They are emitted by industrial activities and by the transport sector. These pollutants create problems on the local scale, but they are also transported in the air over long distances.

One of the international organizations and institutions which study these effects is the UN ECE Convention of Long Range Transboundary Air Pollution (CLRTAP) under which operate the International Cooperative Program on effects on Materials including Cultural Monuments (ICP Materials), that started in 1985. This is one of several effect-oriented International Co-operative Programmes (ICPs) dedicated at studying the harmful effect of air pollution on materials. It was initiated in order to provide a scientific basis for new protocols and regulations developed within the Convention on Long-range Transboundary Air Pollution.

To reduce the harmful effects of pollutants on human health and the environment, the European Directive 1999/30/EC has been issued relating to limit values for sulphur dioxide, oxides of nitrogen, particulate matter and lead in the ambient air. These limit values have been established with reference to health and ecosystem effects but not to effect on building materials and cultural monuments. The European cultural heritage is very large and costs billions of euro

Stefan Doytchinov
ENEA, Unità Tecnica Tecnologie Ambientali

Augusto Screpanti
ENEA, Unità Tecnica Caratterizzazione, Prevenzione e Risanamento Ambientale

Giovanni Leggeri
ENEA, Unità Tecnica Sviluppo di Applicazione delle Radiazioni

Sp

to be maintained. It is important to understand that such materials, from which the cultural monuments are created, are sensitive to pollution at even lower levels than biological systems.

The costs for deterioration and soiling of different materials due to air pollution are huge and the damage to culture targets seriously endangers the cultural heritage. Effective policy-making requires environmental impact assessment, cost benefit analysis and risk management. All these techniques need a serious scientific basis to support the assessment and the calculation of the effects of pollution.

In this study a methodology has been applied to estimate the real surface of the selected monuments and the materials from which they are created, in percentage. Subsequently, the ICP Materials dose-response functions have been used in order to evaluate the corrosion and soiling effects of air pollution on the monuments, and in the next study to calculate the costs of the damage due to the deterioration of the materials that the monument is made of. Air pollution data for 2009-2010 have been used.

The Methodology [1]

The methodology applied consists of a real in-the-field inventory. The dimensions of the monuments was identified by direct examination, images, photos, drawings and other data available in literature and from the internet sources. The dimensions of monuments allowed to calculate their surface by valuating the surface covered by windows, doors, etc.

The nature of the materials employed was determined by direct examination of the building façade or using the literature sources. The proportions of materials was roughly evaluated in percentage. The dimensions of each monument were taken using the literature sources, images and proportions. When this information was not available, the height of the building was estimated by counting the number of floors and attributing them an individual average height of 3 m. A control of this arbitrary height of 3m per floor was performed using a laser beam measurement and the error did not exceed - 10% (Paris (3)).

The determination of the length of the façades was obtained by measurements on the available city maps. Having height and length, the surface was easily deduced. The surface of the apertures (windows, doors), classically considered by architects equal to half of the total surface of the façades, was deduced from the surface materials of the monument.

The height and length of the Parthenon were obtained from the official technical documents available and from the literature data.

Dose-Response Functions

Europe. It was established that the target for 2020 y. corresponds to n=2.5. Considering the background corrosion rates during the first year of exposure taken from the UN/ECE Mapping Manual, the estimated tolerable corrosion rates calculated from Equation (2) are almost identical to the tolerable levels established from maintenance intervals (corrosion depth before action/tolerable time between maintenance). It was decided that the target for 2050 y. corresponds to n=2.0. In Table 1, the tolerable corrosion rate for the first year of exposure for limestone is indicated for the 2020 and 2050 targets. The tolerable corrosion rates given in Table 1 are those used for further assessment of target levels and are thus considered a conservative lower estimate of the tolerable level. We may calculate the The most recent development of dose-response functions for corrosion in the new pollution situation in Europe has been developed in cooperation with the EU project MULTI-ASSESS based on data obtained in the ICP Materials multi-pollutant exposure program. The degradation of limestone is expressed as surface recession (R, μm). This function includes a range of pollution and climate parameters (Portland limestone):

$$\mathbf{R = 4.0 + 0.0059[SO_2]RH_{60} + 0.054Rain[H^+] + 0.078[HNO_3]Rh_{60} + 0.0258PM_{10}} \qquad (1)$$

Stock at Risk

We need a uniform approach for policy-makers that might indicate them the target levels of corrosion. When the UN/ECE Mapping Manual is applied to

Material	Background corrosion	Background corrosion depth (BCD)	Factor for acceptable corrosion	Tolerable corrosion rate per year
Limestone		3.2 μm	2020 target (2.5 times BCD)	8.0 μm $year^{-1}$
Limestone		3.2 μm	2050target(2.0 timesBCD)	6.4 μm $year^{-1}$

TABLE 1 Tolerable corrosion rate based on background corrosion rates and the targets for 2050 (n=2.5) and 2020 (n=2.0)
Source: [1]

tolerable levels, the tolerable corrosion rate, first year exposure (K_{tol}) can be calculated as:

$$K_{tol} = n \times K_b \quad (2)$$

where n is a factor and Kb is the background corrosion rate, first year exposure for corresponding acceptable pollution concentrations from the tolerable corrosion rate using the dose-response functions. From the tolerable corrosion rates indicated in Table 1 and the real measured or estimated corrosion rates we may establish if a specific site may be classified as tolerable or exceedence (risk) site.

The Parthenon in the Acropolis, Athens

The Parthenon [2] (Coordinates: N37O 58' 15".132, E23' 43' 34".248) was included in the UNESCO CH list in 1987. The Acropolis hill (acro - edge, polis - city), so-called "Sacred Rock" of Athens, is the most important site of the city and constitutes one of the most recognizable monuments of the world. The monuments on the Acropolis reflect the successive phases of the city's history. It is 3.045 ha. Types of main external materials used in percentage: limestone - pentelic marble - (95%), porous stone, sandstone.

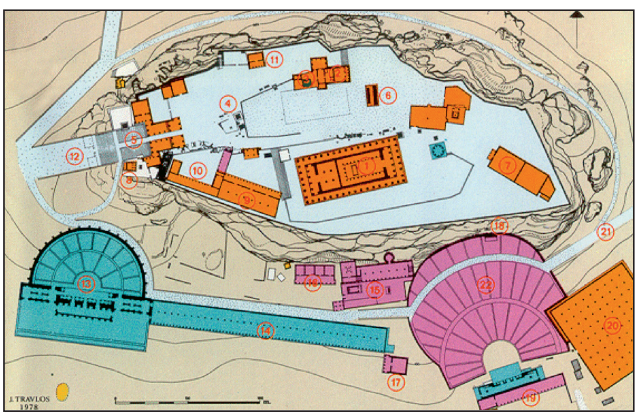


FIGURE 1 The map of the Acropolis with the monuments and periods of creation (Orange: Monuments of the 5th century BCE; Rose: Monuments of the 4th century BCE; Blue: Hellenistic and Roman monuments)
Source: [2]

The Parthenon is the most important and characteristic monument of the ancient Greek civilization and still remains its international symbol. It was dedicated to Athena Parthenos (the Virgin), the patron goddess of Athens. It was built between 447 and 438 B.C. and its sculptural decoration was completed in 432 B.C. The sculptural decorations of the Parthenon are a unique combination of the Doric metopes and triglyphs on the entablature, and the Ionic frieze on the walls of the cella.

As indicated before, in order to valuate quantitatively the loss of materials due to the air pollution and to make an economic assessment, it is important to know the surface dimensions of the studied monument. From the literature we found the general external measures of the monument. The rest was valuated using the ratios between known and unknown dimensions of the temple. For this reason, we evaluated and calculated the surface of the external (visible) part of the Parthenon. Many original parts of the Parthenon are lost. And now the Temple is without roof and internal cell (naos) where the God's statue was originally situated (Fig. 2). Four columns are broken. The most important parts of the Parthenon still existing are the columns, the lintel, the tympanum.

- Columns: their surface is not smooth but fluted (Fig. 3). The columns are 10 m high and their diameter is 1.9 m. The columns are not cylinders but the lower part is around 30% larger than the upper one. In order to find the column circumference we used a section of it and then applied the AutoCAD software. This way, the circumference of a column was found to be 7.05 m. The surface of one column is 10 m (h) x 7.05 m. = 70.5 m^2. In the temple we have 47 columns.

FIGURE 2 The Parthenon view from North-East
Source: [2]

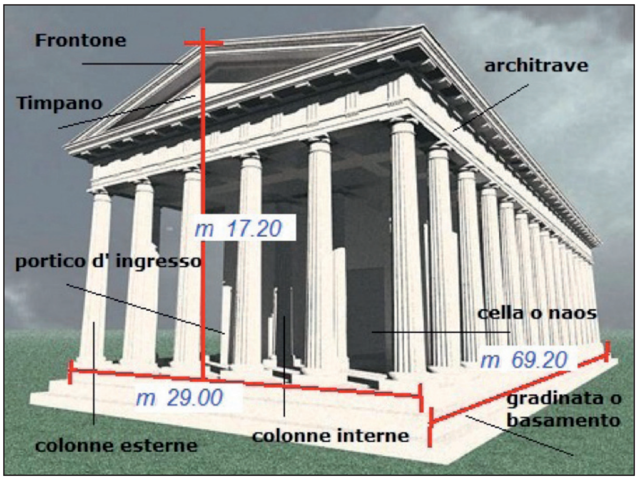


FIGURE 3 Scheme of a Greek temple
Source: [2]

Four of them are broken and we considered that they are 50 % lost. *The surface of the columns is: 43 columns x 70.5 m^2 = 3031.5 m^2; 4 columns x 35.2 m^2 = 140.8 m^2.* Total surface of the columns is = **3172.3 m^2**.

- Lintel: the short sides of it are relatively integral. They are 29 m long and 3.5 m. high. The East side is 29 m (l) x 3.5 m. (h) = 101.5 m^2. The West side is 29 m (l) x 3.5 m. (h) = 101.5 m^2. The North side is relatively integral and is 69.2 m (l) x 3.5 m (h) = 242.2 m^2. The South side is damaged and 29 m. are lost, so it is 69.2 – 29 = 40.2 m x 3.5 m. = 104.7 m^2. *The total surface of the lintel is* ***549.5 m^2***.
- Tympanums (triangles): *The East side is relatively integral and is 29 m. (l) x 4.2 m. (h) / 2 = 60.9 m^2.* The North side is very damaged. Using the rations between the integral east part end remaining pieces from the north one *we calculated it as around 15 m^2.* So the total surface of the tympanums is: 60.9 + 15 = **75.9 m^2**.
- The total surface of the Parthenon is: *Columns = 3 172.3 m^2; Lintel = 549.5 m; Tympanums = 75.9 m^2. Total visible surface of the Parthenon is* **3 798.1 m^2**.

The Dose/response function which we used to calculate the recession of the limestone material (see equation 1) for *the Parthenon indicates that the corrosion depth after one year of exposure is* ***5.60 μm***. Table 1 shows that this result is lower than the tolerable corrosion rate per year for the 2020 target, which is 8.0 μm year^{-1} for limestone. This result is very close to the tolerable corrosion rate per year for the 2050 target, which is 6.4 μm year^{-1}. On the other hand, the calculated corrosion rate for the Parthenon is almost two times as high as *the background corrosion depth indicated in Table 1 (**3.2 μm**).* This means that *in 2009-2010 the corrosion depth in the Parthenon was almost two times as high as the background corrosion rate, which is due to air pollution, but it is steel in the range of tolerable corrosion rate for the 2020 target.*

The Façades in the Centre of Paris

The banks of the Seine (Coordinates: N48 51 30 E2 17 39) have been included in the UNESCO List of the World Cultural Heritage (Fig. 4) since 1991 [3]. We should consider that many important monuments are situated in this area.[See Report 68 (1)]. This study consists in the evaluation of the stock of materials at risk of degradation (corrosion, soiling) due to atmospheric pollution, between the Sully Bridge on the eastern side, and the Pont-Neuf on the western side. It includes the Ile Saint Louis, the Ile de la Cite´ and the right bank of the Seine facing these two islands (Fig. 4). This sector is the very centre of Paris. The territory inscribed on the UNESCO List, extends towards West as far as the Eiffel Tower. This study includes roughly one-third of this territory and contains buildings dating from the

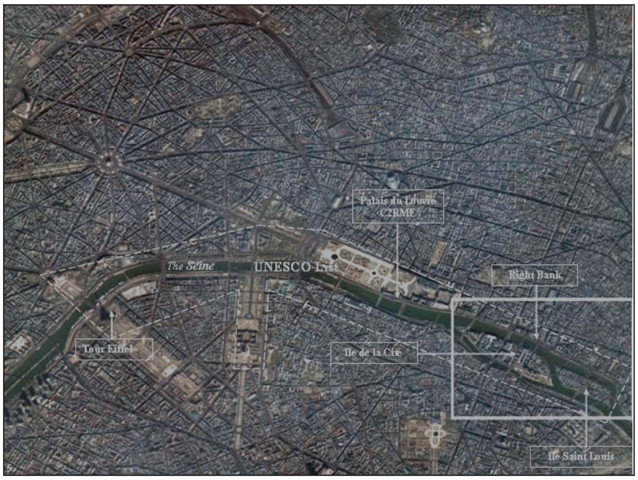


FIGURE 4 Satellite view of the centre of Paris
Source: [3]

XVII and XVIII centuries, Haussmannian buildings (end of XIX century), as well as important monuments like Notre Dame and Sainte Chapelle, dating from the Middle Ages. Quays and bridges were not taken into account in this evaluation.

The authors methodology to calculate the surface of the monument consisted in a real in-the-field inventory, façade by façade, building by building, and monument by monument, based on the Paris Map at the scale of 1:2 000. They determinated the nature of the materials employed by direct examination of the building façade (Lutetian Parisian limestone, rendering/ mortar/ plaster, painting, brick, metal, modern glass) and their proportions were roughly evaluated in percentage. They estimated the height of each building by counting the number of floors and attributing them an individual average height of 3 m. A control of this arbitrary height of 3 m per floor was performed using a laser beam measurement: the error does not exceed - 10%. The determination of the length of the façades was obtained by measurements on the Paris Map. Having height and length, the surface was easily deduced. This entire surface was attributed to the constituting materials according to their proportions. The surface of the apertures (windows, doors), classically considered by architects equal to half of the total surface of the façade, was not deducted because it compensates for the roughness of the façade (sculptures, decoration, balconies, ...). In summary, the total calculated surface was attributed to the constituting materials and half of this surface was arbitrarily attributed to the modern glass of the windows. Only the street facing, external façades were taken into account due to their direct exposure to pollution from traffic and the inaccessibility of interior private courts.

The authors decided to measure the surfaces of historical monuments directly in the field, according to the same methodology employed for private buildings. In the Ile de la Cité, the quantity of historical monuments and official buildings is very high. On the right bank of the Seine, three important monuments exist and in the Ile Saint Louis there are only two historical Monuments.

In total, the measurement of the length of each construction on the map of Paris, the counting in the field of the number of floors and the characterization and evaluation of the respective proportions of the constituting materials were performed on the façades of 525 buildings and monuments in the Centre of Paris, giving an excellent statistical value to the results presented below.

The total surface in m^2 of the ***525*** *façades of buildings* and monuments of the studied area, and the distribution of the different materials in these façades are given here below on the basis of a 3m mean height. The surface of modern glass is arbitrarily estimated as half of the total surface of the façade. The two historical monuments of the Ile Saint Louis have their façade entirely in limestone, covering 768 m^2, and the other six, in the Ile de la Cité accounting for 71,586 m^2.

With these results, the authors demonstrate that the main material present in the façades in the Centre of Paris is the Lutetian limestone (roughly 76%), followed by painting (15%) and then by rendering (7%). Brick (1%) and metal (0.02%) play a very minor role. Thus, limestone dominates in the Ile de la Cite´ and on the right bank facing it, due to the presence of many important monuments and Haussmannian buildings, whereas painting and rendering are more important in the Ile Saint Louis, where buildings are dating from the XVII and XVIII centuries.

Total Paris Centre: 525 façade = **200,305 m^2**, length of 11,203 m Limestone: 15,933 m^2 (76%) Modern glass

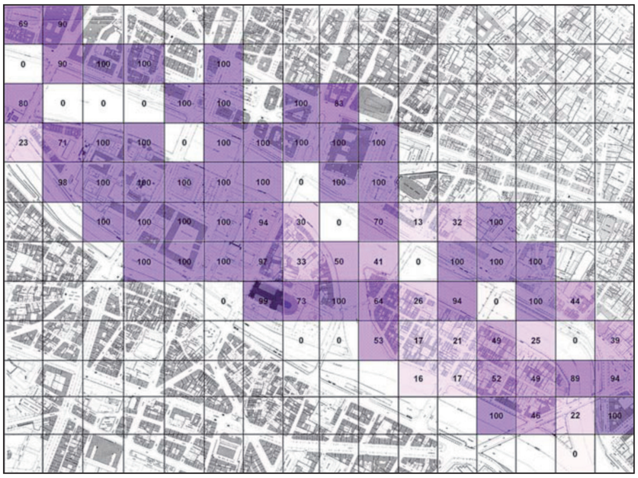


FIGURE 5 Geographical distribution of the percentage of limestone in the façades of buildings and monuments of the studied area, on a grid with cells of 100 m x 100 m (floor mean height=3m)
Source: [3]

(estimated): 100,152 m^2 (50%), others 47,247 m^2 (24 %). *(Monuments):* **72,354 m^2** - *100% Limestone.*

The geographical distribution, on a grid of 100m x 100m cells, of the total surface of the façades, of the surface in limestone and of the percentage of limestone in the façades, is given in Fig. 5. This confirms more in detail that limestone is mostly in the western part of the studied area.

The main risk for buildings and monuments in the centre of Paris is air pollution due to traffic, causing the soiling of façades by deposition of black carbonaceous particles, especially in the parts sheltered from rain, and the surface recession of these façades by erosion-dissolution in the parts exposed to the rain. The Dose /response function which we used to calculate the recession of the limestone material (see equation 1) *for Paris Centre indicates that the corrosion depth after one year of exposure is* ***5.75 μm.***

Table 1 shows that this result is lower than the tolerable corrosion rate per year, which is 8.0 μm year $^{-1}$ for the limestone 2020 target. This result is very close to the tolerable corrosion rate per year for the 2050 target, which is 6.4 μm year $^{-1}$. On the other hand, the calculated corrosion rate for the Paris Centre is almost two times as high as the background corrosion depth indicated in Table 1 (3.2 μm). This indicates that in 2009-2010 *the corrosion depth in the Paris Centre was almost two times as high as the background corrosion rate, which is due to air pollution, but it is steel in the range of tolerable corrosion rate for 2020 target.*

Conclusions

The present study gives results from the quantitative census of materials in monuments based on a real in-the-field inventory, and on direct examinations, applying maps, images and other documents at the available scales.

The type of materials used in the monuments was determined by direct examination of the building façade, and their proportions was roughly evaluated in percentage. Different types of limestone were used in the construction of the studied monuments.

The dimensions of the monuments were identified using direct examination, images, photos, drawings and other documents available in literature and from the internet sources. The dimensions of monuments then allowed to calculate their surface by valuating the surface covered by windows, doors, etc.

As limestone is the dominating material, the dose-response function for limestone was calculated in order to determine the corrosion of the materials used for constructing the monuments.

Using the pollution data for 2009–2010, the estimated recession rate for both sites does not exceed the 2020 target for limestone (2.5 times the background or 8.0 μm $year^{-1}$), but is very close to the 2050 target (2.0 times the background or 6.5 μm $year^{-1}$). However, the calculated corrosion rate for both sites is almost two times as high as the background corrosion depth indicated in Table 1 (3.2 μm).

References

[1] S. Doytchinov, A. Screpanti, G. Leggeri, C. Varotsos: *Pilot study on inventory and condition of stock of materials at risk at (UNESCO) CH sites.* UN ECE ICP Materials Report 68, November 2011, prepared by the sub center of stock of materials including CH at risk.

[2] C. Varotsos, University of Athens, Faculty of Physics, Dept. of Applied Physics, Laboratory of Upper Air. Bldg Phys 5., 15784 Athens,GR, Private Communication.

[3] J. Watt, S. Doytchinov, R.A. Lefèvre, A. Ionescu, D. Fuente de la, K. Kreislova and A. Screpanti (2009): Stock at risk, pp 147-187, in *The effects of air pollution on cultural heritage,* Watt J, Tidblad J, Kucera V and Hamilton R, Eds., Springer, New York, USA.

Energy-Related Innovative Concepts, Methods and Techniques for Sustainable Protection and Conservation of Historic Buildings in Urban Areas

The present paper is dedicated to a new integrated approach for the conservation of historic buildings and the application of sustainable technologies for Diagnostics, in order to increase the buildings' lifetime and the maintenance of their performance characteristics. The research activities have incorporated monitoring, NDT techniques and intervention works aimed at improving the energy efficiency of historical buildings

Stella Styliani Fanou, Timo Kauppinen, Paola Bartoccini, Alessandro Colucci, Francesco Di Biagio, Chiara Di Sarcina, Gaetano Fasano, Nicola Labia, Emanuela Martini, Riccardo Maso, Massimo Poggi, Angelo Tatì

Introduction

Italy has a large historic building heritage consisting of a) monumental complexes, protected by specific laws, b) immovables serving the main assets, as common historical buildings with or without characteristics of artistic value, but still having historic/artistic authenticity, and c) certain assets of landscape value, as they could be, for example, the historical centres.

Stella Styliani Fanou, Gaetano Fasano, Nicola Labia, Massimo Poggi
ENEA, Unità Tecnica Efficienza Energetica

Timo Kauppinen
VTT, Technical Research Center of Finland

Chiara Di Sarcina
Comune di Vittorio Veneto

Paola Bartoccini, Alessandro Colucci, Francesco Di Biagio, Riccardo Maso, Angelo Tatì
ENEA, Unità Tecnica Tecnologie dei Materiali

Emanuela Martini
Student candidate for thesis ENEA Code 2004 P4D6

This historic building heritage, mostly still in use, requires improvements in terms of energy efficiency and design interventions, in order to appropriately meet the increasing demands of users concerning hygrometric and moisture comfort, acoustic comfort and energy efficiency. In addition, the on-going global economic and social competition requires a number of operations essential to ensure that those historic buildings remain alive and also attractive for the housing market. Then the use of historic buildings and monuments under the best conditions of comfort and security is not merely a legal obligation but an essential part of the enhancement of this heritage and its protection.

Often do historic buildings and monuments remain "off limits" regarding energy efficiency; their restoration, very attentive to historic and aesthetic instances, completely excludes aspects involving

sustainable energy. It would be advantageous that the rules on energy efficiency and those on protection and conservation are closely co-ordinated in order to address the problem of energy optimization in historic buildings, otherwise their management in terms of cost and consumptions is unsustainable and with no guarantee for their protection, conservation and use.
In this context, research and decision-makers have to make an effort to overcome the gap between scientific resources and real applications: this effort must reformulate the role of technologies in the field of cultural heritage, respecting the fruition of historic buildings and monuments and their conservation.
In this line ENEA provides its wealth of expertise developed during the years in the field of energy, environment and new technologies in order to address the problems of conservation and use of this heritage with a systemic approach that, starting from the structural and material recovery, ends in the resolution of issues related to energy efficiency and plants.

The Project: Methodology, Objectives and Strategies

On the above premises, we introduce a new integrated approach for the conservation of heritage buildings, the application of sustainable technologies for Diagnostics and some intervention works, in accordance with the results of the interventions, studies, and technologies, finalised at the realisation of low energy standards in historic buildings. This article refers to the results of thermal scanning and other Non Destructive Techniques of some historic buildings of Serravalle's historic centre (fig.1) in Vittorio Veneto, a small city, situated in Veneto, at around 40 km from Venice. This Diagnostic analysis belongs to the project called "Contratti di Quartiere II". The project is developed by an Italian partnership. ENEA is the scientific partner of the project and has involved the VTT Technical Research Centre of Finland in the same tasks. Within the project, ENEA has developed a methodology based on a systemic and integrated approach which takes into consideration the particular monumental character of the historic buildings (protected by conservation laws), the current needs of their users and, last but not least, the optimization of the energy performance of buildings in compliance with the recent European directives.

FIGURE 1 Serravalle historic centre, City of Vittorio Veneto, Treviso
Source: Ufficio Tecnico del Comune di Vittorio Veneto

The project started on 2006 and currently more than 80% of the scheduled works have already been carried out. The works involved a surface of 90.000 m^2 and an amount of 25 million euro invested mainly by the Italian Ministry of Infrastructures, with the support of regional and some private funds.
Some of the buildings involved, constructed between the XIII and XVIII centuries,. were of residential use, some of them empty, partly deteriorated and not in use. The overall objective renovation program is to find a new use, mainly public, for the buildings and innovative energy efficiency solutions to improve their comfort and performance levels in an acceptable contemporary stage. Before the renovation works, a large series of studies were accomplished, concerning the identification, measurement and documentation of technical performance parameters of the historic buildings, and also the quality of the indoor environment conditions. In fact, a correct intervention on a historic structure should begin from an accurate diagnosis of the building in order to minimize the interferences of the intervention with the historicity of the architectural structures, through a good knowledge on the existing materials and techniques of construction. The intention

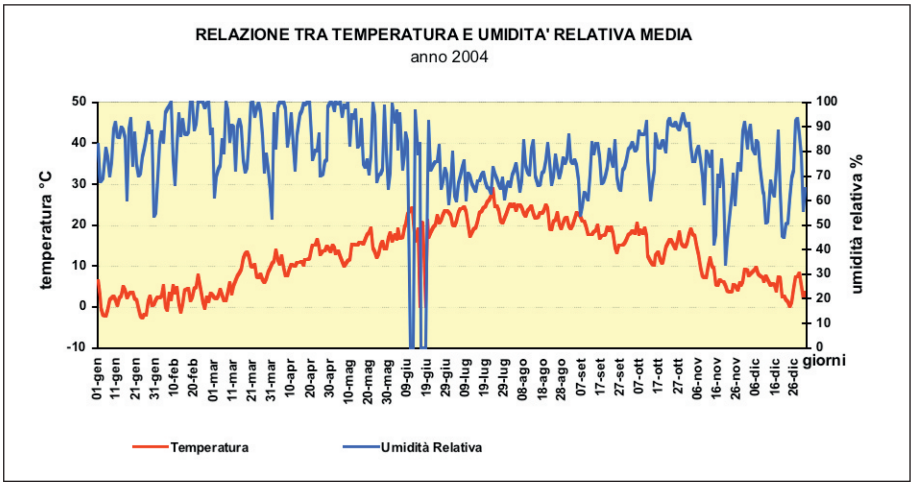


FIGURE 2 Thermo-hydrometric diagram elaborated on the basis of the collected data with relative relationship between temperature and relative average damp
Source: ENEA elaborations

of the project was to improve and conform the energy performance and the indoor conditions of the buildings involved and to assure the protection and sustainable conservation of their historicity, through the application of new technologies –such as non-destructive testing techniques, systems and innovative materials– and with the introduction of automation /smart systems for the building management.

Applications of Non-Destructive Testing Techniques in the Diagnostic Investigation of Historic Buildings

The analysis and diagnostic evaluations of historic structures have been executed with the application of Non Destructive Testing Techniques and monitoring during ante, intra and post operam. Some typical and difficult problems have been solved by the combination and the complementary use of different investigation techniques, such as endoscopy and videoscopy, IR thermography, Ground Penetrating Radar, ultrasonic testing, specific physico-chemical, and mineralogical petrography investigation. The NDT techniques can be very useful in finding hidden features, the presence of structural defects and the signs of damage detected on the building, but most of the NDT can give only qualitative results.

In addition, micro- and macro-climatic monitoring have been carried out for a long period, beginning from November 2007. These environmental investigations have allowed to determine the climatic profile of the historical centre of Serravalle (Fig. 2) and to process the main bearing elements for the buildings' recovery plan (Fig. 3), in compliance with the recent European Directive on the buildings performance. These environmental investigations and the results obtained have been used as input parameters for the creation of numerical models. NDTs have been applied in strategic points of the structure, previously identified, in order to know details on the geometry of the architecture and to solve the most difficult problems of hidden situations.

The building called *Palazzo Ex Monte dei Pegni* is the result of the transformation of more ancient buildings from the XII century, whose modifications have also involved the space of the main public square. The knowledge of the historical evolution of the building architecture is important to explain some evident signs of damage on the structures. The complementary use of different techniques on this historic building, as Ground Penetrating Radar (GPR) and sonic-ultrasonic tests, has allowed to verify its historical evolution and to accredit the hypotheses made on the basis of direct observations and bibliographical/archives information. The historic evolution of the building is connected to the transformations suffered by the surrounding space

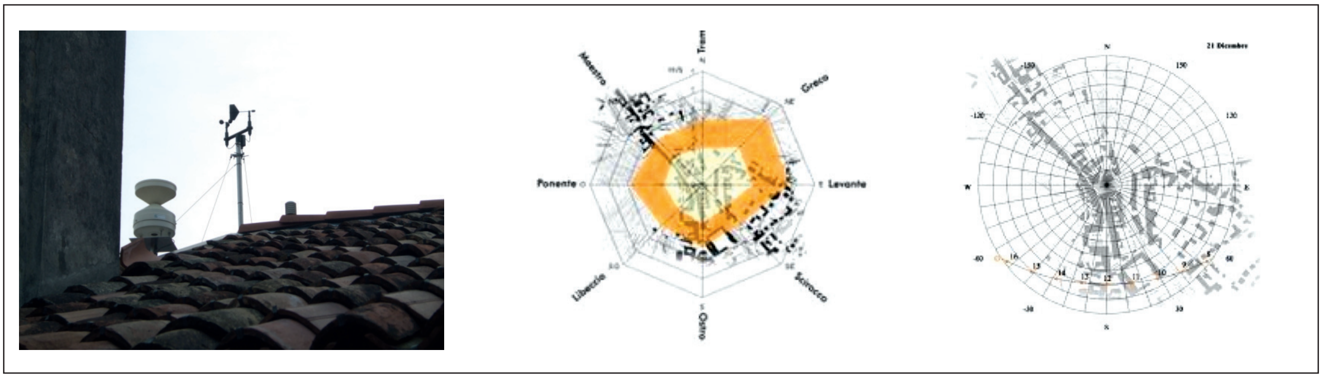


FIGURE 3 Prevailing winds and sun path diagrams on December 21st
Source: ENEA elaborations on ARPA Veneto and CRA-CMA climatic data

of the main square, in fact the columns of the porch are currently included in the masonry (Fig. 4).
Ground Penetrating Radar (GPR) investigations have permitted to find deep defects and hidden inclusions. This technique has consented to recognize the wall morphology and the presence of local defects, and has given information on the moisture presence within the floor and masonry. GPR technique uses a transmitting antenna to send a pulsed signal into the ground or into a wall or floor and an antenna to receive the echoes reflected by interfaces. The transmitted wave hits objects with different electromagnetic properties and the reflected signal is received by a radar antenna. The recorded information is reflected on a computer display. Suitable processing was used to reveal the presence of the hidden structures and to characterize their morphological properties. GPR provides a radargram, that is the image of the echoes reflected by the embedded scattering object. (Fig. 5)
Sonic and ultrasonic tests were used to detect the inside density of the material and cracks, and to control the masonry characteristics and the effects of the previous interventions (Fig. 6)
NDT testing, in particular IR Thermography carried out on the principal façade of *Palazzo Todesco* (XIII-XVII centuries) permitted to verify the state of damage to surfaces, the thermal bridges of the structures and material decay. The set-up of IR technique for the detection of a particular defect (discontinuities under the surface, hidden structures, moisture growth,

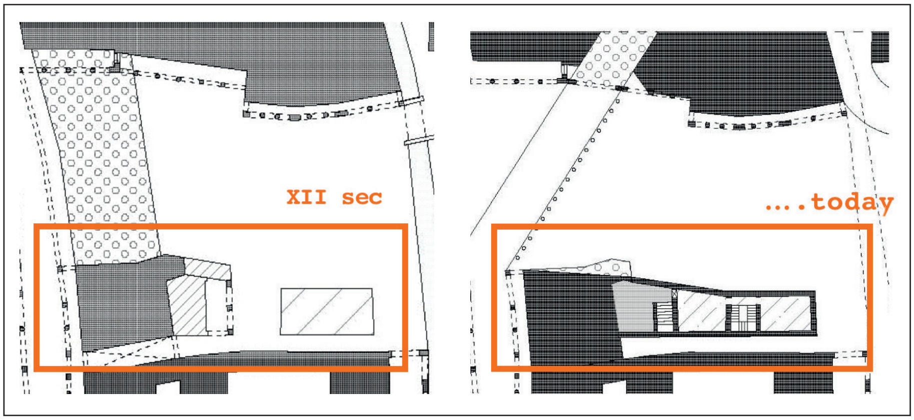


FIGURE 4 Palazzo Ex Monte dei Pegni: phases of historic evolution
Source: ENEA elaborations

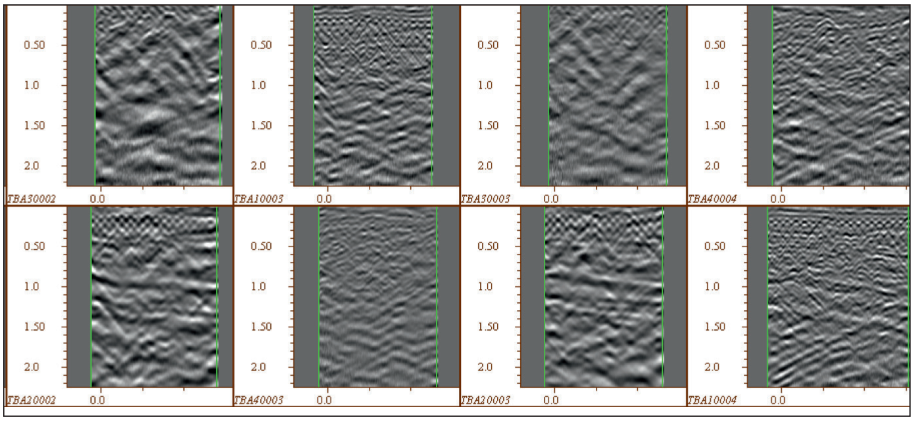


FIGURE 5 Processing of the radargrams at different depths
Source: ENEA elaborations

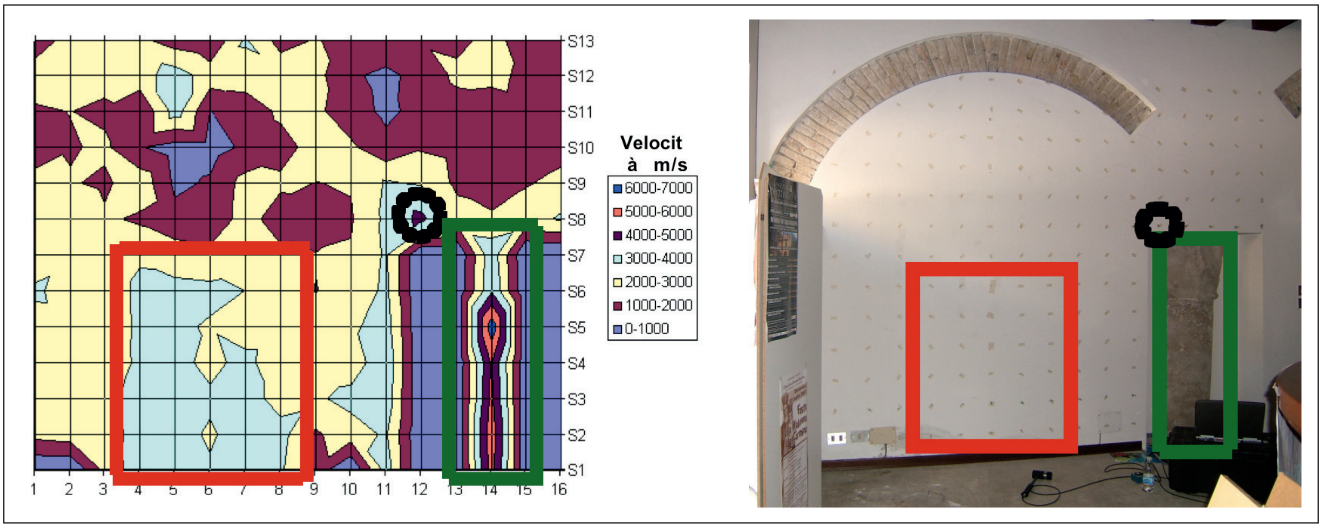


FIGURE 6 Distribution of the pulse sonic velocity on the wall
Source: ENEA elaborations

detachment from a wall) in an ancient structure needs a specific IR calibration. The IR Thermography allowed to create maps (thermograms) of the macroscopic defect distribution on the principal façade on the Flaminio square. This thermograms map has been compared to that of macroscopic damage on the south side.
In the building called *Palazzo Todesco*, sonic tests were carried out on the columns of the external porch on the west side. These tests have permitted to verify the structural damage to every single architectural element and the material homogeneity (internal crack, absence of material), and so to calculate the elastic 'modulo' and the mechanical resistance of the structures. The knowledge of the health conditions of the historical *Palazzo Todesco* has been essential for the preservation of its historical identity. In fact, these non-invasive techniques were applied to identify the structural integrity of the building (Figs. 7 and 8).
In the *post operam* phase, NDTs have permitted to verify and control the project standards previously characterized, and the energy efficiency of the buildings. In particular, the thermal scanning method

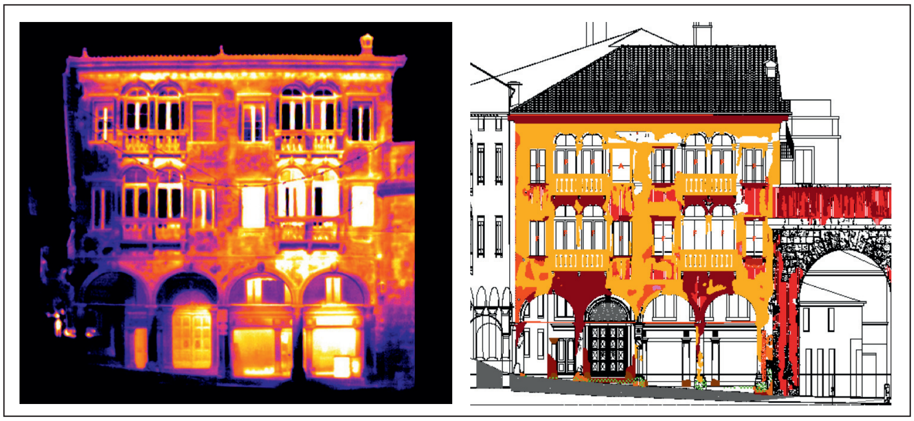


FIGURE 7 Thermovision applied to the principal façade of Palazzo Todesco and relative mapping of damage
Source: ENEA elaborations

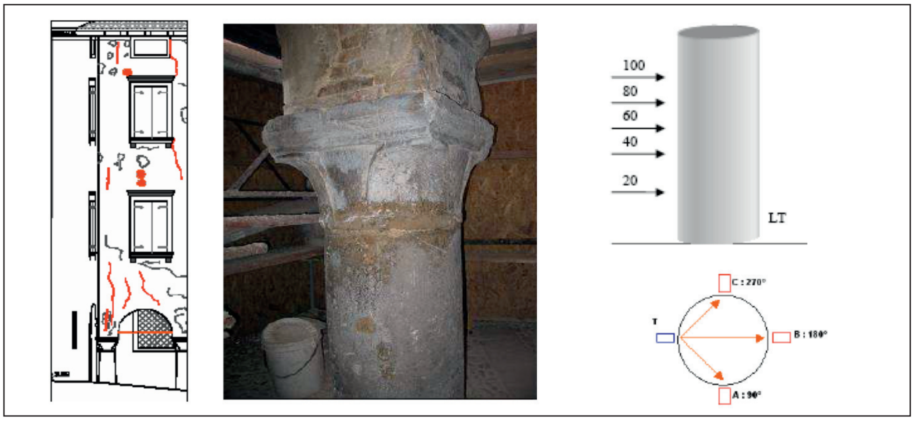


FIGURE 8 Palazzo Todesco. Crack pattern survey of the external west side and distribution of the pulse sonic velocity at a column of the porch
Source: ENEA elaborations

is finalized to study historic structures and their state of the art. IR Thermography is an effective NDT method for the evaluation of the indoor thermal-hygrometric conditions and the materials decay (with some limitations); it is used for the assessment of various traditional–historical materials and structures after they have been restored or repaired using different treatments. Thermography is a contactless and non-destructive investigation technique suitable for acquiring significant information about hidden structures and for long-term monitoring. As concerns historic structures, it allows investigating details of construction, damage and material decay, and interventions.

Thermography was one tool in the non-destructive testing toolbox, which was used to research on the condition and performance of exterior walls. Within thermography, also other indoor environment measurements were made by imaging with a thermal camera: CO_2, RH (relative humidity) and temperature measurements (air temperature and air speed), fundamental environment parameters. The distribution of the surface temperature is of course very important, but the correct approach is to measure the boundary air conditions, at the same time.

Thermal scanning of the building envelope and of other structures was made in the winter 2008. Two buildings were scanned outdoor and indoor with supporting indoor air condition measurements (*Palazzo Monte Dei Pegni and Palazzo Piazzoni*). Two buildings were scanned only outdoor (*Palazzo Todesco and Palazzo Ex Carceri*). The outdoor conditions were relatively good compared with the prevailing weather, because the temperature differences during the scanning varied between 15-20 °C and the weather conditions had been relatively stable 2-3 days before the measurements. Sun radiation impeded the scanning, so some façades could not be measured. The results were used in the planning of the renovation measures. The aim was to find and localize possible defects, subsurface structures and thermal bridges by thermal scanning. The renovation works are still in progress, and the performance of completed buildings will be confirmed by the same type of measurement set.

Palazzo Monte dei Pegni is situated on the principal square of the historical center. In this building, which was of residential use, 4 flats and one office were measured. The measurements included CO_2, indoor temperature, RH and pressure drop between indoors and outdoors. The room spaces had slightly negative pressure drop compared with outdoors' (measured from the level 1.5 m from the floor); the pressure difference varied between -1 Pa--3 Pa. Variation of indoor temperatures: 13 °C – 23 °C (the lowest indoor temperature was in the office, not occupied at that moment); CO_2-level: 620 ppm (the office) – 1100 ppm (depending on the persons inside the apartment); RH-level: 27%-44%. The indoor temperature depended on the control of the heating system.

Some investigations have concerned the north and the east side of one of the examined buildings, called *Monte dei Pegni.* The building was an apartment building, but it is planned to change to residential and office uses. The building had a natural ventilation system and water circulation based radiator heating system, partially fan coils. The measurements showed that the exterior wall structures varied a lot also in the case of the same buildings. Subsurface constructions, covered openings, thermal bridges, uneven structures, etc., were found (Fig. 4). Some of these findings must be taken into account in the renovation design (Figs. 9-13).

The thermal scanning must be done before the sun

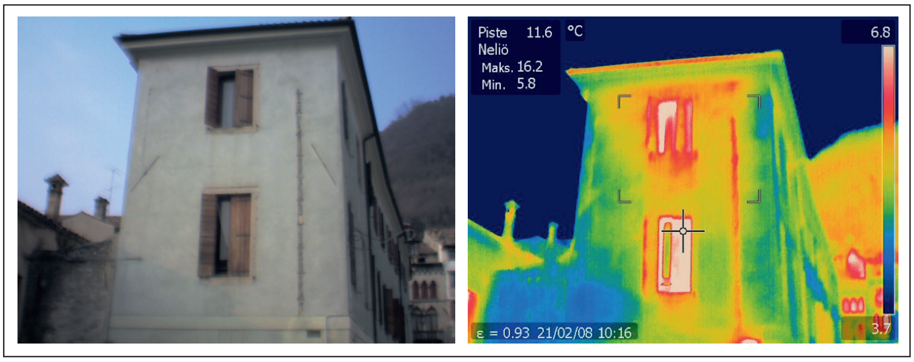


FIGURE 9 Thermal image applied to detect discontinuities beneath the surface, using an inclusive range among 3.7° and 6.8° for the thermographs staircase. It is possible to see a different superficial temperature of materials for that heated places internally
Source: ENEA and VTT elaborations

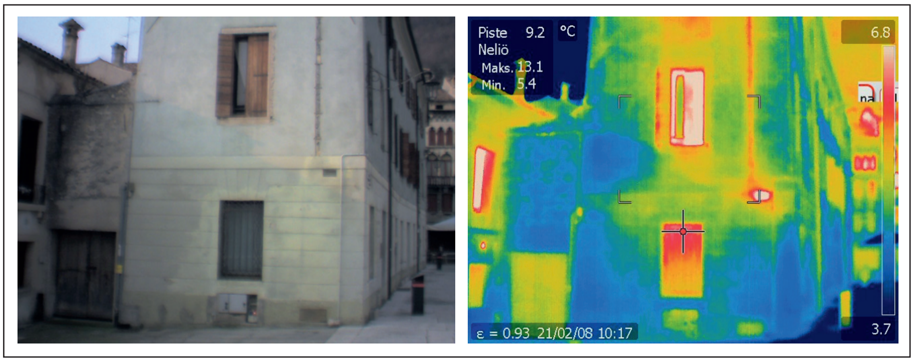


FIGURE 10 Moisture distribution and moisture growth detected by thermal scanning
Source: ENEA and VTT elaborations

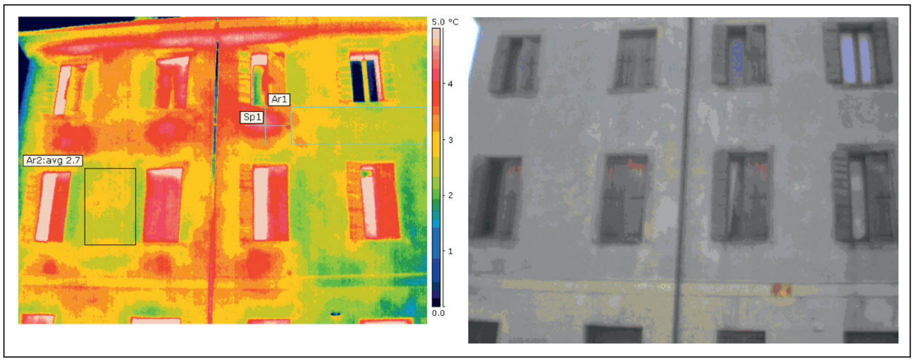


FIGURE 11 The upper part façade in the morning, before sunrise. The radiators and also the intermediate floors, walls, both pipelines are visible
Source: ENEA and VTT elaborations

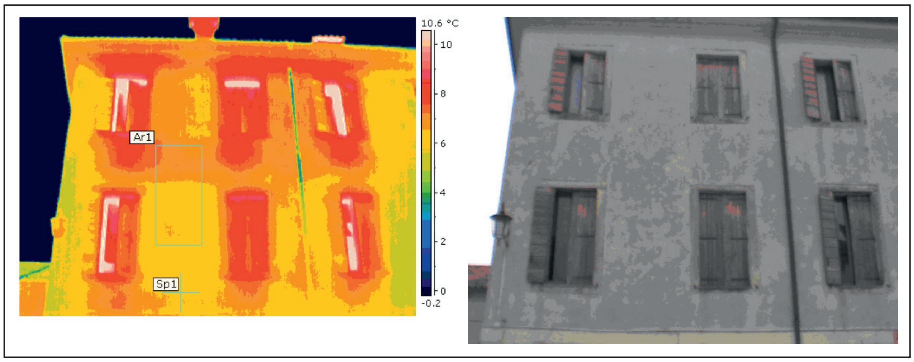


FIGURE 12 The same façade during sun radiation. The external heat source removes the structural details
Source: ENEA and VTT elaborations

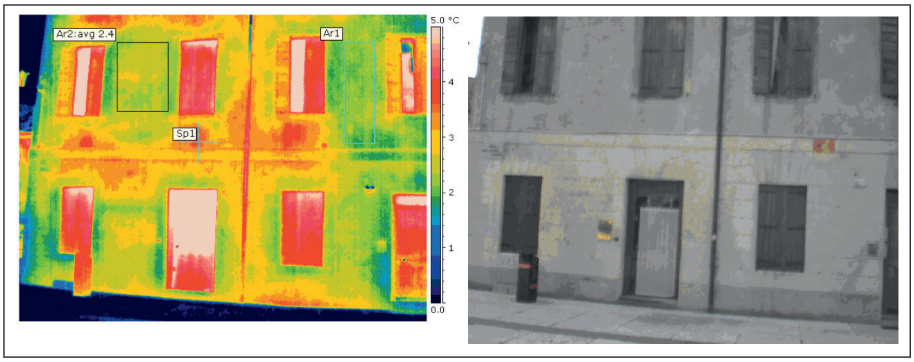


FIGURE 13 Lower part of the façade in the morning. The earlier door place can be seen between the window and the door
Source: ENEA and VTT elaborations

begins to affect the surfaces. The measurements can be repeated during the heating up period and then during the cooling down period – during heating and cooling delamination structures and different structural elements can be seen, depending on the differences of thermal capacities.

Indoor measurements showed temperature variations on the surfaces. Thermography allows to check the condition of radiators and windows. The thermal conditions of external walls varied, and the thermal performance was not uniform. Retrofit of historical buildings means a challenge if there is no possibility to have any additional external insulation. If internal insulation is used, it will decrease the floor a little bit but will increase the effect of thermal bridges in the joint of floors and walls, also in the joint of intermediate walls and exterior walls. By comparing the results of outdoor and indoor scanning, one can decide for renovation needs. The change / repair of windows may be the most efficient measure. The ventilation and heating systems must be totally renovated, which means mechanical ventilation with heat recovery (installation problems), or less effective mechanical ventilation, or hybrid solutions.

Conclusions

Improving the energy efficiency of valuable cultural heritage targets and areas is a challenging task in more ways– the goal depends on the possible planned new use, or use of the building, the actual condition of the building, the performance of the target, the indoor environment and many other factors. There are certain limitations for refurbishment, especially dealing with façades and interiors. But historic building should meet the requirements and not have any health hazards or structural risks. In most cases historic buildings have defied the pressure of centuries and changing times – but the performance of the buildings must be assured.

The historic buildings and also historic centres must be submitted to holistic studies, in which both the building structures and the building systems will be considered.

In the case of energy efficiency it means:

- How the heating system could be renovated or modernized
- How the ventilation system and indoor environment can be improved
- How the cooling system can be improved or added to the existing one
- How to improve the energy efficiency of the historic building envelope

Energy efficiency cannot be improved just focusing the measures on one system only, therefore the most essential thing is to have a holistic view and to try integrating the different systems affecting on historic building performance so that they can interact in an optimal way. This requires first that both the survey of the building conditions and the energy performance of the building have been audited (condition and energy assessment). Then the next step is to have conclusions about the actual performance of the building and the investments needed; it also means that the project requirements and the key performance indicators have to be properly set. It is very important that, except the renovation measures, also the need of facilities and energy management are taken into account. This implies that the performance requirements are set, and on the other hand, one must know what indicators must be monitored.

Using building automation systems (BAS), building energy manage systems (BEMS) and facility management tools means:

- new instrumentation and sensors; (*what can't be measured, can´t be managed!*)
- monitoring and reporting systems, and procedures based on the automation systems and measurements.
- feedback of the results

Improving the facility management system necessarily implies:

- the short- and long-term maintenance procedure.

The paper is also intended to open the discussion about some innovative applications of IR automation thermography and other NDT-methods for cultural heritage buildings. In this project there was no possibility to make larger thermography surveys in different weather conditions. The next test will be made when all the buildings are renovated. Thermography is just one tool of the NDT toolbox and NDT- and NDE-methods (non-destructive testing, non-destructive evaluation) are just a part in the condition and energy assessments of buildings. Anyway, the essential topic is that the performance of historic buildings has been verified by various methods for evaluating the retrofit measures needed.

The effective and proper use of thermography needs a lot of research and development work so that the procedures could be applied more widely. Thermography can be used in detecting the moisture distribution; also some structural deviations can be determined. Both types of damage can be detected by using dynamic thermography applications. Thermography, however, is one tool in NDT-toolbox, and more attention should be paid to combine various methods. In any case, in evaluating the thermal performance of the historic building envelopes, thermography and additional supporting methods, such as air-tightness measurements, heat flux measurements, etc., are the only covering techniques to give a full-scale conception of the performance.

The moisture distribution and some subsurface structures should be found for the future planning and refurbishment measures – in some cases the variations in exterior walls can be critical, e.g., in earthquakes.

One difficult task is to find out how the thermal performance of exterior walls could be improved. The walls are massive, even the U-value is low, there is not so much to do if we want to maintain the façades in the original form. New surface treatments through multi-functional materials, such as thin composites nanostructure insulators, spray or paints, could improve thermal mass, self-cleaning and fire resistant behaviour of the historic buildings, thus contributing to cultural heritage conservation, restoration and rehabilitation. In this direction, research will have another frontier to overcome.

The air-tightness of walls, and especially of windows and doors, is a very crucial factor in energy efficiency – uncontrolled leaks mean uncontrolled ventilation, the share of which can be as significant or even greater than the controlled part of ventilation. Air leaks can be located by thermography and the air tightness of the whole, or part, of the building can be measured by the airtightness test (blower-doors).

References

[1] Kauppinen T. (2009). *"The Use of Thermography in Energy Performance of Buildings directive"* (EPBD)-applications. Thermosense XXXI Proceedings, Bellingham, WA.

[2] Avdelidis N.P., Kauppinen T.T. (2009). *"Thermography as a tool for building applications & diagnostics"*. Thermosense Proceedings, Bellingham, WA.

[3] Fanou S., Kauppinen T. (2009). *"Indagini sul comportamento termico post-operam di un edificio scolastico"*, Atti Conferenza Nazionale sulle Prove non Distruttive, Monitoraggio e Diagnostica, Roma.

[4] N. Avdelidis, C. Catsanedo, E. Cheilakou, C. Ennaceur, S. Fanou, T. Kauppinen, M. Koui, X. Maldague, E. Saarimäki, Transient thermography tools for NDT & E of composites. NDT Conference, Canada 2009.

[5] N.P. Avdelidis, A. Moropoulou, *"Emissivity considerations in building thermography"*, J. Energy & Buildings 35(7), (2003), pp. 663-667.

[6] N.P. Avdelidis, A. Moropoulou, *"Review Paper: Applications of infrared thermography for the investigation of historic structures"*, J. Cultural Heritage 5(1), (2004), pp. 119-127.

[7] N.P. Avdelidis, A. Moropoulou, D. Stavrakas, *"Detection and quantification of discontinuities in building materials using transient thermal NDT techniques: modelling and experimental work"*, J. Materials Evaluation, 64(5), (2006), pp. 489-491.

[8] Fanou S., Tati A., Labia N., Colucci A., Di Biaggio F., Di Sarcina C., Maso R., Martini E., Bartoccini P., Lazzaroni F., (2009). *"L'impegno ENEA per il Patrimonio Culturale – L'attività sperimentale del progetto Vittorio Veneto"*, Rapporto Tecnico ENEA 65/08, pp. 1-41.

ICT to Increase Knowledge of Cultural Heritage

The advanced Information and Communication Technologies, combined with the development of applications based on Artificial Intelligence, open new possibilities to investigate CH in depth. Through GRID computing it is possible to directly access distributed databases by Web, creating a network of different archives. Instruments for Augmented Reality, modeling, simulation and virtual 3D reconstruction are useful both to predict the process of deterioration and to create innovative means to disseminate knowledge

Silvio Migliori, Dante Abate, Luciana Bordoni, Beatrice Calosso, Vincenzo Fiasconaro, Graziano Furini, Samuele Pierattini, Simona Guiducci, Belén Jiménez Fenández-Palacios, Fabio Remondino, Alessandro Rizzi

Introduction

The set of skills developed during several years, expertise and innovative tools that the Technical Unit for IT and ICT Systems Development (ENEA-UTICT) provides the CH sector with defines a process mostly aimed at promoting the integrated knowledge of CH within its context. Therefore, this process becomes a factor of growth in the cultural, social and economic system, in specific geographical areas. The range of services offered has been developed specifically to meet the needs expressed by stakeholders operating in Restoration, Cultural Tourism and Research.
The process incorporates specific methodologies and technologies for:

- integrated knowledge, aimed at acquiring and sharing information and data, by means of artificial intelligence;
- diagnostic monitoring, carried out through the analysis of the state of disrepair of artworks and monuments, leading to planning the most suitable restoration interventions;
- sustainable use and dissemination of the results obtained by interventions;
- enriching and integrating the visit of sites and monuments by using 3D reconstructions and applications of Augmented Reality.

Three experiences, which represent how this process can be realized, will be described in the following chapters.

Dante Abate, Luciana Bordoni, Beatrice Calosso, Vincenzo Fiasconaro, Graziano Furini, Silvio Migliori, Samuele Pierattini
ENEA, Unità Tecnica Sviluppo Sistemi per l'Informatica e l'ICT

Simona Guiducci
ENEA Guest

Belén Jiménez Fenández-Palacios, Fabio Remondino, Alessandro Rizzi
Bruno Kessler Foundation – FBK

Remote Rendering and Visualization of Large Textured 3D Models

The platform implemented and here presented allows an efficient and effective multi-user online sharing of high quality 3D textured models with no need for users to download it locally whilst exploiting the performances of a remote HPC infrastructure.
So far the presence of 3D models on the web is not very frequent, despite the increasing developments

of libraries, plug-in applications, games, etc.[1]. Nevertheless the scientific community and end-users are expressing an increasing need to exploit 3D models with a client-server architecture. Yet, when it comes to the visualization and interaction of big polygonal datasets online, the reliable commercial solutions are weak. The main problems are due to the bandwidth of the network and the protection of online shared and rendered 3D models. Indeed, sharing online digital archives of 3D CH models presents new challenges for the protection of intellectual property rights (IPR). Different approaches [2, 3, 4, 5] were proposed to protect piracy, copies and misuse – still allowing an interactive sharing – but the topic is still open. Here we present the study regarding the implementation of a hardware-software platform which permits a multi-user access to a repository of 3D models exploiting different applications. Thanks to this, the end user no longer needs specific HW and SW resources during the interaction and visualization of a 3D model whose resolution remains constant during the navigation. At the same time, the system protects the intellectual property of 3D models since they are not downloaded locally, but they remain safely stored on the remote repository. This project, called ARK3D [6], uses the ICT infrastructure of ENEA-GRID and, in particular, the graphic cluster belonging to the project CRESCO. The AFS geographic file system is used to implement the 3D repository.
3D models can be uploaded together with different kinds of metadata by users through a web-based interface following a dedicated registration procedure. The database is queried via web by free search keywords. The result will contain the metadata attached to the models, together with a link to the 3D remote application. The rendering (Fig. 1) is performed using the dedicated remote cluster and guarantees the protection of data, which can be manipulated although they cannot but be downloaded through a secure ftp.
The database is queried via a web page: unregistered users can only visualize an image (screenshot) of a 3D model, whereas users with credentials can choose and run the remote application to visualize and analyse the selected model. To do that, it is not required to know any configuration feature or install any other SW.

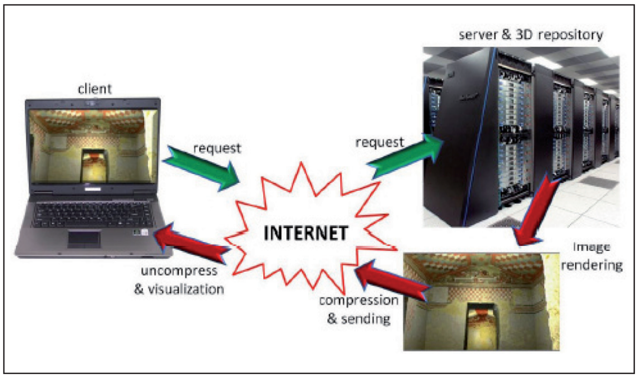


FIGURE 1 Remote 3D rendering based on Cresco graphic section
Source: ENEA

With this technology the final user can work over very large 3D models and visualize them using standard consuming computers, just connecting to the remote cluster via web. Through the dedicated web page, it is possible to upload 3D data onto the repository and eventually upload metadata attached to the 3D object. The metadata are represented by basic information such as the model author, upload/creation date, file name, etc., either in form of strings of characters or of independent files like images or documents (pdf, doc, jpeg, etc.). The remote displaying can be basically occur through any graphic application (proprietary and open-source).
In order to test the possibility of processing and editing 3D data, another solution available in ARK3D for the remote rendering of large 3D models is given using Meshlab [7]: 3D models (compatible with the file formats supported by Meshlab) can be displayed and edited using the functions available in the open-source program (Fig. 2).
Thus the user can: load and work with range maps, unstructured point clouds or polygonal data (millions of triangles), even on a standard laptop with limited computing resources; edit and analyse the model; extract geometrical information, or run batch processes.
This kind of approach is intended to stimulate the sharing and diffusion of 3D models among the communities in order to promote collaborative works

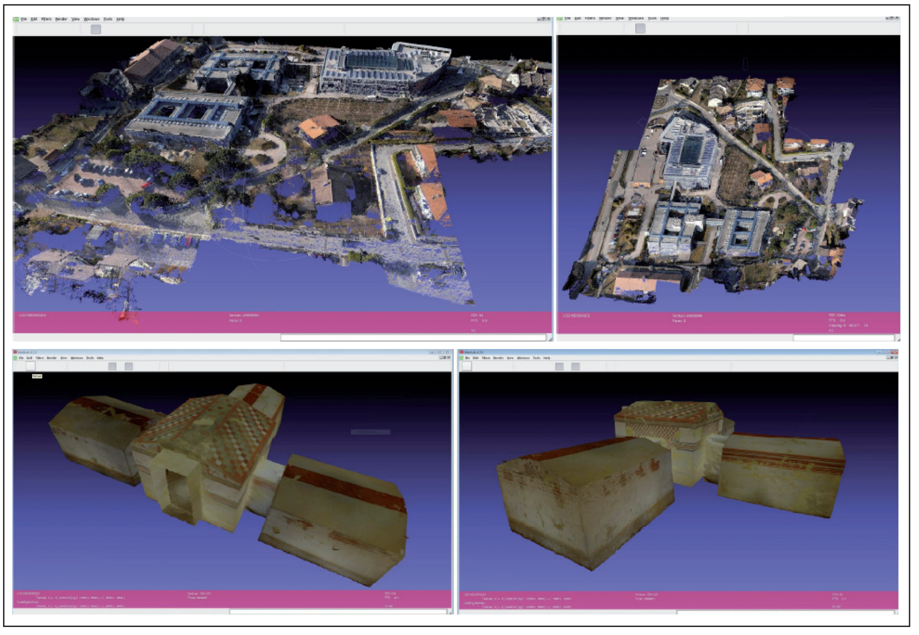


FIGURE 2 Example of a UAV-derived cloud with 108 mil. points with related RGB colour loaded remotely using Meshlab (a). A textured polygonal model with 3 mil. polygons and ca 115 MB texture displayed within Meshlab (b)
Source: ENEA

among technicians and non-experts without the limitations imposed by missing computing resources.

The Aras Project: Augmented Representation of Archaeological Sites

Whilst "Virtual Reality" stretches to totally replace the vision of the real world, "Augmented Reality" aims at enriching its representation, yet maintaining a connection with "reality."
Mixed Reality is the term commonly used for referring to environments that arrange real and virtual objects with visual representations of the real and virtual spaces.
In the ARAS Project the attention is focused on the individual, who becomes the protagonist of the action: we can speak of "augmented walk", a walk in the scene for discreet points.
Inside the archaeological site, along a pre-arranged path, some removable supports will be positioned and "camouflaged" with the environment (for instance, small columns), on which AR telescopes (where the real sight is superposed by virtual objects) are mounted.
The visitor can walk in the site being free from backpacks or glasses and, once reaching the observation point for the augmented reality, he can then decide whether to look through this "time window" and be taken several millennia back in time.
This way the visitor chooses the "augmented walk" in the archaeological site, but the necessary technology to make a "trip back in time" is not considerably visible, as in the case of the systems HMD (Head Mounted Display). The systems based on the HMD technology force the visitor to wear a series of instruments that allow to see the reconstruction of the environment surrounding him. In the realization of our project we have made some considerations: the instruments to be put on may not be easy to use for some categories of visitors as, for instance, old and disabled people; not necessarily may the visitor want to immerse himself continuously in the augmented HMD reconstruction; a first approximation of the visitor's position a GPS signal is used, which sometimes could not be received causing the loss of visualization.
Using this technique allows all visitors to benefit from the additional material and they will go deeper into cultural subject thanks to this combination of education and entertainment (*edutainment*).

In many archaeological sites, moreover, there are buildings closed to the public in order to avoid their total destruction. Now it is possible to reopen these places virtually creating their 3D models.

In order to show the application potentialities of the ARAS Project, we have realized a model (Fig. 3) of an archaeological site provided with special supports to arrange the video cameras, that simulate the telescopes AR, on which we have overlapped the virtual models of the 3D reconstructions of the Temple of Jupiter and of a detail of the House of the Faun (Fig. 4).

The idea introduced with the project is to partially get around the phase of recognition of the marker, introducing a preliminary step: the memorization of an initial position of the video camera related to the marker.

Moreover, in this preliminary step the marker will not be a figure alien to the landscape, but an integral part of it: the trusts, that show the historical data placed side by side on monuments, can be used to such purpose, modifying them so as to be recognized as a marker.

This way the only required data are the initial position and the recorded displacements of the video camera through the gyroscopes, so that it is no longer necessary to estimate the position of the video camera frame by frame.

Clearly this approach avoids the lack of visualization depending on occlusion phenomena and changes of brightness. Another important element to be considered is the use of the VRML language: it is possible to generate a real virtual life using animations, so as to create a greater emotional involvement of the customer who visits the archaeological site.

The visitor, in fact, will find himself facing the reconstruction of scenes of life from the places he is observing, with his consequent greater participation.

Our main objective has been to develop an application capable of replacing the *Archeoguide System*, offering the visitors the chance to observe the reconstruction of monuments needless of any visualization device to bring along. The application can be enriched by integrating the monument reconstructions with a vocal description of details and historical information.

The software can be implemented with applications for PDA, tablet and smartphones. An application for online Museums can be developed. The objects of the Museums can be shown so that the customer can virtually hold an artistic object in his hands and observe it from several angle-shots.

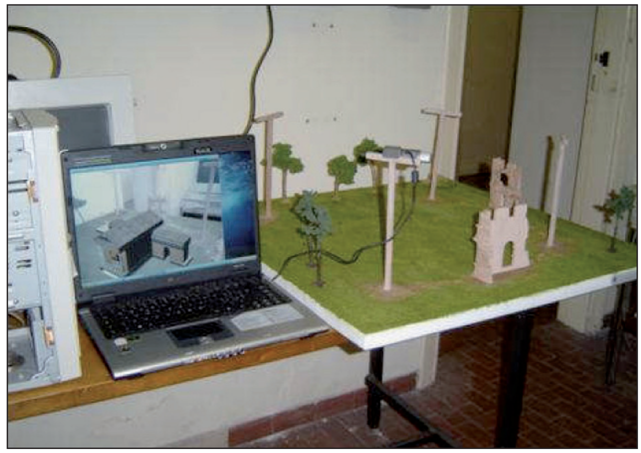


FIGURE 3 Model that shows the ARAS prototype
Source: ENEA

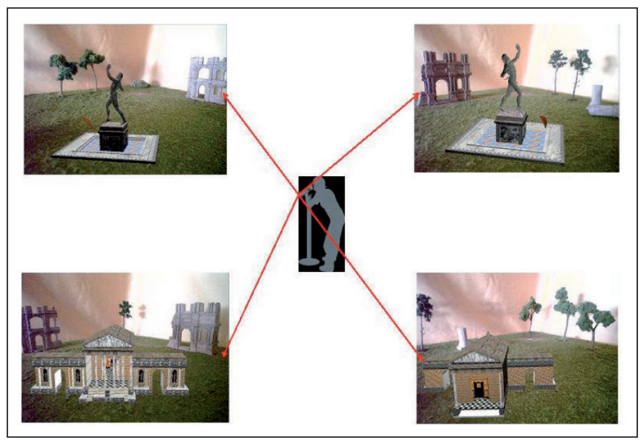


FIGURE 4 3D reconstructions of the Temple of Jupiter and of a detail of the House of the Faun
Source: ENEA

A Case Study for Cultural Tourism: the Latin Latium

Cultural Heritage Tourism has become a major source of revenue for many communities and states across the globe. Not only does it create jobs, but it has the potential to stimulate the local economy, beyond the capacity of its residents. As the Web has changed people's daily life, it has significantly influenced the way that information is gathered and exchanged in the tourism sector. Information technology starts playing a challenging role in the domain of tourism, such as Semantic Web and Web2.0. In the tourism domain different in-house taxonomies and catalogues already exist which are designed and used internally by tourism agents to help them manage heterogeneous tourism data. Efforts are made to generate global standards to facilitate inter- and intra-tourism data exchange (e.g., by the World Tourism Organization). Mediation, ontologies and semantic web can create an image of a future harmonised electronic tourism environment. Ontologies play an important role to facilitate the semantic integration of heterogeneous data [13]. They can assist organisation, browsing, searching, and more intelligent access to information and services available online [14]; for this reason several formal tourism ontologies publicly available have been created [15].

Since the beginning of the 2000s, Semantic Web technologies and their potentials for the integration and exploitation of digital CH information have drawn increasing attention, and today they represent an exciting and dynamic field of interdisciplinary research [16]. Many little-known areas have interesting "heritage" to be capitalized on, promoted, and rendered useable by and attractive to the broader public.

The territory of Latium, in particular, offers considerable development opportunities with the creation, for example, of appropriate infrastructures that do not simply connect the centre with the outskirts, but are vehicles for the region's deeper economic and cultural integration.

The object examined in this case study is the area in the Latium Region, south of the Tiber, where the Latin civilization was born and developed. Still little known and visited, as confirmed by statistics, and only partially included in parks and natural reserves, this area possesses a vast archaeological, artistic, ethnographic, natural, historic, and scientific heritage. It has been studied, analysed, protected by different stakeholders throughout the history (people and institutions), each of them documenting their actions and knowledge in all kinds of records, monographs, articles, legal texts, collections, etc. This knowledge comes from different sources (encyclopaedias, reference books, finding aids, government publications, databases, web sites, etc.) that can be accessed only in a fragmented way, without any or with weak interconnection. Moreover, they are at different stages of formalisation, standardisation or,

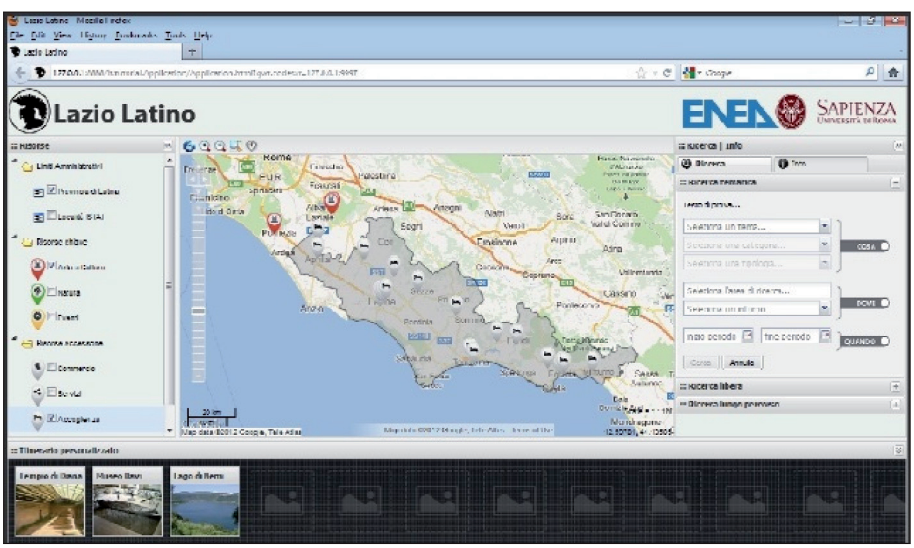


FIGURE 5 A screenshot of the portal
Source: ENEA

even, digitisation. All that has been described above makes it very difficult to access the information. This case-study intends to make it possible to: 1) capitalizing this area of Latium, emphasizing its singular nature and great worth; 2) facilitating the visits by providing the user with all the necessary and useful services; 3) permitting cultural enrichment through easy learning and full understanding of the place's historical, artistic, and cultural issues.

For this purpose, semantic web technologies are proposed for application to diversify the information sources that may be referred to two major areas of cultural tourism interest: services (transport, hospitality, etc.) and culture (history, art, traditions, etc.) [17].

The portal (Fig. 5) is the main step of this application and is conceived to offer easy access to all the contents gathered. For this case-study two application scenarios have been elaborated. A "static" scenario permits cultural enrichment through easy learning and full understanding of the place's historical, artistic, and cultural issues. A "dynamic" scenario allows virtual tourists to exchange opinions and experiences on itineraries in the Latin origins of ancient Rome through the use of WebGis technologies and social media.

References

[1] A.M. Manferdini, F. Remondino, "A review of realitybased 3D model generation, segmentation and web-based visualization methods", in Int. Journal of Heritage in the Digital Era, Vol.1(1), pp. 103-124, 2012.

[2] D. Koller, M. Tutitzin, M. Levoy, M. Tarini, G. Croccia, M. Cignoni and R. Scopigno, "Protected interactive 3D graphics via remote rendering", in Proceedings of ACM SIGGRAPH, pp. 695-703, 2004.

[3] F. Uccheddu, M. Corsini, M. Barni, "Wavelet-based blind watermarking of 3D models", in Proc. ACM Multimedia and Security Workshop, pp. 143-154, 2004.

[4] J. Zhu, J.Z. Bakdash, D. Koller, T. Banton, D.R. Proffitt, and G. Humphreys, "Quantifying usability in secure graphics: assessing the user costs of protecting 3D content", in Proc. Of the Symposium on applied Perception in Graphics and Visualization (APGV), 2008.

[5] E. Zagrouba, S.B. Jabra, "A new approach of mesh watermarking Based on maximally stable meshes detection", in Proceedings of the 3rd International Conference on New Technologies, Mobility and Security (NTMS), pp.1-5, 2009.

[6] https://www.ark3d.enea.it/home.php

[7] http://meshlab.sourceforge.net/

[8] P. Milgram, F. Kishino (1994). A taxonomy of mixed reality visual displays, IEICE Transactions on Information and Systems Special Issue on Networked Reality (E77D), 12, 1321-1329.

[9] ARToolKit Developer Homepage, http://sourceforge.net/projects/artoolkit/

[10] ARCHEOGUIDE Augmented Reality-based Cultural Heritage on-site Guide, http://www.aec2000.it/archeoguide /

[11] L. Cinque, V. Fiasconaro, S. Guiducci, Realizzazione di un prototipo di "Augmented Reality" in un ambiente strutturato, Tesi di Laurea, Università di Roma "La Sapienza", 2009.

[12] T.R. Gruber, A translation approach to portable ontologies, Knowledge Acquisition, vol. 5, no.2, pp. 199-220, 1993.

[13] W. Vongdoiwang Siricharoen, Enhancing semantic web and ontologies for e-tourism, International Journal of Intelligent Information and Database Systems, vol. 4, no. 4, pp.355-372, 2010.

[14] K. Prantner, Y. Ding, M. Luger, Z. Yan, C, Herzog, Tourism ontology and semantic management system: state of the art analysis, IADIS International Conference WWW/Internet 2007, pp.111-115.

[15] G. Mantegari, M. Palmonari, G. Vizzari, Rapid Prototyping a Semantic Web Application for Cultural Heritage: The Case of MANTIC. ESWC (2) 2010, pp. 406-410.

[16] L. Bordoni, "Technologies to support cultural tourism for Latin Latium", Journal of Hospitality and Tourism Technology, Vol.2, Iss:2, 2011, pp.96-104.

Scanning Lidar Fluorosensor for Remote Diagnostics of Artworks

The Laser Induced Fluorescence (LIF) technique has been applied in the field of cultural heritage as a diagnostic tool for the advantages it offers of minimal invasiveness, in situ applicability, remote measurement capability and high sensitivity. Scanning hyperspectral systems based on LIF have been designed and built at the Diagnostics and Metrology laboratory of ENEA-Frascati in order to obtain analytical information on CH surfaces by 2D images collection

Luisa Caneve, Francesco Colao, Roberta Fantoni, Luca Fiorani, Antonio Palucci, Maria Pilar Ortiz, Vasco Fassina

Introduction

The respect of the artwork, its conservation status and the preservation of the historical-environmental context are at the centre of the modern concept of restoration. Innovative non destructive diagnostic technologies, suitable to the characterization of historical surfaces, as painted surfaces, multilayer frescos or decorations on wood, are then currently under development to meet the conservators' requests, to gain information on past and not well documented restoration steps, as well as to investigate the possible cleaning procedures effects.

To this aim, laser-based techniques are successfully used as diagnostic tools in the field of cultural heritage [1]. The increasing application of these non destructive technologies, both for conservation and restoration actions, is mainly due to the advantages offered by the use of laser, that allows to perform measurements on remote targets at large distance with minimum invasiveness. In particular, the realization of accurate laser scanning systems originated the development of remote spectroscopic diagnostics, by which a complete optical and spectroscopic characterization of outer surface layers can be achieved and high resolution 2D images can be released.

Among the spectroscopic techniques appropriate to remote application, the Fluorescence Induced upon ultraviolet Laser excitation (LIF) is able to supply valuable information: it allows indeed for identification of fluorophores groups relevant to different substances either present onto the surface due to biodegradation and environmental pollution or forming the outermost layers, for instance pigment, binders and consolidants in the case of painted surfaces. In particular, restorers need a precise knowledge of surface materials once engaged in removing traces of former restorations.

The Laser Induced Fluorescence (LIF) technique has already been used in the monitoring of the protective treatment on stone surfaces [2], to identify some acrylic resins of interest for artworks [3], or to detect cultures of fungal and bacterial strains [4].

Remote sensing systems have recently found application in high resolution scanning devices for mapping the actual preservation status of cultural heritage surfaces [5, 6].

Scanning hyperspectral systems based on Laser-

Luisa Caneve, Francesco Colao, Roberta Fantoni, Luca Fiorani, Antonio Palucci
ENEA, Unità Tecnica Sviluppo di Applicazioni delle Radiazioni

Maria Pilar Ortiz
Universidad Pablo de Olavide, Sevilla (ES)

Vasco Fassina
Soprintendenza per i beni storici, artistici ed etnoantropologici per le province di Verona, Rovigo e Vicenza

FIGURE 1 From left to right: Hrastovjie Church (Slovenia) (http://www.randburg.com); Sucevita Monastery (Romania) (ENEA source); S. Telmo Palace in Seville (Spain) (http://www.minube.it)

induced fluorescence (LIF) have been designed and built at the Diagnostic and Metrology laboratory of ENEA-Frascati in order to obtain analytical information on CH surfaces by 2D-image collection.
Thanks to sophisticated data processing techniques, such as false-colour imaging, principal component analysis (PCA) [7] on spectra and spectral angle mapping (SAM) [8] on images, features invisible to the naked eye, as pigment compositions (e.g. titanium white vs. zinc white), pigment diffusions (lime and casein) [9], deteriorations, depigmentations, retouches and varnishes can be detected.
Real-time diagnoses of historical artworks have been performed during several in-field campaigns as, for example, in Slovenia, Romania and Spain (see Fig. 1).
In particular, the analyses performed on frescos inside the S. Telmo Palace in Seville, under a scientific cooperation between ENEA UTAPRAD and *UPO Natural Science Department of Seville*, and the Baptistery of Padua, under a collaboration signed with *Soprintendenza ai Beni storici Artistici e Etnoantropologici per le province di Venezia Belluno Padova e Treviso*, will be presented as successfully applications of the LIF line scanning system in the cultural heritage field.

Experimental Apparatus

The LIF technique is a molecular spectroscopy for surface analysis based on the interaction of the ultraviolet radiation emitted by a laser with the matter [10]. The emission of radiation by luminescent materials is observed whenever an absorption of energy sufficient to activate the allowed electronic transitions occurs. In a typical LIF instrument, an ultraviolet (UV) laser beam irradiates a sample and an optical system collects and measures the emitted fluorescence signal. The spectral content of the radiation coming from the examined surface supplies information on the composition of the outer layers, once interrogated at different excitation wavelengths. It is a fast, non invasive, remote, sensitive and selective technique.
A LIF scanning instrument able to collect hyperspectral fluorescence images on large areas has been realized at the ENEA in the Diagnostic and Metrology laboratory of Frascati. The system has been developed with the aim of increasing the performances in terms of space resolution, time resolved capabilities and data acquisition speed with respect to the previous versions [11]. The main improvement of the new recently built LIF system consists on the line-by-line scanning process, particularly suitable for investigation on large areas. A point-by-point LIF scanning system was, in fact, previously developed in ENEA [11] and applied in several campaigns of measurements due to its compact, reduced size and light weight. These allow for an easy transfer of the system and its operation from scaffoldings, in the case of surfaces out of the current maximum range for remote operation (10 m).
The new system and the related scheme are reported in Fig. 2.

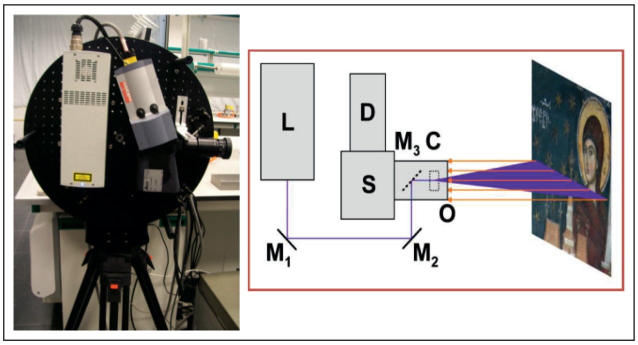


FIGURE 2 ENEA compact LIF line scanning system with the related scheme: L-laser, D-detector, S-spectrometer, M-mirrors, C-cylindrical lens, O-objective
Source: ENEA

The laser beam has a light blade shape. With the optical system based on the use of cylindrical lens, focusing the laser spot as a line, an image of $1.5\times 5m^2$ is currently scanned in less than 2 minutes at 25 m. A diode-pumped Nd:YAG laser source has been utilized to generate the UV radiation at 266 nm or 355 nm, depending on the applications, with repetition rate of 20 Hz, pulse duration of 10 ns and energy of 1.5 mJ. This arrangement is characterized by having the target spatial and spectral information on two mutually orthogonal directions imaged on the detector, with a sub-millimeter spatial resolution and a spectral resolution better than 2 nm. Moreover, time resolved measurements on the nanosecond scale can be performed by controlling the electronic detector gate in a boxcar-like configuration. The collected data are released as false colour reflectance and fluorescence images suitable to the identification of original and added materials.
Each scan is controlled by a portable computer where a specific program developed in LabView allows to set experimental parameters, control data acquisition, and perform a preliminary data analysis. In the main control panel, data are shown both as 2D monochromatic images (1024x1024) and LIF spectra for each pixel. Additionally, the LIF scanning system can be utilized, with the laser switched off, to collect reflectance images upon the availability of an intense standard light source. When using a continuous light source like a lamp, the synchronism for data acquisition is given by the detector itself. Both fluorescence and reflectance images can be reconstructed in false color by using the three most intense features detected, associated respectively to Red, Green and Blue channels (RGB).

Results

The results obtained from the LIF system application on two different artworks are reported here below as successful case studies.
LIF analyses inside the monumental complex called S.Telmo Palace have been carried out on the fresco *"La Glorificacion de la Virgen"* from Domingo Martinez in the *Virgen del Buen Aire Chapel*, in order to reveal traces of former restorations to which the presence of consolidants and retouches on the pigments could be ascribed.
The most significant spectral features of LIF spectra have been identified by the Principal Component Analysis (PCA) [7]. By analyzing the LIF spectra from a portion of the vault (Fig. 3a), the identification of areas which have been heavily treated during the restoration can be documented by using the band fluorescing at 360nm.
In Fig. 3b, the fluorescence black and white image obtained with the band at 360nm is shown.
The black corresponds to pixels with high fluorescence emission intensity, whereas the white area to pixels with low fluorescence. A conventional photo of the same scanned fresco surface is reported in the figure, for comparison.
The presence of the same band peaked at 360 nm has also been revealed on the other LIF images acquired in the same chapel, with maximum intensity at precise locations, presumably related to the restoration treatment. Although a precise identification and/or discrimination is not immediately possible, it is worth noticing that we obtain an extremely good localization of the use of such a chemical. Moreover, the grey level scale gives a qualitative evaluation of the amount of film used, since a direct proportionality between the film thickness and the LIF signal intensity should hold. Colour rendering has been chosen (Fig. 3c) in order to better distinguish low (in yellow) and high (in blue) intensity from the material fluorescing at 360 nm.

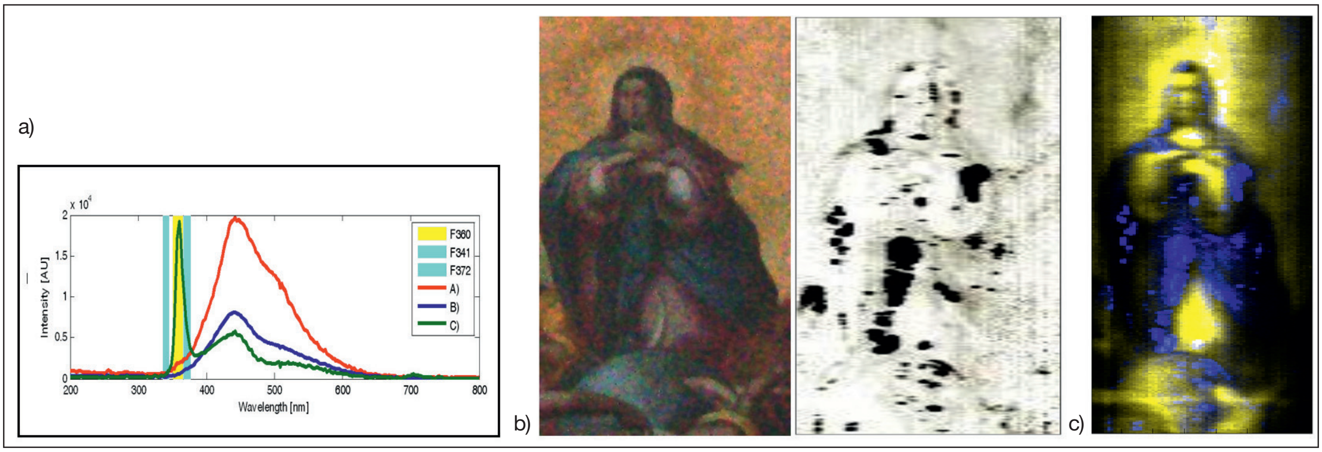


FIGURE 3 a) LIF spectra from different areas. Specific band at 360nm in evidence; b) Black and white fluorescence image at 360 nm, compared to a conventional photo; c) Colour rendering from fluorescence image at 360 nm
Source: ENEA

The vault was analyzed not only for the purpose of retouch identification, but for pigment analysis also. In this case, the Spectral Angle Mapper (SAM) algorithm for LIF image analysis has been used. SAM is a classification method that permits rapid mapping from a comparison between a reference spectrum and the measured spectra [8]. According to SAM, the spectrally resolved intensities can be treated as vectors' components, and it is then possible to compute the angle between a given pixel spectrum and a reference spectrum: the smaller the angle, the higher the similarity between pixel and reference spectra will be. To improve the diagnostic readability of images and to emphasize the selected areas, a threshold for the spectral angle has been introduced, thus obtaining a black and white version of the original scanned image. Whenever the reference spectra pertain to a specific pigment, this processing highlights only these areas significant for that pigment diagnostics.

In Fig. 4, SAM similarity maps obtained using blue and red pigment reference spectra, respectively, are shown.

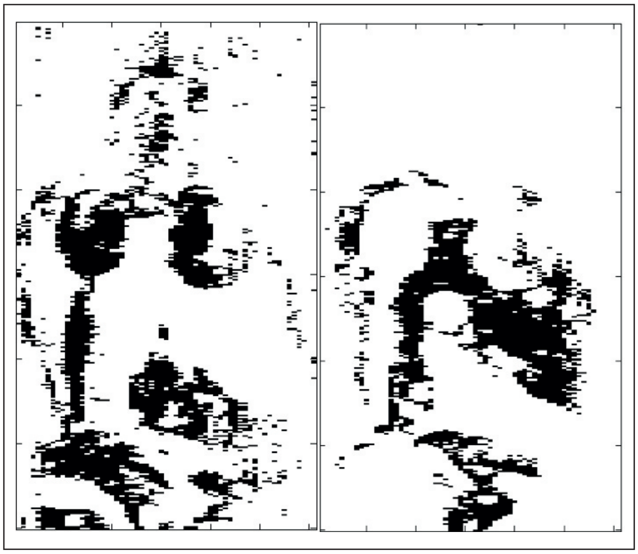


FIGURE 4 SAM analysis by the reference spectra of blue (on the left) and red pigment (on the right), respectively
Source: ENEA

During the in-field measurements in the Padua Baptistery, LIF spectra and images have been collected and processed in order to retrieve information on constituent materials. The field campaign was carried on in June 2010, prior to planning the following restorations. To this aim, the investigation was focused on the recognition of consolidants and binders, with the support of an available data base and the development of statistical tools for main spectral-band identification.

The construction of the Padua Baptistery, located on the right side of the cathedral, started in the XII century and was accomplished in 1281. Its frescos are considered Giusto de' Menabuoi's masterpiece. Two selected areas of the Paradise fresco on the central dome and of the Genesis on the tambour have been investigated by means of the ENEA LIF scanning system.

In the Baptistery, different fresco portions have been scanned within the dome and on the tambour. Data were acquired at a 15 m distance from the dome at a slightly smaller distance from the tambour. The images collected are shaped as rectangular stripes about 1.5 m wide and typically from 8 m to 12 m long.

Data were acquired operating the set-up both in reflectance and fluorescence acquisition mode, the latter upon excitation at 266 nm, and also in this case processed by means of the automatic statistical analysis (PCA). Once the major fluorescence bands have been identified, their assignment has been checked against the available consolidant data base by means of SAM projections, and the relevant distribution on the image has been obtained. Conversely, the contribution of pigments, which cannot be effectively disentangled from the emission of plaster and binders, was investigated mostly in the reflectance images analyzed by means of SAM maps based on an internal standard for each color, so that spatially non-homogenous changes in the spectral content could be recognized, and possibly ascribed to the pigment deterioration or retouches.

The band analysis, upon which the monochromatic images reconstruction reported in Fig. 5 is based, derives directly from the PCA results. In particular, the narrow UV bands at 293 and 370 nm have been considered.

In A and B insets the absolute intensity measured at 293 nm is shown, which appear to generate a quite uniform distribution on the entire images. Upon the assumption of a linear dependence coupling the quantitative distribution of fluorophores to the respective peak intensity, we infer a corresponding uniform distribution of the compound. A similar situation has been observed for all scanned areas in the dome, thus supporting a diffuse and homogeneous use of the compound characterized by the emission at 293nm, in general compatible with acrylic resins (e.g., primal AC33). On the right side of Fig. 5 (C and D insets), the absolute intensity measured at 370nm is shown, which is peaked on well localized areas. Concerning the identification of the compound to which this emission could be ascribed, although several compounds present this signature, most probable candidates among consolidants are vinyl compounds

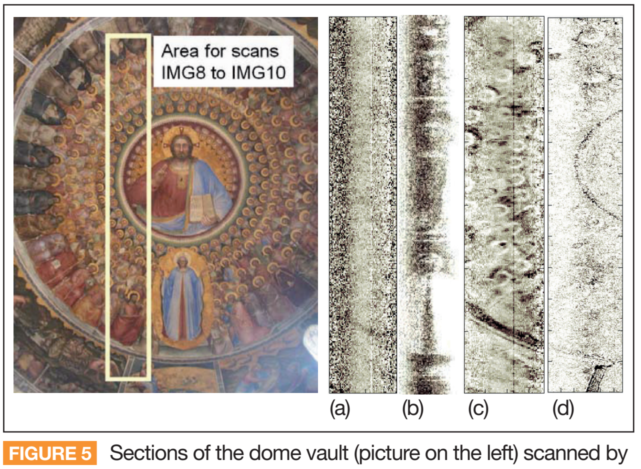


FIGURE 5 Sections of the dome vault (picture on the left) scanned by LIF. Grey levels correspond to different emission intensity (black represent the highest intensity); A) and B) band at 293nm; C) and D) band at 370nm
Source: ENEA

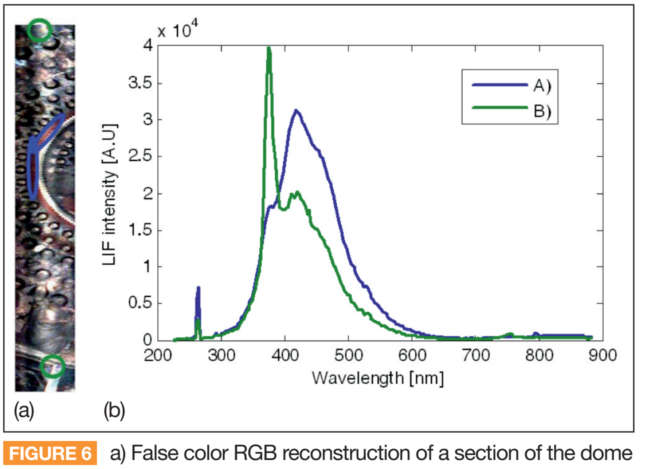


FIGURE 6 a) False color RGB reconstruction of a section of the dome vault based on bands at 293nm, 370nm and 550nm; b) average spectral content in selected spectral regions, which are marked on the left image
Source: ENEA

(e.g., mowilith), which emit at longer wavelength with respect to acrylic resins.

Further qualitative results of LIF scanning can be obtained by combining three significant bands in a single false color image. An example of this elaboration is presented in Fig. 6 (for the monochromatic image shown in Fig. 5D). The inset (a) shows the RGB reconstruction based on bands peaked at 550nm, 370nm and 293 nm, while the inset (b) shows the average spectrum in the respective circled area on the left, where significant emissions at 375nm and at 293 nm (confirming PCA results) are observed, their possible assignment to different consolidants being discussed above.

Conclusions

LIF scanning has shown, in conclusion, its versatility in obtaining valuable information on the presence and distribution of different species on large areas. In particular, traces of former consolidants have been remotely revealed and mapped on frescos in the Virgen del Buen Aire Chapel in Seville and on Padua Baptistery vault.

The results here reported demonstrate that laser-based imaging on surfaces of interest for Cultural Heritage permits to obtain valuable information from fluorescence data remotely and non invasively. The capability of remote material identification by means of the available data processing methods on raw hyperspectral images has been demonstrated, whereas quantitative data acquisition still requires additional reference measurements.

References

[1] C. Fotakis, D. Anglos, C. Balas, S. Georgiou, N.A. Vainos, I. Zergioti, V. Zafiropulos (1997), *"Laser Technology in Art Conservation"*, OSA TOPS on Lasers and Optics for Manufacturing 9, pp. 99-104.

[2] G. Ballerini, S. Bracci, L. Pantani, P. Tiano (2001), *"Lidar remote sensing of stone cultural heritage: detection of protective treatments"*, Optical Engineering 40, pp. 1579-1583.

[3] L. Caneve, F. Colao, R. Fantoni, L. Fornarini, *"Laser induced fluorescence analysis of acrylic resins used in conservation of cultural heritage"*, Proc. OSAV'2008, The 2nd Int. Topical Meeting on Optical Sensing and Artificial Vision St. Petersburg, Russia, 12-15 May 2008, pp.57-63.

[4] V. Raimondi, L. Palombi, G. Cecchi, D. Lognoli, M Trambusti, I. Gomoiu (2007), *"Remote detection of laser-induced autofluorescence on pure cultures of fungal and bacterial strains and their analysis with multivariate techniques"*, Opt. Comm. 273, pp. 219-225.

[5] R. Grönlund, J. Hällström, A. Johansson, K. Barup, S. Svanberg (2006), *"Remote multicolour excitation laser-induced fluorescence imaging"*, Laser Chemistry, Article ID 57934.

[6] D. Lognoli, G. Cecchi, I. Mochi, L. Pantani, V. Raimondi, R. Chiari, T. Johansson, P. Weibring, H. Edner, T. Svanberg (2003), *"Fluorescence lidar imaging of the cathedral and baptistery of Parma"*, Appl. Phys. B 76, pp. 457-465.

[7] K.V. Mardia and J.M. Kent, (1979), Multivariate Analysis, Academic Press, London.

[8] G. Girouard, A. Bannari, A. El Harti and A. Desrochers, *"Validated Spectral Angle Mapper Algorithm for Geological Mapping: Comparative Study beteewn Quickbird and Landsat-TM"*, presented at the XXth ISPRS Congress, Geo-Imagery Bridging Continents, Istanbul, Turkey, 12–23 July 2004.

[9] F. Colao, R. Fantoni, L. Fiorani, A. Palucci, *"Application of a scanning hyperspectral lidar fluorosensor to fresco diagnostics during the CULTURE 2000 campaign in Bucovina"*, Revista Monumentelor Istorice / Review of Historical Monuments n. LXXV/1-2 (Bucharest, 2006) pp. 53-61.

[10] J.L. Kinsey (1977), *"Laser-Induced Fluorescence",* Annual Reviews Physical Chemistry 28, pp.349-372.

[11] F. Colao, L. Caneve, A. Palucci, R. Fantoni, L. Fiorani (2008), *"Scanning hyperspectral lidar fluorosensor for fresco diagnostics in laboratory and field campaigns"* in J. Ruiz, R. Radvan, M. Oujja, M. Castillejo, P. Moreno (Eds.) Lasers in the Conservation of Artworks 149-155.

Terrestrial and Subsea 3D Laser Scanners for Cultural Heritage Applications

Methodologies in cultural heritage applications are slowly but steadily evolving with the introduction of bespoke innovative technological tools. Beyond complementing the work of the experts, these cutting-edge innovations may also provide new and stimulating paths for artworks fruition. In this framework, terrestrial and subsea 3D laser scanners developed at ENEA mark a one-of-a-kind achievement, as witnessed by the results of the several measurement campaigns conducted. The devices are designed to provide 3D accurate models of targets of interest both in terrestrial and in subsea environment. In particular the terrestrial version, the RGB-ITR, is equipped for unique color rendering of the investigated scene

Luigi De Dominicis, Giorgio Fornetti, Massimiliano Guarneri, Mario Ferri de Collibus, Massimo Francucci, Marcello Nuvoli

Introduction

An increasing interest appears to be emerging within the cultural heritage (CH) community over the use of cutting-edge technologies. Remarkable results of field trials have been instrumental for raising the awareness that improved technological capabilities could enable innovative practices in the fruition, preservation and restoration of art works. Among the several technological tools deployed, one has particularly seized the attention of the general public and is steadily gaining ground among CH professionals, namely the 3D laser scanning. It is a relatively new technology that has been in development over the last 15 years. Several different setups are available – like laser beam modulation with coherent or incoherent detection techniques, time-of-flight scanners based on pulse beams, triangulation and structured light systems – but all of them are capable of recording geometric spaces in 3D with great accuracy [1]. If on the one side digitization of artistic monuments with 3D laser technologies has always a huge visual impact, on the other an increasing number of professionals and stakeholders acknowledge its potentialities as an improved diagnostic and monitoring tool. To date, the debate in the CH community over the usefulness of this technology is still ongoing, with innovators opposing to many still skeptical and reluctant to accept its introduction. Nevertheless, there is an application where the point of view is unanimous: this is when it comes to subsea applications, particularly those for visualization and diagnosing in marine archeology. The subsea environment is hardly accessible but is

Luigi De Dominicis, Mario Ferri de Collibus, Giorgio Fornetti, Massimo Francucci, Massimiliano Guarneri, Marcello Nuvoli
ENEA, Unità Tecnica Sviluppo di Applicazione delle Radiazioni

home to cultural heritage of inestimable value, which witnesses the evolution of mankind, its struggle to make sea a less hostile environment, and the evolutionary path of navigation. Here, the line of separation of 3D laser imaging as a tool providing a striking but needless visual impact from a "game-changing" factor in subsea CH practices is less sharp and the CH community more keen to admit the value of this innovative technology. Nevertheless, subsea 3D laser imaging comes with specific issues to face, the solution of which requires the development of bespoke methodologies and techniques. The presence of water and the demand to operate at depth add considerable scientific and technological challenges to face and this explains why subsea 3D laser vision lags largely behind its counterpart on dry environment.
At ArtVisLab (Artificial Vision Laboratory) of ENEA Frascati considerable efforts are underway for consolidating the achievements in developing innovative terrestrial 3D laser scanners tailored for CH applications. A proven track record of trials conducted on masterpieces of global importance witnesses the high profile of the scientific and technological findings. In particular, the Red Green Blue Imaging Topological Radar (RGB-ITR) scanner is the last prototype developed in ArtVisLab and it allows simultaneous measurement of distance and color of each pixel recorded over the scene. Far from being a pure scenic effect, color registration enables a new methodology in remote colorimetry, where data are not affected by the influence of external light sources and are reusable over time for further analysis comparison.
At the same time ArtVisLab has the in-house scientific and technological skills which have been instrumental for developing the prototype of a subsea 3D laser scanner for application in marine archeology. ArtVisLab is a unique laboratory in this sector with a dual commitment (terrestrial and subsea applications), where the learning process in one field suggests new and innovative developmental paths for the other.
In this contribution this specificity is outlined with:

- Up-to-date results from an experimental campaign where the digitization of the "Amore e Psyche" lodge, with frescos painted by Raffaello Sanzio and his school, was performed by means of the RGB-ITR laser scanner.
- a breakthrough coming from the laboratory where, for the first time, colored 3D images of samples immersed in water have been recorded with a modified version of a prototypal subsea 3D laser scanner.

The RGB-ITR Colour Laser Scanner

RGB-ITR is a patented 3D colour laser scanner completely designed and realized at ENEA laboratories. The competitiveness of this instrument with respect to the commercial ones can be mainly summarized in three points: it was developed trying to focus the attention on specific needs of CH professionals (e.g., non-invasiveness and versatility), introducing quantitative remote analyses useful for restorers and cataloguers (like remote colorimetry combined with structure monitoring) and getting advantage by the instrument prototypal status for expanding the scanner features, involving a large community of professionals and stakeholders.
The technique adopted for the simultaneous collection of distance and colour information is based on amplitude modulation [2,3] of three monochromatic laser sources (650 nm, 532 nm, 450 nm), which operate as carrier waves. The distance and colour information are extracted from modulating waves by phase-shift and reflectivity responses of the target at the three wavelengths.
The precision of distance measurements is ensured by the use of two modulating sinusoids, one at few MHz (i.e., 5 MHz) and one at several hundred MHz (i.e., 200 MHz): the first wave gives a rough measurement of the distance between the centre of the instrument and the target (up to 30 m), meanwhile the second wave gives a very high-precision distance measurement, without ambiguity, in a shorter range (i.e., a 190 MHz modulation frequency can work, avoiding the ambiguity, in a range of about 0.78 m). The result of the combination of these two data is a very high-precise distance measurement (about 0.2 mm at 10 m).
The non-destructive character of the technology has been tested on different painted surfaces prior to

application. For instance, on Renaissance frescos the absence of photobleaching has been verified on historical pigments specimens irradiated with 3mW for 1 sec on a 0.5 mm dia. spot at 5 m (for an exposure time exceeding of a factor 10 that needed during the measurements). Two proprietary software applications complete the system with ScanSystem used for system control and ItrAnalyzer for data processing and visualization.

From Remote Diagnosis to Virtual Fruition: Digitization of the "Amore e Psyche" Lodge

An accurate digitization of the "Amore e Psyche" lodge was performed in June 2011 by means of the RGB-ITR laser scanner. In four days and four nights the scanner collected the entire vault, storing both colour and distance information for each sampled point. The mean distance between the centre of the scanning mirror and each part of the lodge was about 8 m and the spot size was about 0.2 mm. The scanner was mounted in the configuration shown in Fig. 1, which permitted a very fast movement of the entire system in the room and let the possibility to allow daily visits of the lodge, interdicting only a very small area (about 1 squared meter).

FIGURE 1 RGB-ITR scan system in tower configuration. Lasers and electronic units are allocated in the yellow boxes, while the optical head is above
Source: ENEA

The initial idea of the vault digitization was to document the stability of the structure and the state of conservation of the frescos painted by Raffaello Sanzio and his school. The digitization was divided into four scans and the system calibrated after each scan by executing a measurement of a standard white target (SPECTRALON STR-99-020) placed at various distances (the range was between 5-12 m with a step of 0.50 m), obtaining three colour curves for the three lasers utilized in the digitization. The importance of this calibration is essentially due to the possibility to normalize the back-reflected light, collected by the three photodiodes used by the RGB-ITR, for future data comparison acquired also by means of other instruments. This feature is extremely important in the CH environment because it permits to observe the status of pigment conservation of the work of art over time and to monitor changes after a restoration. Due to the generalization of the data structure acquired by the ITR systems, the result of digitization can be used not only for restoration and cataloguing, but also for fruition and educational purposes. The high quality of data allows high level zooming of images, permitting to observe details that a visitor cannot see in standard conditions. Differently by commercial instruments, the post-processing time needed for building a usable 3D model for fruition purposes is reduced by the intrinsic feature of the collected data: in fact, the possibility to acquire both colour and structure information at the same time permits to obtain a self-registered mesh with texture, which can be directly utilized in 3D theatres or educational games, without the use of any invasive backreflected targets or algorithms for the stitching of 2D over 3D images. A view of the 3D complete mesh with texture of the lodge is shown in Fig. 2.
The complete and accurate 3D model of the lodge was shown in important exhibitions in Rome ("The Renaissance in Rome" at Palazzo Sciarra, and "Amore and Psyche" at Castel Sant'Angelo). In both exhibitions the idea was to give continuity to the narration of the exhibition, showing also monuments which cannot

Sp

be physically present, although are important for a complete explanation of an artistic period or subject. In Fig. 3 an example of data analysis with ItrAnalyzer is shown. It is possible to select a row of the matrix representing the three superimposed back-reflected laser layers and the software will show the reflectivity of every single pixel. With this instrument is possible to perform the so-called differential colorimetry: at the moment the results of the lodge digitization, made by the RGB-ITR scanner, cannot be directly compared with colorimeter measures, but they can be used for monitoring the state of the art of the pigments over time, and for comparisons in future different measures collected by the scanner during scheduled periods.

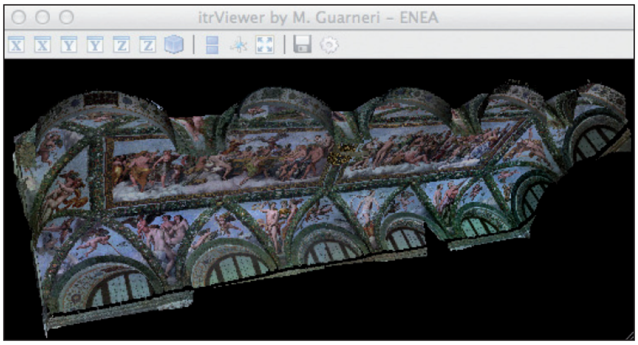


FIGURE 2 3D view of "Amore and Psyche" Lodge
Source: ENEA

Subsea 3D Laser Scanner

Recording faithful and accurate 3D images of subsea targets by means of laser-based devices is a challenging task, mainly when water turbidity increases. This because seawater is a medium which absorbs and diffuses light at the same time and in a more severe way as the concentration of dispersed particles increases [4]. In particular the backscattering process, where a fraction of the laser light is reflected backwards, gives rise to an unwanted disturbance signal which limits the performance of a 3D laser imaging system. This makes the development of a subsea 3D laser scanning system not a mere transposition for operation at depth of its terrestrial counterpart. So, new scientific and technological challenges arise and, after several years of experimental [5] and theoretical researches [6], carried out in the framework of the BLU-ARCHEOSYS[1] project, ArtVisLab has completed the realization of a prototype (Fig. 4) for subsea 3D laser imaging, named RE-VUE (REmote Viewing in Underwater Environment). In its basic configuration the device is based on a continuous-wave (CW), amplitude-modulated (AM) laser source (405nm, 20mW) whose wavelength matches a minimum in the absorption curve of clean seawater. The RE-VUE device can investigate scenes with a horizontal angle of view of 40° and a vertical one of several tenths of degrees. It is fully remotely operated by a laptop, where a proprietary software is installed, capable of working at a maximum depth of 400m.

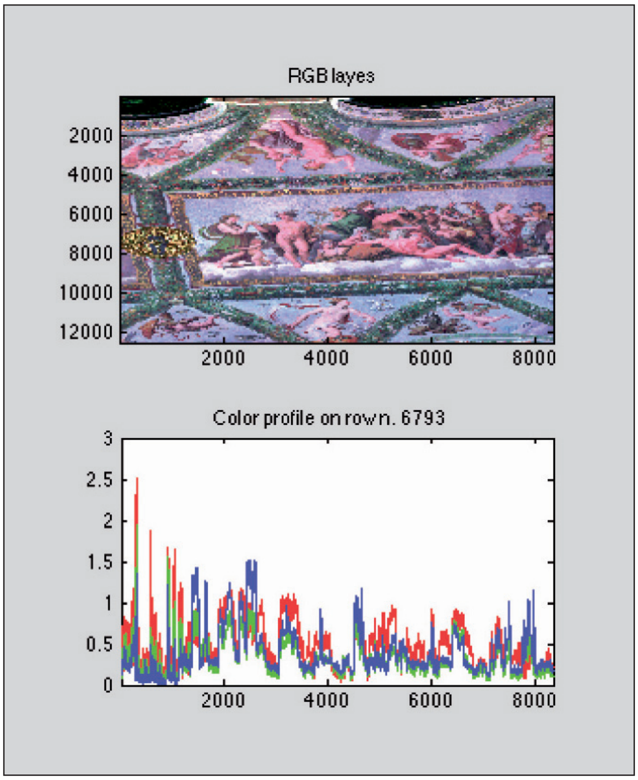


FIGURE 3 Colour profilometry of row 6793
Source: ENEA

During 2011 the RE-VUE system has been immersed in a test pool filled with relatively clean water, and submillimetric range resolution of targets at 7m of distance from the sensor has been recorded. Being

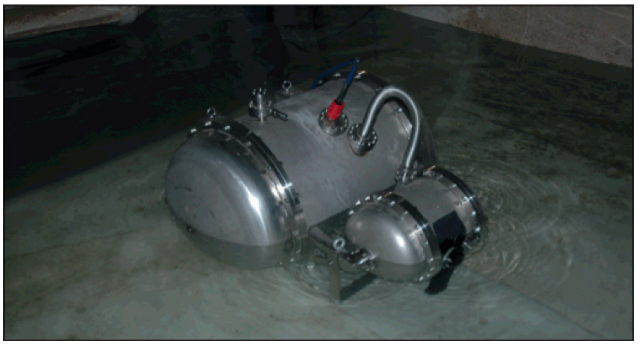


FIGURE 4 Photo of the RE-VUE system used for underwater 3D imaging. The small cylinder contains the laser source, the scanning system and the receiving stage (lens and fast photomultiplier). The big cylinder, instead, hosts the electronic modules (e.g., lock-in amplifier)
Source: ENEA

based on a single laser source, the RE-VUE maps the reflectivity of the investigated scenes in gray scale. The device is ready for installation onboard a ROV (Remotely Operated Vehicle) and deployment for inspection of subsea archaeological sites.

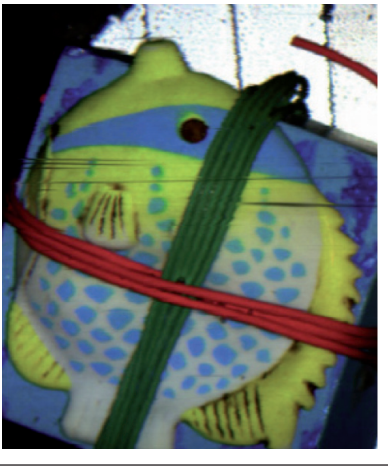


FIGURE 5 Result obtained by an upgrade of the RE-VUE system equipped with three CW AM laser sources at 450nm (blue, fm=100MHz), 532nm (green, fm=30kHz) and 650nm (red, fm=190MHz): high-resolution and high-contrast 3D color image of a plastic fish immersed in a 2m-high clean water column acquired at high rate (1000 sample points per second)
Source: ENEA

Moving from the experience acquired in developing RGB-ITR, a first attempt devoted to acquire 3D color images of underwater targets has been recently performed by using an upgrade of the RE-VUE where three low-power (mW), continuous wave, amplitude-modulated laser beams at 450nm (blue), 532nm (green) and 650nm (red), respectively, are used for scanning the target under investigation. The three laser beams are combined into a single white ray by means of a dichroic optical component. A first result obtained by means of this upgrade of the RE-VUE is shown in Fig. 5. In detail, the figure provides the 3D color model of a plastic fish immersed in a 2m-high clean water column. The fish model is characterized by high resolution and shows high contrast. This last result has been obtained with an acquisition rate of 1000 sampled points per second and with high angular resolution (some thousandth of degrees as steps of scan motors). Furthermore, such a result demonstrates the possibility to perform high-quality 3D color imaging even in underwater environment. This finding has prompted a new perspective for subsea 3D laser colour imaging, and ArtVisLAb is actually working on the development of a marinized prototype under the IT@CHA project[2].

Conclusions

In this contribution we have outlined the commitment of ArtVisLab at ENEA Frascati to develop 3D laser scanners for application in Cultural Heritage both in terrestrial and subsea environment. This activity demands multidisciplinary skills covering optoelectronics, photonics, theory of laser beams propagation in turbid media, software development, instruments' programming, mechanical design, subsea engineering, data processing, digital and analog electronics, colour theory, image processing. The recent campaign, where RGB-ITR has been used to digitize the whole Sistine Chapel inside the Vatican City and with a laser beam for the first time ever projected onto the "Universal Judgment" of grandmaster Michelangelo, tells a fascinating story. Processing of the massive quantity of data is still underway, but what emerges is that a cutting-

edge technology is unveiling, in the experts' opinion, details never recorded before.
With the RE-VUE and its improved version to acquire 3D colour images in the subsea environment, ArtVisLab is ready to give its contribution for introducing best and innovative practices in marine archaeology. In this case the way ahead is full of scientific and technological challenges to face, but the consensus coming from the CH community over the project is encouraging and instrumental for a positive completion.

Notes

1. BLU-ARCHEOSYS (Innovative Technologies and Advanced SYStems as Support in Underwater ARCHaeology) FAR – D.M. 593 8 august 2000 – art. 5 – Ministry of Education, University and Research.
2. IT@CHA – Italian Technologies for Advanced application in Cultural Heritage Assets. PON 2007-2013 – Beni Culturali

References

[1] G. Vosselman, H.G. Maas (2010), Airborne and terrestrial laser scanners, CRC Press.

[2] M. Guarneri, M. Ferri De Collibus, G. Fornetti, M. Francucci, M. Nuvoli, R. Ricci (2012), *"Remote colorimetric and structural diagnosis by RGB-ITR color laser scanner prototype"*, Advances in Optical Technologies, 2012, 1-6.

[3] R. Ricci, L. De Dominicis, M. Ferri De Collibus, G. Fornetti, M. Guarneri, M. Nuvoli, M. Francucci (2009), *"RGB-ITR: an amplitude modulated 3D colour laser scanner for cultural heritage applications"*, Proceedings of the International Conference LACONA VIII – Lasers in the Conservation of Artworks (Sibiu, Romania, 21-25 Settembre 2009).

[4] L. Mullen, A. Laux, B. Concannon, E.P. Zege, I.L. Katsev, A.S. Prikhack (2004), *"Amplitude modulated laser imagers"*, Applied Optics, 43, 3874-3892.

[5] L. Bartolini, L. De Dominicis, M. Ferri de Collibus, G. Fornetti, M. Guarneri, E. Paglia, C. Poggi, R. Ricci (2005), *"Underwater three-dimensional imaging with an amplitude-modulated laser radar at a 405nm wavelength"*, Applied Optics, 44, 7130-7135.

[6] R. Ricci, M. Francucci, L. De Dominicis, M. Ferri de Collibus, G. Fornetti, M. Guarneri, M. Nuvoli, E. Paglia, L. Bartolini (2010), *"Techniques for effective optical noise rejection in amplitude-modulated laser optical radars for underwater three-dimensional imaging"*, EURASIP Journal on Advances in Signal Processing (special issue on Advances in Signal Processing for Maritime Applications), 2010, 1-24.

Investigation and Characterization of Artistic Techniques in Works of Modern and Contemporary Art

The scientific study of pigments and materials used by painters in their works is clearly important for the knowledge of the different artistic techniques, for planning the appropriate interventions of cleaning and restoration of the paintings. Moreover, identification of industrial varnishes and pigments in artistic works often helps the art historian and the conservator to date the considered paintings or, at least, to define post quem chronology.

The present research and study, conducted on titanium white and its applications in the field of historical works of art, is focused on two important but different artists and related paintings of the modern era as Sargent's "Caffè Orientale sulla Riva degli Schiavoni", oil on canvas, 1882, and Picasso's "Cubist Figure", oil on canvas, 1909. The analysis has been carried out using modern diagnostic technology: stereomicroscope and SEM/EDAX

Stefania Bruni, Giuseppe Maino, Carmela Vaccaro, Lisa Volpe

Introduction

The study of color is a very complex research field since color is not to be considered only as a natural phenomenon, but a "complex cultural construction that avoids generalizations and presents difficult problems, [...] the color is primarily a social fact" [1]. This concept is particularly reflected by the color, subject matter of this study: The white pigment based on titanium.

The titanium white is a pigment consisting of titanium dioxide, calcium sulfate and barium sulfate. In nature, titanium exists in various forms (brookite, rutile and anatase) and was discovered in 1791 thanks to rev. W. Gregor, who identified it in ilmenite rocks. Further research – which took place in subsequent years and aimed at finding a pigment with more pros and non-toxic property with respect to the white pigment used until the beginning of XX century (lead white, etc.) – led the chemist H. Rose, in 1821, to discover the compound of titanium dioxide. Officially, the production of this pigment on an industrial scale began from 1916-1918. Although titanium traces can be found in pigments and ink manufacturing prior to 1900, the frequent use of this pigment, in particular the artificial one, will start from 1908. The spread in Europe of titanium artificial white, in particular, will develop from 1910 onwards, when the European Community banned the use of white lead, considered toxic. Several studies have demonstrated the presence of industrial titanium white pigment in

■ **Stefania Bruni**
ENEA, Unità Tecnica Ingegneria Sismica
■ **Giuseppe Maino**
Unità Tecnica Metodi per la Sicurezza dei Reattori e del Ciclo del Combustibile
■ **Carmela Vaccaro, Lisa Volpe**
Università di Ferrara

paintings dated around 1908, thus corresponding to the artists' period of experimentation in leading centers, such as Paris, with these new industrial products.
The present research and study, conducted on titanium white and its applications in the field of art-historical works, is focused on two important but different artists and their related paintings of the modern era as Sargent's *"Caffè Orientale sulla Riva degli Schiavoni"*, oil on canvas, 1882, and Picasso's *"Cubist Figure"*, oil on canvas, 1909. Other paintings, namely "Pond" (oil on plywood, 1885 approx.) by a follower of Claude Monet, *"Scholar with the picture book"* (oil on canvas, 1905 ca.) by Amedeo Modigliani, did not show any presence of titanium white as expected, since Modigliani's work belongs to the first Italian period of the artist, whereas the other oil is attributed to a follower.
These two former works have been analyzed using modern diagnostic technology, stereomicroscope, SEM/EDAX, etc. for a better understanding of painting techniques, pigments and materials used by the two artists, with particular attention to the white pigment of titanium, thus deriving information about its possible date and state of preservation, the support too, and a possible future restoration and/or maintenance.

Results

Samples are observed by using a stereomicroscope OPTIKA SZ6745TR (total magnification 90x), equipped with a webcam MOTICAM 2005 5.0 Mp, and the diagnostic tests were performed on Sargent's and Picasso's paintings, by using a scanning electron microscope (SEM) and electronic microanalysis EDAX (Fig. 1), at the Laboratory of Electron Microscopy UTSISM ENEA-Bologna.

Analysis of Sargent's Painting

The study, aimed primarily at identifying the pigments used, focused on the analysis of some samples taken in different areas of the painting, corresponding to regions of light color or white color (Fig. 2) before starting restoration.
The relevant study allowed us to identify different pigments of industrial origin. In particular, the electronic microanalysis of the samples has proved that the pigment is a light-colored titanium white. The chemical microanalysis, in fact, has revealed the presence of elements characteristic of this pigment, like titanium, barium, sulfur, calcium and oxygen, as shown in the following spectrum (Fig. 4) and the corresponding table.
In the observed form, titanium is a white pigment consisting of titanium dioxide, calcium sulfate and barium sulfate and, being extracted from the mineral

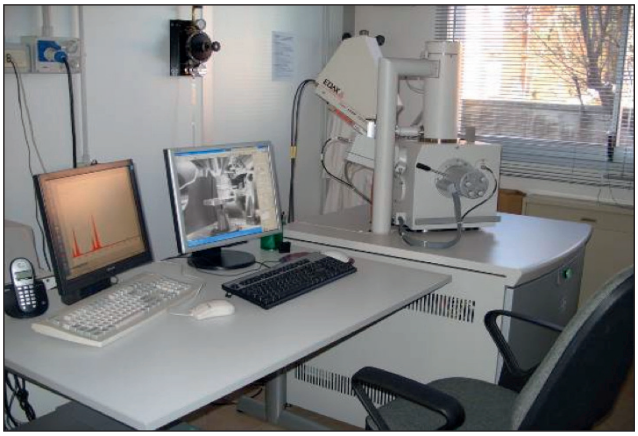


FIGURE 1 Laboratory SEM/EDXRS
Source: ENEA

FIGURE 2 John Singer Sargent - Caffè Orientale sulla Riva degli Schiavoni - oil on canvas, 1980/1882 (Private collection): sampling points
Source: ENEA

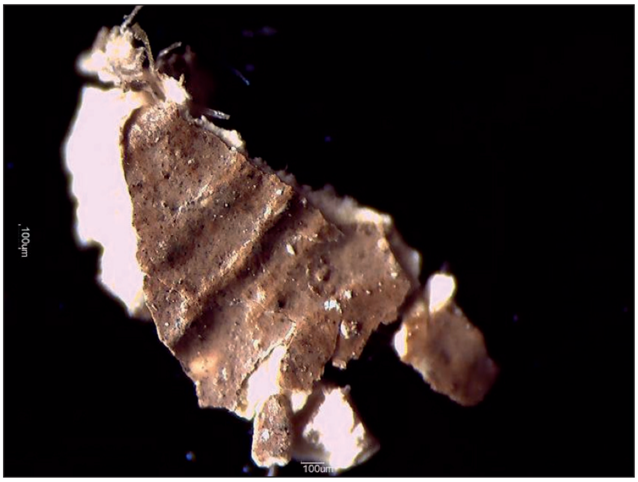
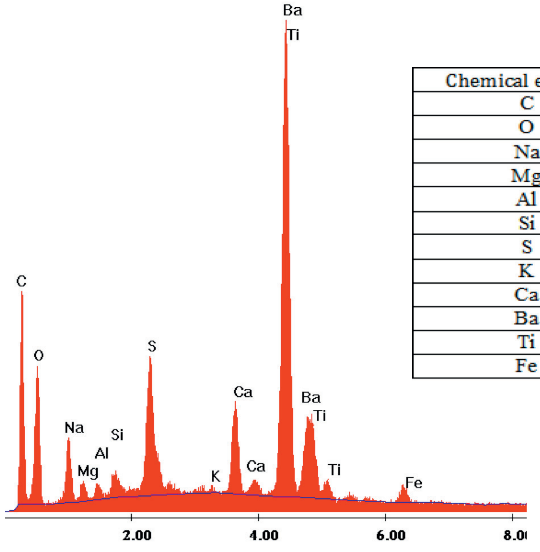


FIGURE 3 Stereomicroscope analysis of a Sargent's sample
Source: Università di Ferrara, Dip. di Scienze della Terra

ilmenite, an iron and titanium oxide ($FeTiO_3$), it may also present iron, silicon, aluminum, magnesium, sodium and potassium in lesser concentration.
From the morphological point of view, the pigment is characterized by small rounded crystals with homogeneous particle size, due to the process of industrial production of the pigment itself. Moreover, analysis of the samples allowed to notice some areas with slightly darker images, characterized by rounded particles larger than those found in areas of pure titanium white.
The latter, in fact, shows particles of infinitesimal size, homogeneous among them and representing – from microanalysis investigation – pure titanium white pigment, unlike those found in a darker region, shown in the former figure, which are the largest form of agglomerations and arise from a mixture of different colored pigments. This may arise because, to get different tones, the white pigment was mixed with other pigments of organic origin or with a medium.
In conclusion, the electronic microanalysis in all analyzed Sargent's samples has identified the pigment as a light-colored titanium white, highlighting the presence of characteristic elements, such as titanium, sulfur, calcium and oxygen (Fig. 6).
It is worth remarking that a related watercolor painting (1880-1982, watercolor on paper, 24.8 x 34.3 cm, private collection) was displayed on the occasion of the exhibition, *Gondola Days: Isabella Stewart Gardner and the Palazzo Barbaro Circle*, Isabella Stewart Gardner Museum, Boston, April 21 - August 15, 2004. Due to the similarities with this work, that of Fig. 2, subject matter



Chemical element	Concentration (%)
C	38.05
O	17.14
Na	2.14
Mg	0.67
Al	0.47
Si	0.68
S	2.42
K	0.05
Ca	0.85
Ba	9.25
Ti	27.75
Fe	0.17

FIGURE 4 SEM/EDXRS analysis of Sargent's sample: White Titanium Oxide
Source: ENEA

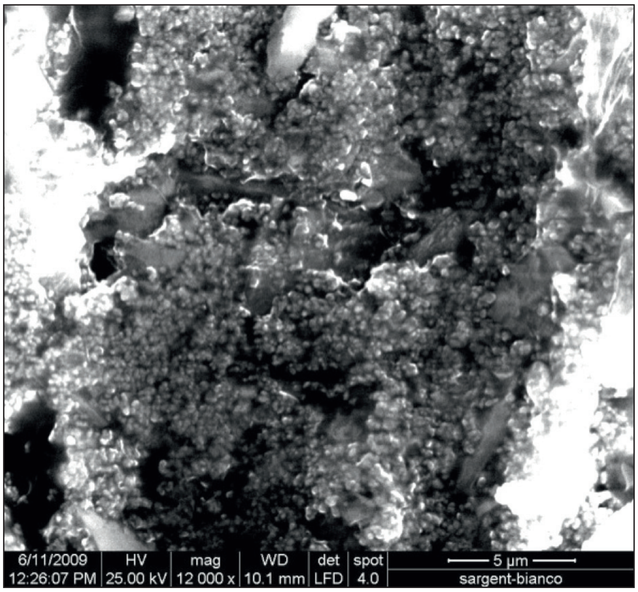
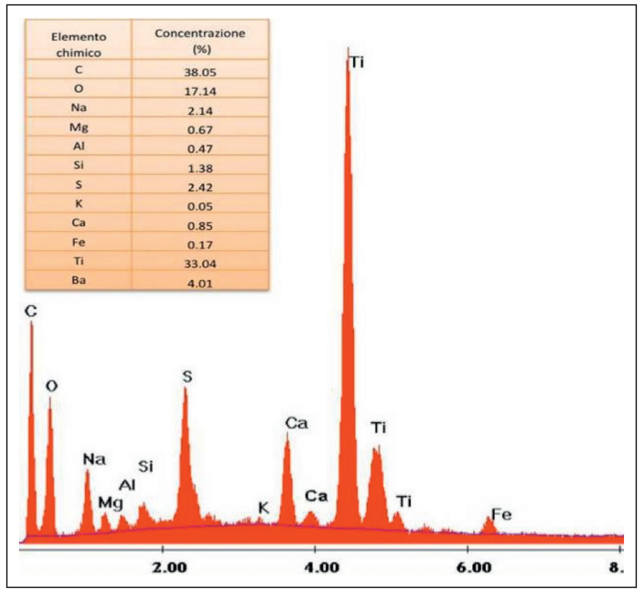


FIGURE 5 SEM analysis of a Sargent's sample
Source: ENEA



Elemento chimico	Concentrazione (%)
C	38.05
O	17.14
Na	2.14
Mg	0.67
Al	0.47
Si	1.38
S	2.42
K	0.05
Ca	0.85
Fe	0.17
Ti	33.04
Ba	4.01

FIGURE 6 SEM/EDXRS Sargent's sample: Titanium White
Source: ENEA

of the present study, was then dated to 1880, but the current findings about the presence of titanium white allow us to propose another dating, close to 1913, when Sargent travelled again to Italy and Venice.

Analysis of Picasso's Painting

In order to extend our investigation to the introduction of artificial titanium white in paintings at the beginning of the XX century, we performed other SEM observations and the relevant microanalysis on a few tiny samples taken from a painting attributed to Picasso (*Cubist figure,* oil on canvas, fig. 7) and dated around 1909. As a matter of fact, the painting appears to be signed and to have a date of '9' near the word 'Picasso'.
The analysis by SEM/EDAX showed the characteristic appearance of titanium white granules, confirmed by microanalysis. In this case, however, one may notice that, in the samples of Picasso's painting the pigment granules are not of perfectly spherical shape, and the microanalysis shows a different chemical composition than that found in the samples of Sargent's work discussed in the previous section; in fact, elements such as sulfur, aluminum, sodium, silicon and calcium are missing. It would seem, therefore, that in Picasso titanium white can be natural and not artificial, as found in the samples of Sargent's painting.

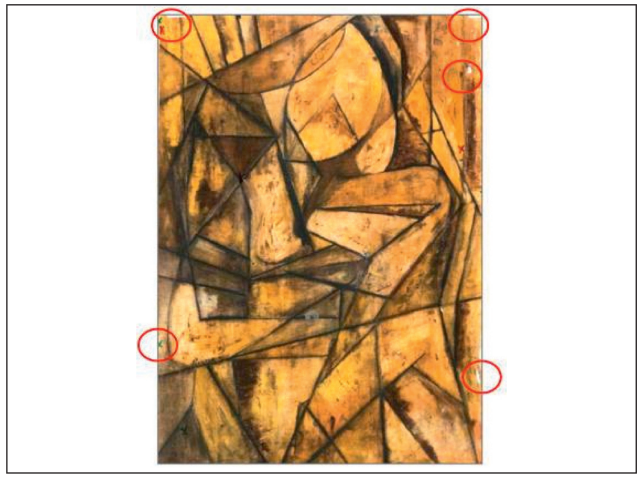


FIGURE 7 Sampling points on "Cubist figure" by P. Picasso (Private collection)
Source: ENEA

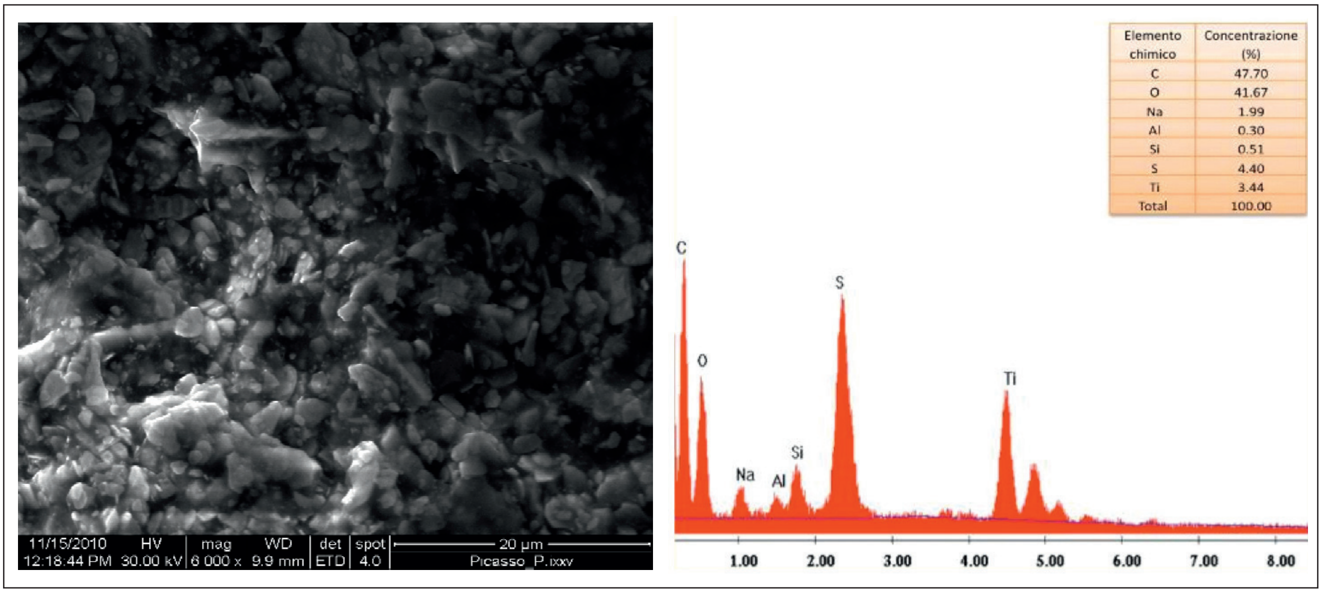


FIGURE 8 SEM/EDAX investigation of Picasso's sample with titanium white
Source: ENEA

Finally, the stereo microscope analysis of Picasso's samples showed that, as for the pigment, the coating is 70 µm thick and it was applied directly onto the canvas, since it is not indeed present in the preparatory layer (Fig. 9).

FIGURE 9 Picasso's sample analysis under the stereomicroscope (90X)
Source: Università di Ferrara, Dip. di Scienze della Terra

Further analyses were performed at the University of Melbourne. Before the SEM microanalysis, a non-destructive investigation was carried out by means of X-ray fluorescence (XRF) with a portable equipment, a Keymaster Bruker portable XXRF Tracer III-V. Results show the presence of elements usually found in pigments such as ochre, barium white, verdigris, lead white and strontium yellow. Also chromium and zinc were found, the latter on the verso of the painting, whereas lead is on the recto. All these data have been then confirmed by the microscopic analyses of the Australian group as well as by our studies.

Important information is provided by the Commonwealth Scientific and Industrial Research Organization (CSIRO; Clayton, Victoria, Australia), the Australia's national science agency, where a Raman spectroscopy analysis was conducted in April, 2010. The Raman spectra indicated the rutile form of titanium, as explained in the relevant Preliminary Report.

Rutile is the most common form of titanium and the Hunter process allows the production of high-quality titanium from it. The Hunter process dates to 1910 and, therefore, the presence of titanium white in this painting is not contradictory with a dating around 1909.

In conclusion, the materials used and the techniques adopted are compatible with an attribution to the Cubist period of Picasso; however, any definite authentication assessment must rely on the provenance and an art-historical study of this work.

Conclusions

The methods of investigation applied to the two works by Sargent and Picasso have revealed two different types of pigment, artificial vs. natural, obtained from different production processes, comparing two well-known painters of different generations and artistic currents, as J.S. Sargent and P. Picasso.

References

[1] L. Appolonia, S. Volpin, *"Le analisi di laboratorio applicate ai Beni artistici policromi"*, Il Prato (2002).

[2] M. Pastoureau, *"Bleu: Histoire d'une couleur"*, Du Seuil (2002), cons. ed. "Blu. Storia di un colore", Saggi Ponte alle Grazie (2008).

[3] M. Laver, *"Titanium Dioxide Whites"* in "Artists' Pigments. A Handbook of Their History and Characteristics", 3, Elisabeth West Fitzhugh, ed., National Gallery of Art, Washington D.C. and Oxford University Press (1997), 295-355.

[4] R. Mayer, *"The Artist's Handbook of Materials & Techniques"*, 5th edition revised and expanded by Steven Sheehan, London (1991), 116.

[5] N. Eastaugh, V. Walsh, T. Chaplin and R. Siddall, *"Pigment Compendium, A Dictionary of Historical Pigments"* (2004), 364-366.

[6] *"Pigment Compendium, A Dictionary and Optical Microscopy of Historic Pigments"* (2008).

[7] L. De Rossi, *"John Singer Sargent, Caffè Orientale sulla Riva degli Schiavoni a Venezia"*, in Arte | Documento 23, Edizioni della Laguna (2008), 236-239.

Analysis by Scanning Electron Microscopy and Microanalysis of Sandstones in Bologna, Petra and Mtskheta

SEM analysis combined with the EDXRS system are performed on many types of artistic and historical assets, in order to obtain information about the materials and their deterioration, the artistic techniques, the presence of damage, etc. This work reports the results of a study carried out on samples coming from the Orsi-Marconi palace in Bologna (Italy), from the Khazneh (House of the treasury) in Petra (Jordan), and from the Holy Cross monastery of Jvari in Mtskheta (Georgia). All these buildings are made of sandstone, the peculiarity of which is the change in colour, due to the different concentration of oxides in their composition

Stefania Bruni, Maurizio Indirli, Giuseppe Maino, Giuseppe Marghella, Anna Marzo, Lorenzo Moretti

Introduction

Electron microscopy analysis is a very useful method in the Cultural Heritage field, allowing to identify artistic techniques and giving important data for restoration and conservation of works of art. *Scanning Electron Microscope (SEM)*, with respect to traditional optical microscopes, can provide three-dimensional images, with higher magnification. Moreover, SEM analysis, once combined with an *Energy Dispersive X-Ray Spectrometry* (EDXRS) system, can be used to detect X-rays emitted by the atoms of the analyzed elements and to yield the chemical composition of the sample.

Many applications of the SEM analysis combined with an EDXRS system are performed on paintings and frescos, stained glasses, sculptures as well as archaeological findings and many other types of artistic and historical assets, in order to get information about the materials and their deterioration, the artistic techniques, the presence of cracks, damage or weaknesses. All these data can be essential for a proper dating of the works of art, or for their attribution to a certain artist, and are very important for the selection of the most appropriate restoration and conservation actions.

This work reports the results of a study, carried out by SEM analysis combined with an EDXRS system, on samples coming from the *Orsi-Marconi* palace in Bologna (Italy) and from two UNESCO world heritage sites, the Khazneh *(House of the treasury)* in Petra (Jordan) and the *Holy Cross monastery of Jvari* in

Stefania Bruni, Maurizio Indirli, Giuseppe Marghella, Anna Marzo, Lorenzo Moretti
ENEA, Unità Tecnica Ingegneria Sismica

Giuseppe Maino
Unità Tecnica Metodi per la Sicurezza dei Reattori e del Ciclo del Combustibile

Mtskheta (Georgia). All these buildings were realized employing sandstone, a sedimentary rock produced by the gradual accumulation and sedimentation of small grains of sand. A particular feature of sandstones is the change in colour, from yellow ochre to red to white, due to the different concentration of oxides in their composition.

Stereo Microscopy and SEM/EDXRS Analyses

The Orsi-Marconi Palace

The *Orsi-Marconi palace* (Fig. 1) is one of the most noteworthy architectures in Bologna: it was realized by the famous Antonio Terribilia in the middle of the XVI century, having a monumental façade decorated with many sandstone ornaments.

During the recent restoration works, some samples were taken from the ornaments to yield chemical composition and identification of the materials by scanning electron microscopy combined with EDXRS system, giving conservators useful data for the selection of both the restoration method and the suitable products to be employed.

SEM analysis shows a characteristic fine grain microstructure, with silicate cluster formed by some small and round quartz elements in a carbonate matrix (Fig. 2a). This morphological appearance confirms the hypothesis that the analyzed sandstone originated from the reworking of oldest *terrigeni* sediments. The sandstones have a yellow-grey colour due to the presence of quartz crystals and to small concentrations of limonite dispersed in the matrix (Fig. 2b).

The microanalysis confirmed the chemical composition of the sample as sandstone, showing the high concentration of carbon of the carbonate matrix and the presence of silica and also calcium (Fig. 3). This

FIGURE 1 The Orsi-Marconi Palace: The main façade
Source: ENEA

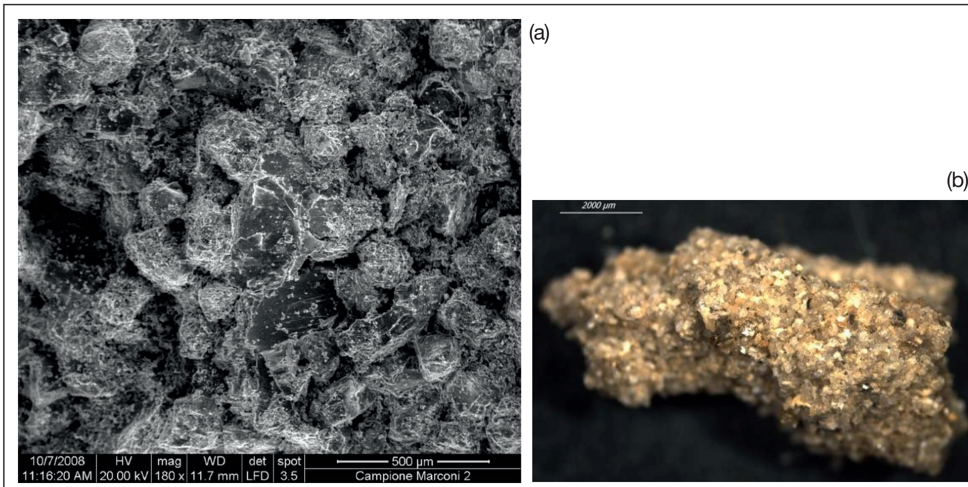
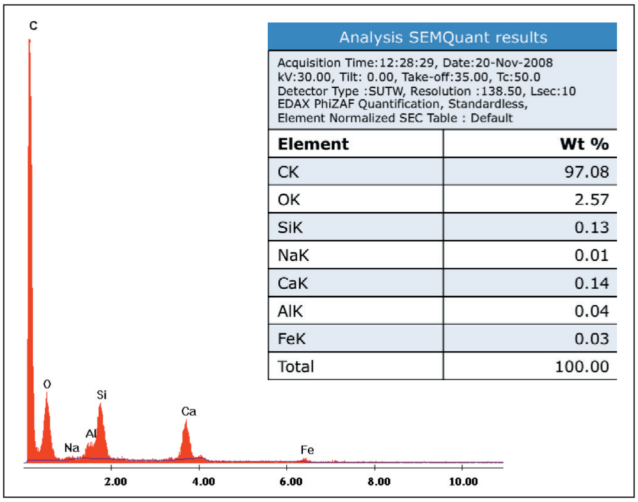


FIGURE 2 SEM (a) and Stereomicroscopic (b) images of sandstone sample n. 2, collected from the ornaments of the Orsi-Marconi building windows
Source: ENEA



Element	Wt %
CK	97.08
OK	2.57
SiK	0.13
NaK	0.01
CaK	0.14
AlK	0.04
FeK	0.03
Total	100.00

FIGURE 3 EDXRS microanalysis of sandstone sample n. 2
Source: ENEA

FIGURE 4 The Khazneh of the Nabataea city of Petra (Jordan)
Source: ENEA

mineralogical composition is typical of the Bolognese Apennines' sandstones, characterized by a high concentration of calcium carbonate. According to Luigi Fantini, a renowned Bolognese archaeologist, this yellow sandstone comes very probably from the Varignana quarry, near Castel San Pietro Terme, as the present analyses confirm on the basis of comparisons between the sandstones of the building and those extracted from the ore. This kind of sandstone was used in the Bolognese area since the Romans' age both for structural and decorative purposes, and can be found in many other artistic monuments in Bologna.

The Khazneh (House of the Treasury)

UNESCO declared the Nabataea city of Petra World Heritage on 6th December, 1985 (Fig. 4): moreover, in 2007 Petra was declared one of the seven wonders of the world. One of the most important monuments of Petra

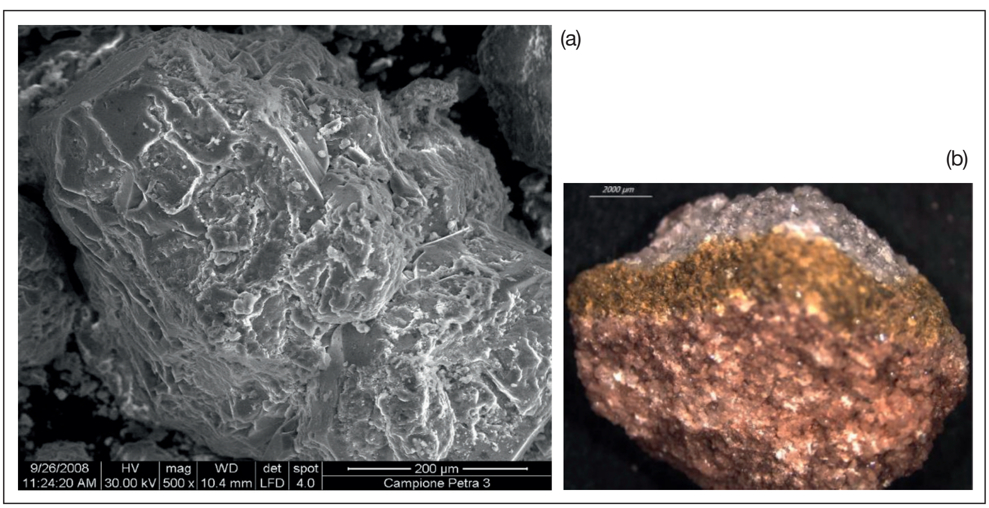
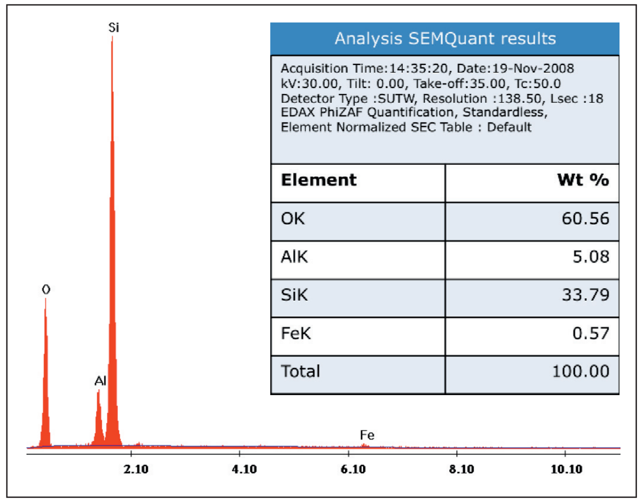


FIGURE 5 SEM (a) and Stereomicroscopic (b) images of a sample taken from the Khazneh
Source: ENEA

is the Khazneh (meaning the Treasury), an elaborate building 30 m wide and 43 m high, directly carved out of a sandstone rock face. Spectacular colour changes, due to the different oxides included in the sandstone during its formation, are visible on the façade and on the ceilings of many buildings of Petra, including the Khazneh.
Some samples were taken from the Khazneh and then analysed by scanning electron microscopy (SEM) combined with the EDXRS system.
The morphological analysis shows a structure with sand grains formed by some small and round quartz elements (Fig. 5a).
The analyzed sample is characterized by the colour changes typical of the Petra sandstone: Three different layers are recognizable and were analyzed: gray, yellow and red (Fig. 5b).
The microanalysis results confirm the presence of quartz grains, detecting a high concentration of silicon and the presence of aluminium in each layer (Figs. 6-7-8). Also iron is always present, but its concentration varies in the different layers from 0,57 Wt%, in the gray area of the sample (Fig. 6), to 2,65 Wt% in the red one (Fig. 7). Thus, the iron concentration and its oxidation state can be related to the different colours of the sample: the lowest iron concentration corresponds to the gray



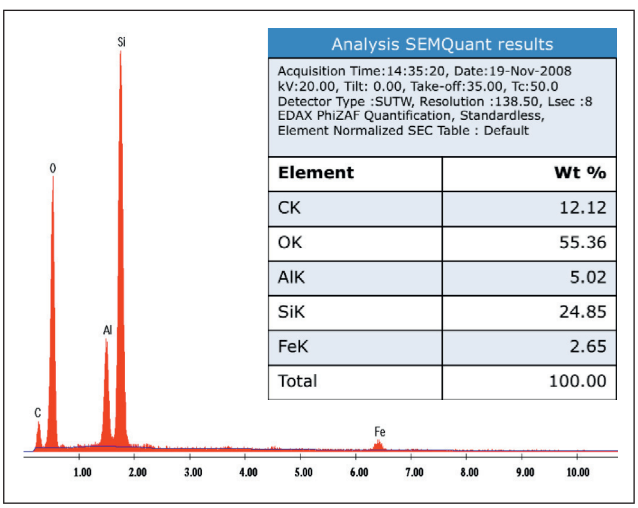
Element	Wt %
OK	60.56
AlK	5.08
SiK	33.79
FeK	0.57
Total	100.00

FIGURE 6 EDXRS microanalysis of the gray layer
Source: ENEA

layer, the highest one corresponds to the red layer; finally, the intermediate concentration corresponds to the yellow layer (Fig. 8).

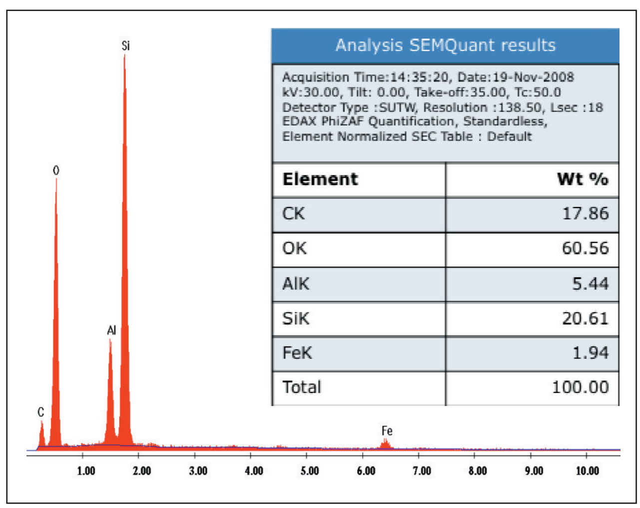
The Holy Cross Monastery of Jvari

Jvari Monastery (Fig. 9) stands on a mountain facing Mtskheta, right at the confluence of the Mtkvari and



Element	Wt %
CK	12.12
OK	55.36
AlK	5.02
SiK	24.85
FeK	2.65
Total	100.00

FIGURE 7 EDXRS microanalysis of the red layer
Source: ENEA



Element	Wt %
CK	17.86
OK	60.56
AlK	5.44
SiK	20.61
FeK	1.94
Total	100.00

FIGURE 8 EDXRS microanalysis of the yellow layer
Source: ENEA

FIGURE 9 Holy Cross Monastery of Mtskheta (Georgia): a view from the Aragvi river
Source: ENEA

the Aragvi rivers. After the conversion of the Kartli region, a large wooden cross was erected on top of this mountain and, between 545 and 586 a.C., a little church was built next to the cross; it is cruciform inside and rectangular outside, while the cross vault is now fallen in. A bigger church was then built between 586 and 605 a.C., enclosing the wooden cross in the interior. This *Church of the Holy Cross* is one of the best examples of the Georgian early architecture and had a deep influence on the further developments of it: Its structure is a four-apse domed building, where walls are faced with smoothly finished sandstone blocks. The octagonal drum has four windows; it is worth remarking that the Holy Cross Church was the first Georgian church to be amply decorated with sculptures. In the XVII-XVIII centuries, a wall was built around the Holy Cross Monastery in order to protect it from invasions by the Caucasian people.

Some samples were taken from **Jvari**, in particular from the arch ornaments of main façade, and then analysed.

The stereomicroscopic observation (Fig. 10a) shows various colorations, from tan to yellow: the three dimensional observation with SEM (Fig. 10b) shows a slightly different morphology, with silicate cluster formed by small sharp quartz elements in a carbonate matrix.

The microanalysis by combined EDXRS system confirmed this composition, showing the presence of silicon and of some oxides as iron and aluminium (Fig. 11). Unlike the samples collected in Bologna and in Petra, magnesium, sodium and potassium where detected too.

Conclusions

The analyses carried out on the samples collected in Bologna, Petra and Mtskheta show a composition

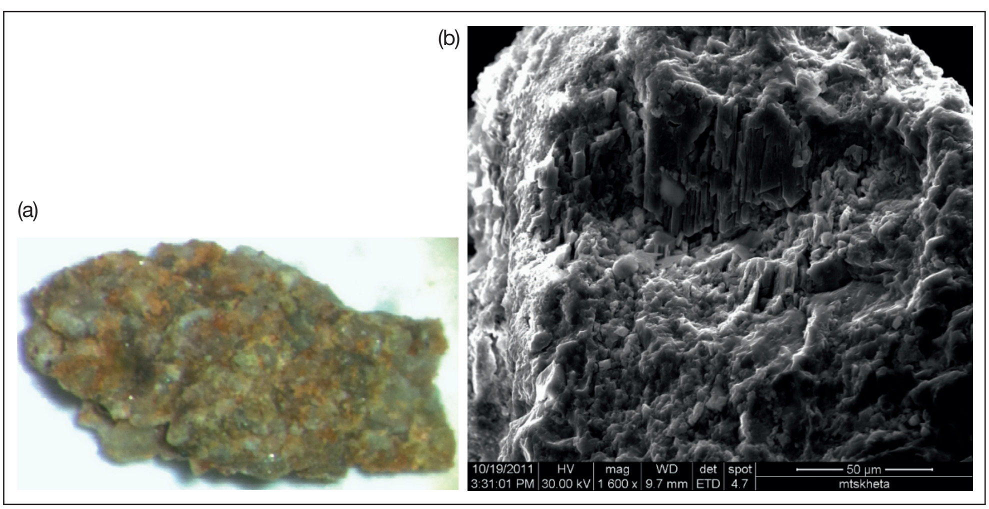
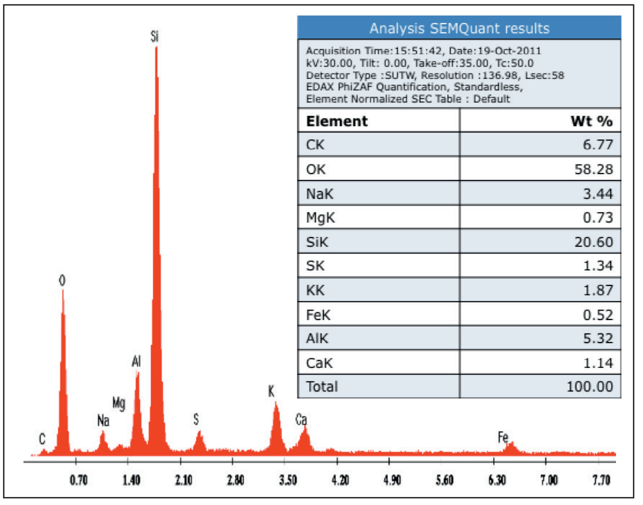


FIGURE 10 Stereomicroscopic (a) and SEM (b) images of a sample taken from the Holy Cross monastery of Jvari
Source: ENEA



Element	Wt %
CK	6.77
OK	58.28
NaK	3.44
MgK	0.73
SiK	20.60
SK	1.34
KK	1.87
FeK	0.52
AlK	5.32
CaK	1.14
Total	100.00

FIGURE 11 EDXRS microanalysis of a sandstone sample
Source: ENEA

basically similar, being the sandstone a sedimentary rock composed fundamentally by sand grain (quartz, feldspar, and/or micas) immersed in a carbonate matrix. The different concentration of the oxides observed in the samples confers a particular colouration to the rock in the three sites of origin: the larger concentration of iron oxide imparts a reddish tint to the samples coming from Petra, whereas the yellow tint of the Orsi-Marconi samples is due to the presence of limonite (small iron concentration). The large number of different oxides detected in the Georgian samples could be responsible for the tint shifting from tan to yellow.

References

[1] G. Cuppini, *L'architettura senatoria. Bologna tra Rinascimento e Illuminismo,* Compositori, Bologna, 2004.

[2] G. Dalman, *The Khazneh at Petra. Mackenzie-Megalithic monuments of Rabath Ammon at Amman,* Palestine exploration fund, Order of the Committee, 1911; id., The Khazneh at Petra: Illustrated by a plan by Francis G. Newton, Annual. Palestine Exploration Fund. 1911, III, Offices of the Fund, 1912.

[3] M. Bulia and M. Janjalia, eds., *Mtskheta*, Tbilisi, 2006

Correlation Between XRF Data and Pigment Radiopacity

The x-ray absorption of paint matter (consequently grey levels directly measured on radiographic films) as well as the data obtained through XRF measurements on it depend on its chemical composition. First of all, the theoretical background was considered; then a series of reproducible standards were carried out and the calculated data for their x-ray absorption was compared with their grey levels (optical densities), measured directly on the x-ray films. In this way it was possible to evaluate the radiopacity of the pigments. The influence of thickness variability was taken into account. As an example, the model was applied to a painting by Antonello da Messina

Pietro Moioli, Claudio Seccaroni

Mass Absorption Coefficients and Reference Standards Preparation

The attenuation of a beam of x-radiation having an energy E which crosses a medium is given by

$$I=I_0 \exp[-\mu(E)\cdot t] = I_0 \exp[-S(E)\cdot x]$$

where I is the intensity of the incident beam, I_0 the intensity of the transmitted beam, μ(E) the mass absorption coefficient [cm^2/gr], S(E) the linear absorption coefficient [cm^{-1}], t the thickness of the medium in gr/cm^2, x its thickness in cm.

For all the chemical elements the absorption coefficients can be found tabulated as a function of the energy [1]. The absorption coefficients of any material having known composition can be calculated as

$$\mu(E) = c_1\mu_1(E) + ... + c_n\mu_n(E)$$

$$S(E)=\mu(E)/\rho$$

where $\mu_1(E)$, ... $\mu_n(E)$ are the absorption coefficients of the constitutive elements, c_1, ... c_n their concentrations, and ρ the density of the material.

Pietro Moioli, Claudio Seccaroni
ENEA, Unità Tecnica Tecnologie dei Materiali

In 1929, A. Martin de Wild calculated mass absorption coefficients for many pigments at the energy of about 15 keV [2]. For a group of these pigments, he also calculated the mass absorption coefficients taking into consideration the quantity of linseed oil required to form an adequate paint layer. This is the only known investigation concerning the calculation of the mass absorption coefficients of pigments. Conversely, more recent publications on the reading of x-radiographs of paintings generally report semi-quantitative evaluations of pigment mass absorption coefficients, where a few categories (such as low, medium, medium-high, high, very high) are individuated [3-5].

Therefore, the contribution of the paint layers to the attenuation of the x-beam may be calculated on the basis of their composition and of the energy of the x-radiation. The radiopacity of the paint layers (i.e., the capability to absorb the x-rays passing through them) depends on the mass absorption coefficient of the materials, which in turn depends on the atomic number of the chemical elements present, and then on the physical density of the materials as well as on the energy of the x-radiation [6]. Directly related to radiopacity, is the grey level of the corresponding area on the radiographic plate, also

	ρ	μ	S	R	σ
titanium white	2.19	34.50	15.75	1.043	0.207
zinc white	2.51	52.57	20.94	1.179	0.198
yellow ochre	1.58	8.02	5.08	0.576	0.390
natural sienna	1.46	10.36	7.10	0.416	0.235
chrome yellow	2.08	42.27	20.32	1.024	0.203
cadmium yellow	1.84	21.06	11.45	0.921	0.196
cinnabar	2.50	88.01	35.20	1.351	0.171
mars red	1.73	16.71	9.66	0.504	0.179
burnt sienna	1.54	11.53	7.49	0.384	0.272
cadmium red	2.02	30.56	15.13	1.089	0.169
alizarin carmine	1.21	1.54	1.27	0.180	0.204
silver white	2.99	65.83	22.02	1.585	0.168
burnt umber	1.43	15.84	11.07	0.430	0.138
Prussian blue	1.23	6.66	5.41	0.135	0.169
ultramarine	1.40	4.09	2.92	0.217	0.209
cobalt blue	1.87	17.07	9.13	0.491	0.183
chrome green	1.41	14.43	10.23	0.348	0.20l
ivory black	1.35			0.190	0.147
white lead	3.03	76.34	25.19	1.827	0.147
massicot	4.85	94.45	19.47	1.973	0.144
Naples yellow	3.67	74.07	20.18	1.973	0.154
carbon black	1.49	0.77	0.52	0.430	0.111
azurite		32.06		0.994	0.193
copper acetate		21.14		0.988	0.101

TABLE 1 Colours applied on a white industrial preparation (colour in tubes)
Source: ENEA

called photographic density, which is measurable by means of optical instruments [7]. For relatively simple paint layers, and in absence of complex stratifications, calibration of reference samples may be useful to read a radiographic image in order to check its composition.

The impossibility of directly evaluating the radiopacity of a pigment by simply measuring the grey level on an x-ray plate is clear, the parameters are many and not all directly controllable as, e.g., the nature of the support and of the preparation, the variation in thickness. Moreover, generally pigments are almost never employed as pure, but in mixtures, and various layers of different composition are superimposed. However, it is possible to perform a calibration carrying out measurements on specially-made samples. The data obtained in this way can be compared with those calculated through the above formulas.

The possibility of measuring the radiopacity of each paint layer is based on the following findings. Suppose that the paint layer is superimposed on other homogeneous layers (i.e., the preparatory ones). If we measure, on the radiographic film, the grey levels in this coloured area as well as outside it, where the paint layer is interrupted, and not the underlying ones, we can evaluate the contribution of the underlying layer.

On the basis of the above considerations, reference

	ρ	μ	S	R	σ
yellow ochre	1.58	8.02	5.08	0.350	0.216
natural sienna	1.46	10.36	7.10	0.302	0.195
cinnabar	2.50	88.01	35.20	1.361	0.201
mars red	1.73	16.71	9.66	0.639	0.251
burnt sienna	1.54	11.53	7.49	0.570	0.264
alizarin carmine	1.21	1.54	1.27	0.248	0.292
burnt umber	1.43	15.84	11.07	0.771	0.241
ultramarine	1.40	4.09	2.92	0.305	0.250
white lead	3.10	76.78	24.77	2.422	0.206
massicot	4.43	93.06	21.01	2.664	0.173
Naples yellow	3.35	71.20	21.25	2.464	0.178
carbon black	1.45	0.77	0.53	0.737	0.170
nero d'avorio	1.35			0.470	0.220
copper acetate		20.84		1.159	0.185
azurite		32.06		1.260	0.259

TABLE 2 Colours applied on a brown preparation (colour in tubes)
Source: ENEA

	ρ	μ	S	R	σ
yellow ochre	1.53	8.32	5.44	0.737	0.292
natural sienna	1.28	8.38	6.55	0.381	0.313
cinnabar	2.85	118.83	41.69	1.916	0.236
natural sienna	1.36	11.71	8.61	0.753	0.362
alizarin carmine	l.l0	0.88	0.80	0.356	0.470
burnt umber	1.33	13.94	10.48	0.463	0.301
ultramarine	1.12	2.89	2.58	0.185	0.402
white lead	2.00	61.66	30.83	2.205	0.273
Naples yellow	2.25	59.54	26.46	1.604	0.312
carbon black	1.20	0.78	0.65	0.411	0.435
ivory black	l.31			0.309	0.310
copper acetate		17.08		0.694	0.454

TABLE 3 Colours applied on a brown preparation (raw pigments and linseed oil)
Source: ENEA

standards have been performed in laboratory with the following modalities: canvas sizing using rabbit skin glue, homogeneous preparation having known composition and thickness, and paint layers with known and constant thickness.

Different types of preparatory layers were taken into account. In particular earth-based preparations using powdered pigments and linseed oil; the same kind of preparation made with ready colours in tubes; white industrial preparations.

For the paint layers, both ready-prepared colours in tubes and powder pigments mixed with known amounts of linseed oil were used. All of them were applied with a silk screen technique, in order to obtain a uniform thickness for all the samples. Moreover, a series of samples was realized with three superimposed layers, so as to verify their behaviour at different thicknesses, and their saturation conditions due to the layer thickness.

Optical Attenuation on Radiographs and Calculation of Absorption Coefficients

For each sample the mass absorption coefficients were calculated, taking into account the quantities of oil medium. For tube colours we considered the composition declared by the manufacturer, taking into account also the presence of filler materials. The densities (ρ) were experimentally measured. For pigments obtained from natural mixtures, the compositions declared in handbooks were used [8-10]. The canvases, prepared as described above, were radiographed using an x-ray generator set to 20 kV and 5 mA.
On the radiographs of each canvas ten attenuation measurements were performed on the coloured areas and on the surrounding preparation, in order to minimize the effects due to inhomogeneities in the paint layer and in the preparation. The mean value and the standard deviation for each group of measurements were calculated. The difference between the mean values measured on each coloured area and on the preparation provides the attenuation due to paint layer alone.
Tables 1-4 show the values for the densities (ρ), the absorption coefficients (μ and S), and the mean value of the optical attenuation (R) for each paint layer and the related standard deviation (σ).
Only in quite simple cases can the contribution of a paint layer be separated from the contribution of the underlying ones, maintaining a good correlation between the optical attenuation measured, and the attenuation coefficient calculated for the corresponding pigment. However, this operation is affected by high measurement errors.

	1 layer R σ	2 layers R σ	3 layers R σ
yellow ochre	0.350 0.216	0.752 0.185	0.984 0.192
natural sienna	0.302 0.195	0.572 0.183	0.798 0.200
cinnabar	1.361 0.201	2.060 0.193	2.226 0.187
mars red	0.639 0.251	1.046 0.236	1.355 0.242
burnt sienna	0.570 0.264	0.939 0.239	1.323 0.230
alizarin carmine	0.248 0.292	0.412 0.246	0.403 0.243
burnt umber	0.520 0.216	0.848 0.209	1.102 0.212
ultramarine	0.246 0.213	0.520 0.211	0.687 0.204
white lead	2.422 0.206	2.702 0.166	2.728 0.165
massicot	2.664 0.173	2.719 0.165	2.715 0.166
Naples yellow	2.464 0.178	2.685 0.166	2.722 0.165
carbon black	0.737 0.170	1.088 0.153	1.364 0.163
ivory black	0.470 0.220	0.674 0.210	0.879 0.211
copper acetate	1.159 0.185	1.749 0.333	1.887 0.150

TABLE 4 Colours applied in three layers on a brown preparation (colours in tubes)
Source: ENEA

XRF Analysis

The XRF (x-ray fluorescence) analysis is a non-destructive technique, which can supply information about the elemental composition of the matters employed on a painting, as it does not require the taking of samples, and an unlimited number of points can be observed.
This technique allows for the elemental semi-quantitative evaluation of all the chemical elements having an atomic number equal to or greater than 20 (i.e., from calcium upwards) [11-12]. It is therefore possible to obtain an indirect identification or characterisation of the mineral compounds/pigments through the detection of heavy elements present in the composition of each observed point as macro- or micro-constituents.
Unfortunately, the impossibility to detect elements with low atomic number does not allow to observe pigments containing only light elements, such as lapis lazuli or organic pigments (red lakes, etc.). For a correct interpretation of the XRF results, it is very important to remember this impossibility. Moreover, the obtained results involve all painting layers,

FIGURE 1 The Trivulzio portrait during the execution of the XRF measurements
Source: ENEA

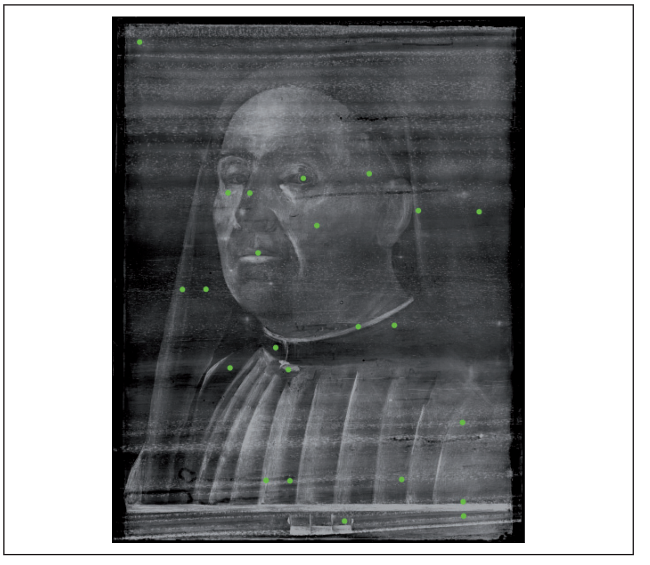


FIGURE 2 Investigated areas enhanced on the radiograph
Source: ENEA and Opificio delle Pietre Dure (OPD)

reaching the support.
At the laboratories of the ENEA Casaccia Research Centre, XRF analysis on paintings has been carried out since 1988. At present, our digital archives contain more than 100,000 spectra referring to about 1,500 works of art, taken with the same XRF system, specifically designed for this purpose, and in the same operative conditions. The XRF system is formed by an x-ray generator Gilardoni CPX-M160 and a Ge(hp) planar detector EG&G ORTEC, having resolution 195 eV at 5.9 keV. The distance sample-detector is 6.5 cm, 0.1 cm the collimation diameter on the incident x beam, 180 seconds the time of each measurement, 4.0 mA the current, while for high voltage two different conditions (60 kV and 20 kV) are generally used. The second condition is adopted in order to better detect all the elements having fluorescence lines with lower energy. In the first condition the incident x beam is shielded, in front of the collimator, with a copper foil 0.05 cm thick, in order to attenuate the low energy component.

A Case Study

As an application example, the model was applied to the *Trivulzio portrait* by Antonello da Messina, belonging to the Civic Museum of Ancient Art in Palazzo Madama (Turin) [13]. The choice of this painting for testing the model was justified by the exceptional thinness of the paint layers and of the panel support, and by the simple and concentrated palette, which determines homogeneity without creating interferences and uncontrolled fluctuations. XRF measurements (Figs. 1, 2) were carried out on 6th May, 2005, at the Opificio delle Pietre Dure in Florence, during the painting restoration; the painting was radiographed by Alfredo Aldrovandi of the Opificio delle Pietre Dure with the following operative parameters: high voltage 32 kV, current 5 mA, exposition time 5 minutes, distance between the x-ray tube and the painting 220 cm.
The relatively low intensities of the fluorescence lines of all the detected elements for this painting ensure that we were far from saturation conditions. The photographic density of each zone investigated by the XRF analysis was measured on the films through an optical densitometer.
Since the photographic density is related to the composition of the material, a multiple linear regression was conducted using the photographic density (D) as

Sp

the dependent variable, and the measured intensities of the fluorescence lines for the various elements as the independent variables. Manganese, calcium and strontium were not considered, the former because it has only been detected twice as a trace, the other two latter elements because they are linked to the composition of the preparatory layers. For this reason, the intensities of their fluorescence lines (which would be almost constant, with no real influence on photographic density) are affected from shield effects by the paint layers, which vary with the colour and the stratigraphy of the zone investigated. The multiple regression obtained is represented by the following formula, whose coefficients are shown in Table 5, whereas Fe, Cu, Hg, Pb, Sn are the intensities of the fluorescence lines of the elements.

$$D = A_0 + A_{Fe}*Fe + A_{Cu}*Cu + \\ + A_{Hg}*Hg + A_{Pb}*Pb + A_{Sn}*Sn$$

From the analysis of the data supplied from the regression, it is evident that the greatest contribution to photographic density is supplied by the wood panel and preparatory layers, which are nearly homogeneous over the entire surface, and which are represented by the constant factor in the formula for linear regression (A_0). As a higher shield causes a lighter areas on the plate, which in turn corresponds to smaller values of photographic density, the contribution to the regression by the five considered elements is systematically negative, so that the values of their respective coefficients are also negative. It is interesting to observe the effects of the individual elements on the changes in photographic density is represented by the absolute value of the respective coefficients. The lowest coefficient is related to the iron which is contained in pigments less radiopaque than those containing the other elements taken into account by the regression, such as copper, mercury, tin or lead.

The value for the tin coefficient is higher than those for mercury and lead, because the regression data used refer to different lines (K lines for tin and L lines for mercury and lead), which have markedly different fluorescence yields. It should be noted however that in XRF measurements on the *Trivulzio portrait* the presence of tin was determined only twice, on the

A_0	3,055
A_{Fe}	-2,581E-04
A_{Cu}	-2,501E-03
A_{Hg}	-6,553E-03
A_{Pb}	-7,733E-03
A_{Sn}	-1,186E-02

TABLE 5 Coefficients of multiple regression analysis relating the measured photographic density on the radiographic films to the XRF measurements
Source: ENEA

baluster in front of the sitter (points 2 and 3). On the other hand, the proximity of the values for the coefficients of mercury and lead is to be expected, especially considering the proximity of their respective coefficients of mass absorption, according to which it is possible to calculate the radiopacity of the pigment, estimated by A. Martin De Wild for white lead (88.5 cm^2/gr for the pure pigment and 70.9 cm^2/gr for the pigment with oil) and cinnabar (81.7 cm^2/gr for the pure pigment and 72.7 cm^2/gr for the pigment with oil).

As a check for the quality of the regression (with

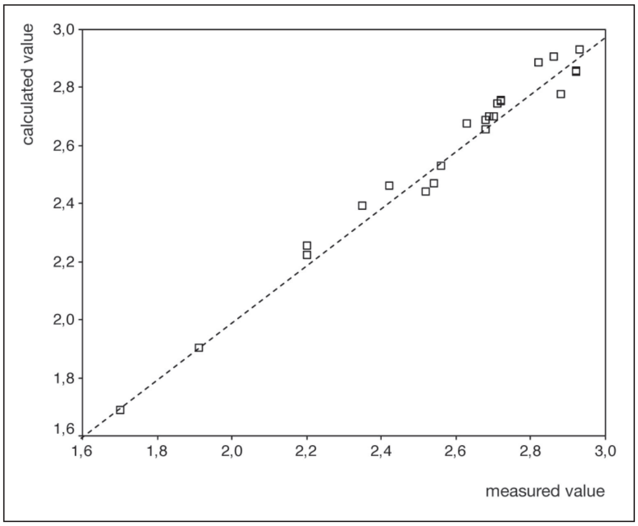


FIGURE 3 Comparison between the values of the photographic density measured on the radiographic film and the calculated ones from the multiple regression
Source: ENEA

a correlation coefficient r=0.989) the density values measured on photographic plates were compared with those calculated from the XRF data on the basis of the multiple regression (Fig. 3). The high correlation demonstrates the correctness of the physical model, and the absence of any saturation effects attributable to thick, or too rich and complex stratifications, which would have involved shield effects on the contributions of some elements, differing from point to point, depending on the composition and the stratigraphic succession of the various levels.
As shown in Fig. 3, differences between the calculated and measured values can be seen where the intensity of the lines of the various elements are smaller, due to measurement errors. However, if we calculate residual values, i.e., the differences between the value calculated and measured at each point, we still have a normal distribution with mean value equal to 0.0 and standard deviation equal to 0.88.
The major differences are observed for some points with higher values of photographic density, but the fact that these areas are those related to the maximum dark provides a physical justification for these discrepancies. In fact, the photographic density of these areas scarcely affects the factors taken into account in the regression, while the XRF analysis gives no information on the elements with low atomic number contained in the dark pigments used, probably based on carbon blacks. On the other hand, the photographic density fluctuations in the darker areas, due to the contribution of the preparatory layers and the panel grain, and consequently the increasing in the standard deviation values appreciably affect the difference between the measured value and that calculated on the basis of the specific XRF analysis.

Conclusions

In this paper we have tried to verify – on theoretical grounds, then experimentally on appositely executed standards and, finally, on a real painting – the effective correlation subsisting between two physical quantities related to the density and composition of matter. This verification was performed by using quantitative parameters derived from non-destructive techniques of investigation, usually performed in the diagnostics of paintings: x-radiography and XRF analysis. The results obtained are encouraging. In fact, the high correlation reached for the data related to the *Trivulzio portrait* by Antonello da Messina, through the evaluation of the grey levels measured on the x-ray plate, allows to extrapolate the compositional results supplied from the XRF also in adjacent areas, where XRF measurements were not performed. In the future, we shall apply this method to other paintings.

Acknowledgements

We would like to thank Alfredo Aldrovandi, Roberto Bellucci, Marco Ciatti and Cecilia Frosinini of the Opificio delle Pietre Dure in Florence.

References

[1] W.H. McMaster, N. Kerr Del Grande, J. H. Mallett, J. H. Hubbel (1969), *Compilation of X-Ray Cross Sections,* Lawrence Radiation Laboratory, University of California, UCRL-50174 Sec. II Rev. I.

[2] A.M. De Wild (1929), *The scientific Examination of Pictures,* G. Bell & Sons Ltd., London.

[3] A. Gilardoni, R. Ascani Orsini, S. Taccani (1977), *X-rays in Art*, Gilardoni, Como.

[4] L. Paderni (1983), "I raggi X nell'arte", 1st International Conference on *"Non-destructive Testing, Microanalytical Methods and Environment Evaluation for Study and Conservation of Works of Art"* (Rome, 27-29 October 1983), I/21.1-13.

[5] M. Matteini, A. Moles (1985), *Scienza e Restauro, Metodi di indagine*, Nardini Editore, Florence.

[6] P. Moioli, C. Seccaroni (2004), *Tecniche radiografiche applicate ai Beni Culturali,* ENEA, Rome, pp. 29-53.

[7] G. Accardo, P. Moioli, C. Seccaroni (1992), "Taratura di lastre radiografiche per analisi di dipinti", *3rd International Conference on "Non-destructive testing, microanalytical methods and environment evaluation for study and conservation of works of art"* (Viterbo, 4-8 October 1992), pp. 21-35.

[8] *Artists' Pigments,* voll. 1 (1985), 2 (1993), 3 (1997), 4 (2007).

[9] N. Eastough, V. Walsh, T. Chaplin, R. Siddal (2004), *Pigment Compendium, A Dictionary of Historical Pigments and Optical Microscopy of Historical Pigments*, Helsevier Butterworth-Heinemann.

[10] R.J. Gettens, G.L. Stout (1966), *Painting Materials. A Short Encyclopaedia,* New York 1966.

[11] P. Moioli, C. Seccaroni (1999), "Analysis of Art Objects Using a Portable X-Ray Fluorescence Spectrometer", *X-Ray Spectrometry,* vol. 29 n. 1, pp. 48-52.

[12] P. Moioli, C. Seccaroni (2002), *Fluorescenza x. Prontuario per l'analisi XRF portatile applicata a superfici policrome*, Nardini Editore, Florence.

[13] R. Bellucci, P. Bonanni, B.G. Brunetti, S. Calvi, C. Castelli, M. Cianfanelli, M. Ciatti, B. Doherty, R. Fontana, C. Frosinini, L. Giuntini, N. Grassi, P.A. Mandò, M. Massi, M. Mastroianni, M. Materazzi, A. Migliori, C. Miliani, P. Moioli, E. Pampaloni, L. Pezzati, P. Pingi, F. Rosi, C. Seccaroni, F. Seracini, A. Sgamellotti (2010), "Il restauro del Ritratto Trivulzio di Antonello da Messina", *OPD Restauro,* 22, pp. 15-54. [P. Moioli, C. Seccaroni, *Le analisi XRF*, pp. 43-52].

Non-Destructive Investigations on Four Paintings by the Master of Castelsardo. A Collaboration Between ENEA and University of Cagliari

An agreement between ENEA and University of Cagliari gave the chance of studying the materials and the technique used by Maestro di Castelsardo, the major artistic figure working in Sardinia during the end of the XV and the early XVI century. The application of non-destructive techniques (x-ray fluorescence, x radiography and near infrared reflectography) to investigate four paintings by Maestro di Castelsardo gave the possibility to characterize the pigments and the constructive technique used by the painter. Some hypotheses on the latter could be formulated by the authors of this article thanks to the comparison of the data obtained

Gianfranco Carcangiu, Ombretta Cocco, Laura Donati, Paola Meloni, Pietro Moioli, Franca Persia, Claudio Seccaroni, Attilio Tognacci, Pietro Usai

The collaboration agreement between ENEA, the *Dipartimento di Ingegneria Meccanica, Chimica e dei Materiali* (DIMCM) – University of Cagliari – and the *Soprintendenza per i Beni Architettonici, Paesaggistici, Storici, Artistici ed Etnoantropologici (BAPPSAE) per le Province di Sassari* e Nuoro provided the opportunity to create a multidisciplinary team working on Cultural Heritage materials. This agreement permitted us to draw up a project concerning diagnostic tasks to preserve and protect the artistic heritage, in order to promote specific exchanges of experience and knowledge, and to focus on the study of materials and artifacts. Such agreement has also allowed us to give young Sardinian people the chance to get new job opportunities, increasing cultural growth. The above mentioned collaboration agreement provides the basis for further collaborations, with the involvement of other partners like, for example, the *Consiglio Nazionale delle Ricerche,* particularly the *Istituto di Geologia Ambientale e Geoingegneria* (IGAG-CNR) in Cagliari, already actively involved in diagnostics on Cultural Heritage, in collaboration with the DIMCM.

The present collaboration allowed to investigate on works by the Master of Castelsardo, the most important

Gianfranco Carcangiu
CNR, Istituto di Geologia Ambientale e Geoingegneria, Sezione di Cagliari

Ombretta Cocco, Paola Meloni
Università degli Studi di Cagliari

Laura Donati, Pietro Usai
Soprintendenza per i Beni Architettonici, Paesaggistici, Storici, Artistici ed Etnoantropologici per le Province di Sassari e Nuoro

Pietro Moioli, Franca Persia, Claudio Seccaroni, Attilio Tognacci
ENEA, Unità Tecnica Tecnologie dei Materiali

painter working in Sardinia at the end of the XV and the early XVI century.

The *Retablo di Castelsardo* is a work of fundamental importance for the development of art history in Sardinia between the XV and the XVI century. From this retablo three panels (representing the *Madonna with the Child and Angels, the Trinity, Saint Michael the Archangel*), and part from the *pradella* with *The Apostles Philip, Bartholomew, Mathias and Mathew* survive. The project, with the execution of diagnostic investigations, was introductory to the restoration and involved the study of three of these four panel paintings.

The anonymous author probably had Catalan origins and moved to Sardinia in the last decade of the XV century, and he is commonly known as the Master of Castelsardo in relation to precisely this *retablo*, originating probably from the Franciscan convent of Santa Maria delle Grazie and now in the cathedral of Sant'Antonio in Castelsardo and in the adjacent Museo Diocesano. The artist was active in Spain, Sardinia and Corsica, and his oeuvre is characterised by strong spatial definition, inside a three-dimensional space, but still having a vague perspective [1-11].

The panels with the *Trinity* (Fig. 1) and *Saint Michael the Archangel* (Fig. 2) retain their original supports, with little additions on the bottom, while the painting representing the *Four Apostles* (Fig. 3) was transferred onto a new wooden support.

FIGURE 1 Master of Castelsardo, Trinity, Castelsardo, Museo Diocesano
Source: Archivio fotografico della Soprintendenza per i Beni Architettonici, Paesaggistici, Storici, Artistici ed Etnoantropologici per le province di Sassari e Nuoro

FIGURE 2 Master of Castelsardo, Saint Michael the Archangel, Castelsardo, Museo Diocesano
Source: Archivio fotografico della Soprintendenza per i Beni Architettonici, Paesaggistici, Storici, Artistici ed Etnoantropologici per le province di Sassari e Nuoro

Sp

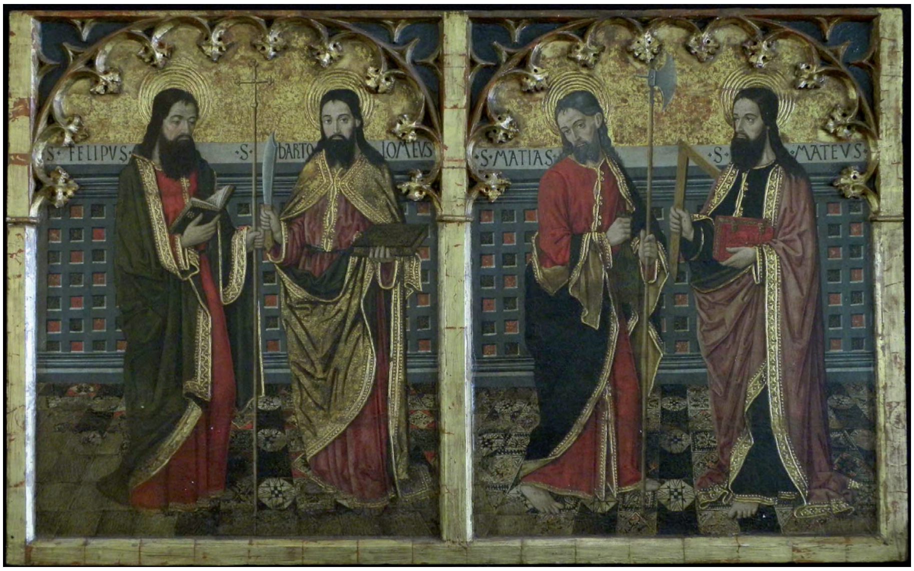


FIGURE 3 Master of Castelsardo, Four Apostles, Castelsardo, Museo Diocesano
Source: Archivio fotografico della Soprintendenza per i Beni Architettonici, Paesaggistici, Storici, Artistici ed Etnoantropologici per le province di Sassari e Nuoro

The diagnostic campaign was carried out in July 2011, in the Studio Abacus in Cagliari. In order to compare the findings from the dismembered *Retablo di Castelsardo* with other paintings attributed to the Master, a small panel representing an *Angel with tambourine* from the *Retablo della Porziuncola* (post 1492) in the Pinacoteca Nazionale in Cagliari was also examined.

Infrared Reflectography

The study of the underdrawing – including in this term the preparatory drawing, pentimenti, signatures, graphic prospective designs, dates, chromatic codes lying under the surface of the pictorial layer – has been carried out with infrared reflectography (IRR). This is an optical technique that, through a detector sensitive in the IR region (from 0.7 to 2.2 micron), acquires reflectograms (images in black and white) of the back-scattered infrared radiation from the painting, which is illuminated by two lamps with IR light.
A standard CCD camera[1] was used for this, with a spectral range between 0.7 and 1.2 microns; and two 250 Watt Nitraphot-S lamps as well as Photoshop software (to construct a mosaic with all the acquired images) were used.
IR reflectography was performed on the panels with the *Trinity, Saint Michael the Archangel, Four Apostles,* and also on the small panel representing an *Angel with tambourine.*
The overall results showed affinities in the studied paintings in the use of broad lines applied to reinforce the profiles of all the figures, as well as in every detail in the paintings. Indeed, the possibility of investigating paintings by the same author offers the opportunity of understanding the characteristic preparatory technique used by the painter in realizing his work.
In the *Trinity*, there are only a few light traces of preparatory drawing, and they are only visible in some areas: the profile of the *mandorla*, the fingers, the nose and the loincloth of Christ. In all other areas, profiles are reinforced with a liquid medium, using a brush, with strong lines. Beneath the red mantle of God-the-Father, which is painted using a transparent pigment, probably an organic lake pigment, many lines are visible, forming almost a sketch, modeling the knees. A slight *pentimento*, looking like a correction, is visible in Christ's hands, which are smaller in visible light.
An interesting particular is visible in the right knee of God-the-Father: a word, which could be deciphered as *ocra*. Due to the thinness of the pictorial layer, this word is also visible to the naked eye. The color painted

on the knee does not correspond to the beige colour that the word indicates.

Beneath the paint surface of *Saint Michael the Archangel*, the outlining of all the figures with intense dark lines painted with a brush is detectable. Only in the face of the Saint, are the lines thin. In the internal part of the mantle, the lines are hatched to show the pleats of the mantle. In the lower part of the drapery a circular line, which corresponds to nothing on the surface of the painting, can be seen clearly. This line may have been drawn as an aid to drafting the composition, perhaps to indicate the length of the skirt.

There is a slight *pentimento* in the right hand, in which a correction to the knuckles is well visible. And a stronger one (or an evident change carried out during a restoration) has been detected in both shoes: in the earlier version the shoes were decorated, instead now they are entirely red without any kind of drawing.

In the *Four Apostles* all the outlines have been broadly delineated with a brush. Only in the anatomic particulars (eyes, nose, mouth), are the lines thin.

A significant detail has been discovered on the panel: two words have been detected. The first one is under the red tunic of Saint Matthias (Fig. 4), and it can be interpreted as the word *vermell*, the Catalan term for red. The second one, under the drapery of Saint Bartholomew, is illegible. These chromatic indications can be interpreted either as a code for someone else within the studio who was to paint the red drapery, or else as a kind of reminder to the artist himself.

On the small panel of the *Angel with tambourine* from the *Retablo della Porziuncola,* the same pictorial technique with broad lines used to reinforce the outlines has been detected. There are many losses in the paint layer in this panel.

FIGURE 4 Four Apostles, detail of the red drapery of Saint Matthias with the color notation "vermell", IR reflectrography
Source: ENEA

Radiography

Only the three panel paintings from the *Retablo of Castelsardo* were radiographed. An x-ray generator ART-GIL, Agfa D7Pb films 30x40 cm wide, Agfa Structurix G 135 for the photographic processing, and Agfa Structurix G 335 as fixing bath were used. The current at the filament of the x-ray generator tube was 5.0 mA and 40 kV the voltage; the distance from the film to the x-ray generator was 100 cm; the exposure time was 60 seconds.

The radiographs make it possible to study in detail the types of joins in the planks, the non-original crossbars, the presence of nails (both original and non-original), the screws, and the wood inserts (the result of past restorations).

The surface of the three painting supports was lined with a rather coarse weave canvas which does not cover all the surface of the paintings, but ends a few centimetres shorter than the original borders of the panels.

The greater thickness of the preparatory layers in the gilded decorations in the haloes, the drapery and the backgrounds, is easily read in the radiographs. It was noted that the collar and the upper part of the central vertical band of the armour of the gilded areas in *Saint Michael the Archangel* are not in relief, as are other details of the same armour, but were applied directly onto the dark blue paint of the armour, which indicates variations during execution.

In the two panels representing the figures painted on a larger scale (the *Trinity* and *Saint Michael the Archangel*), the figures are defined in a different manner. In the flesh areas, the initial chiaroscuro of the volumes defines the shapes and the figures as

geometric volumes; this is due to the richness in lead white, and to the strong radiopacity of the pigment. This plastic research is one of most peculiar aspects of the Master of Castelsardo, and it can be related to the influence of the works of Antonello da Messina.
In the *Trinity*, precisely in the green reverse of God-the-Father's cloak, the paint shows the characteristic *craquelure* resulting from the presence of excess oil binding medium.
The colours of the two largest figures in the *Trinity* do not match, hence in order to avoid a wet-in-wet application of the paint, the resulting separation lines were not eliminated by the finishing layers, and the forms enhanced with dark lines. In the radiographs, the strongest of these *contours* are evident, delineating the arms of Christ, but are not so visible to the naked eye because of the poor contrast between the dark colours. In addition, in the area of the armpits (and the left one in particular), these en reserve outlines increase both in area and take on shape, defining the shadow area. In contrast, the smaller details are not defined by such en reserve contours, but are painted directly over larger areas of different colour. For instance, Christ's hair is painted over the flesh tones of the neck and the shoulders.
The only pentimenti identified on the radiographs of the Trinity, are of no great importance. They involve the fingers of God-the-Father, which are slightly longer in their final version, and a series of radio-opaque round areas in the red cloak, about six centimetres distant from the gilded embroidery border of the cloak. They seem to define a different initial decoration on the cloak, which was executed only on the left side of the painting.
In *Saint Michael the Archangel*, the radiographs (Fig. 5) show very different images from what is visible for the wings. Losses in the paint of the first version attest that the change was not due to an original *pentimento*, but to a later intervention. In fact, the version readable on the radiographs is comparable with the *painted* wings of the angels of other paintings ascribed to the Master of Castelsardo. Indeed, they are never entirely covered by gold or silver leaf, but are bi-chromatic and have an elongated and tapered shape, whereas the later version on this painting is not painted, but

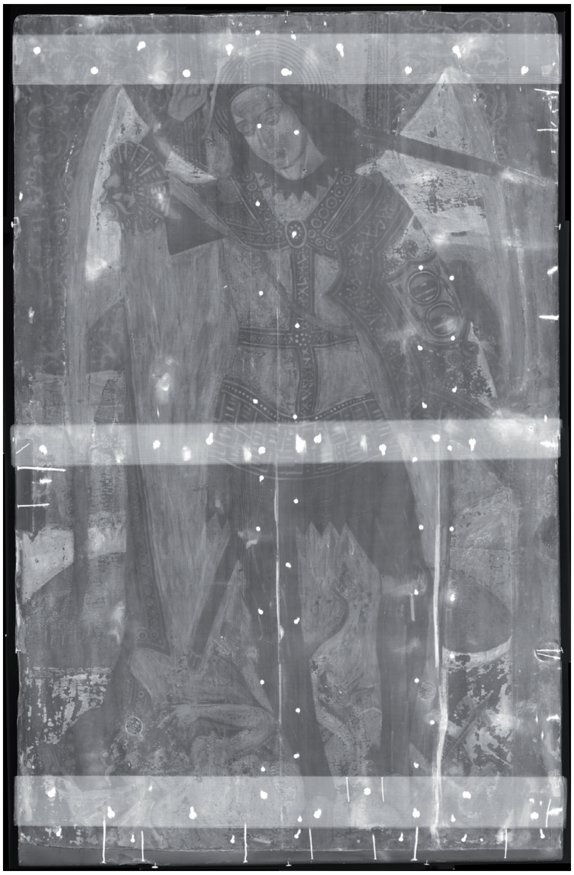


FIGURE 5 Saint Michael the Archangel, radiographic image
Source: ENEA

has a surface decorated with reliefs and incisions. In addition, the use of silver leaf, covered with a yellow varnish glaze (*mecca*) simulating gilding, was detected on these wings but was never detected on other details in this painting nor in the other three paintings by the same artist previously analysed. This confirms that the later version of the wings is the result of a spurious reconstruction.
As an example of the empirical perspective used by the Master of Castelsardo, in the panel representing *Four Apostles* one can see that the floor was initially set with horizontal bands carried out with broad brush strokes, while the tile borders in perspective were incised. The light appearance of these incisions in the radiographs seems to attest that they were incised

before the horizontal definition of the floor, as they were filled with the lead white containing film. In this painting, only a few variations were detected on the radiographs, and these of no great importance and only in the area corresponding to Matthias' right ankle, where the initial composition shows a series of folds not present in the final version.

XRF Analysis[2]

The results obtained involved all layers down to the support. The panels were prepared with a calcium rich compound (gypsum), characterised by the presence of iron and strontium impurities, generally detected on the paintings previously investigated. The strontium impurities are due to strontium sulphate (celestine).
For all of the four paintings investigated, the iron rich pigment (bole) used for the preparatory layers for the gilding contains titanium and manganese impurities.
The original palette is composed by lead white, copper-based blue and green pigments, lead tin yellow, brown red-orange and yellow iron-based pigments, cinnabar/vermilion (mercury sulphide), red lakes and, only in the *Angel with tambourine*, minium.
Generally, the quantity of copper is higher in blue areas than in green ones.
Lead-tin yellow is generally used in combination with copper-based pigments in the green areas, or iron-based pigments in the yellow areas, with tin increasing in light tones and iron increasing in dark tones.
Red areas are characterised by the use of cinnabar (the brighter ones), or of organic lake pigments (the less saturated ones, from pink to dark red).
Flesh tones contain lead white, iron based pigments (earths and/or ochres), and small amounts of cinnabar/vermilion and lead tin yellow. Copper-based pigments were added to the composition of shadow areas. Obviously, in Christ's skin in the *Trinity*, the quantity of iron present is lower and mercury is absent, as it is the complexion of a dead man which is represented. Other exceptions are present in results from the panel representing *Four Apostles*, where lead tin yellow was detected only in the cheeks of Saint Matthias and Saint Philip, and no copper based pigments were used for shadowing the flesh tones. This latter peculiarity characterises also the flesh tones of the *Angel with tambourine.*
Brown areas were painted with iron based pigments, sometimes darkened with the addition of copper-based pigments.
The modern pigments used in past restorations were also investigated. Titanium, zinc, and barium whites were both found in different areas, and combined together in one area. The presence of three different modern white pigments must be related to the *stratification* of different restorations and/or, perhaps, also to the use of some of these modern white pigments as extenders in industrial colours. In the latter hypothesis, the presence of one of these three elements should in some cases be related to the unintentional choice of the restorer. The presence of chromium was detected in yellow, green, grey-greenish and dark blue areas. Cadmium yellow was identified in brown and grey-greenish areas. Moreover, a mixture of zinc and barium whites with Prussian blue, even not ever in constant proportions, was detected in some areas of the panel representing the *Four Apostles*, which in the past was transferred onto a new support.
More interesting are the findings concerning the metallic decorations in the paintings representing the *Trinity* and *Saint Michael the Archangel*.
In the *Trinity*, the gold leaf used for the *mandorla* for Christ's halo and for the background is very thick, if compared with the gold leaf employed in other contemporary paintings executed in Italy and analysed in the past. A further typology of gildings was found in the Cherubs' halos, where both gold and silver were detected. From XRF data only, it is impossible to verify whether these elements are alloyed together or beaten in a double leaf (*Zwischgold*). However, the intentionality in the use of gold, and gold-silver leaf is evident.
On *Saint Michael the Archangel*, both gold leaf and silver leaf were detected. Generally, and in this painting, gold leaf is very thick and it was used on the background and in the decorations of the armour. Silver leaf was used for the chainmail, for the greaves, for the sword and for the umbo of the shield, whereas gold leaf was used for the borders.
In the old spurious reconstruction of the wings of Saint

Michael, identified during the present diagnostic campaign, silver leaf was used but as a surrogate for gold, as it is covered by a transparent yellow varnish glaze (*mecca*). Furthermore, over the mecca, there is polychrome decoration with semitransparent paint layers simulating feathers. This decoration was executed using organic pigments for dark yellow and red colours, and diluted copper-based pigment as blue colour.

Conclusions

The results described above, represent the first published information on the most important artist working in Sardinia between the XV and the XVI century. Some of his particularities, such as the volumetric enhancement of the figures and his use of empirical perspective were documented analytically. Even if his palette is quite limited in terms of the most important pigments available to artists during this period, a highly developed use of metal leaf was documented, aimed at achieving rich and differentiated appearance. Very interesting is the use of colour notations, a well documented practice in Spanish contemporary workshops [12-14]. Also important, for further studies on this artist, was the identification of a later reconstruction of the wings of *Saint Michael the Archangel,* which was not known prior to the present investigation.

Recently, a micro-sampling has been carried out on the investigated paintings; their analysis is still ongoing and will provide further details about the artist's palette and technique. In the future, we hope to investigate, under this collaboration agreement, other paintings by this important artist as well as works by contemporary artists, in order to include the results of the present study in a wider and more representative context.

Acknowledgements

We would like to thank the *Ufficio Diocesano per i Beni Culturali Ecclesiastici (U.B.C.) - Diocesi di Tempio Ampurias,* represented by Don Francesco Tamponi, and the restorers Gerlinde Tautschnig and Paolo Oggiano of Abacus (Cagliari), for their availability and collaboration during the diagnostic investigation.

Notes

1. Apparatus NIR DIGI 1200 from OptoLab Milan.
2. For information about this analysis technique and the operative conditions adopted see, in this issue, the paragraph "XRF analysis" in the paper *Correlation between XRF data and pigment radiopacity*, pp. 144-145.

References

[1] W. Biehl (1916), "Der Meister von Castel Sardo. Ein Beitrag zur Geschichte der sardischen Malerei im 15. bis 16. Jahrhundert"*, Mitteilungen des Kunsthistorischen Institutes in Florenz*, 2 n. 3/4, pp. 118-148.

[2] C. Aru (1926-27), "Il maestro di Castelsardo"*, Annali della Facoltà di Lettere e Filosofia della R. Università di Cagliari*, 1-2, pp. 27-54.

[3] R. Serra (1980), *Retabli pittorici in Sardegna nel quattrocento e nel cinquecento*, Associazione fra le Casse di risparmio italiane, Roma.

[4] R. Sfogliano (1981), "Il retablo di Castelsardo"*, Archivio Storico Sardo di Sassari*, 7, pp. 284-295.

[5] R. Sfogliano (1987), "La cultura figurativa in Sardegna nella seconda metà del sec. XV e gli influssi antonelliani nel maestro di Castelsardo e in Giovanni Muru", *Antonello da Messina*, Messina, pp. 439-453.

[6] R. Serra (1990), *Pittura e scultura dall'età romanica alla fine del cinquecento*, Nuoro.

[7] S. Mereu (1999), "Osservazioni sull'opera del Maestro di Castelsardo"*, Studi sardi,* 32, pp. 367-384.

[8] G. Goddard King (2000), *Pittura sarda del quattro-cinquecento*, Ilisso, Nuoro.

[9] L. Agus (2000), *Gioacchino Cavaro: il maestro di Castelsardo*, Cagliari.

[10] F. Poli (2001), "La prospettiva nelle opere del Maestro di Castelsardo (e altre considerazioni)"*, Archivio storico sardo*, 41, pp. 387-483.

[11] Pillittu (2002), "Una proposta di identificazione per il maestro di Castelsardo", *Archivio storico sardo*, 42, pp. 327-359.

[12] G. Finaldi, C. Garrido (2006), *El trazo oculto. Dibujos subyacentes en pintura de los siglos XV y XVI*, p. 183 and fig. 8 at p. 180, Museo del Prado, Madrid.

[13] G. Poldi, G.C.F. Villa (2007), "Dalla conservazione alla storia dell'arte". *Riflettografia e analisi non invasive per lo studio dei dipinti*, p. 503, Edizioni della Normale, Pisa.

[14] C. Barry (2011), "Technical Study of the Altarpiece from the Cathedral at Ciudad Rodrigo by Fernando Gallego and his workshop", *Studying old master paintings: technology and practice, the National Gallery Technical Bulletin 30th anniversary conference postprints,* edited by M. Spring, pp. 80-88, Archetype-The National Gallery, London.

Phase-Sensitive Reflective Imaging in the Terahertz and mm-Wave Regions Applied to Art Conservation

Non-destructive technologies, especially those based on THz sources, have been developed at the ENEA Research Centre in Frascati for monitoring applications in the Cultural Heritage Conservation field. Some of the most significant examples of research studies will be presented, with particular attention on those enlightening the specificity of the ENEA tools

Andrea Doria, Gian Piero Gallerano, Emilio Giovenale, Giovanni Messina, Ivan P. Spassovsky, Anne Cecile More, Alberto Petralia

Introduction

In the past few years, growing interest has been directed to find newer and newer applications for radiation in the Terahertz (THz) frequency range, including those in the field of analysis and conservation of cultural heritage [1].

THz radiation ranks in the electromagnetic spectrum between the Infrared (IR) and millimetres waves (mm-wave) and has the peculiarity of being a non-ionizing radiation capable of penetrating most plastics, cellulose and dielectric materials. The THz propagating through the material suffers of a minor scattering process if compared with infrared and visible radiation. In biological systems, absorption and reflection from water limit the penetration of THz radiation to the surface layers, but at the same time provide a powerful contrast mechanism that allows to detect the presence of biodegradation affecting the object. Despite the long wavelengths employed, Near Field Microscopy techniques can be used to reach high spatial resolution. Advanced THz technology for non-destructive analysis of art objects, including paintings, murals and sculptures has also good chances to become an imaging and analytical method for investigation. THz imaging and spectroscopy can indeed be used to characterize in a non-invasive way every layer and interface from the surface to the supporting material of a painting or mural. Accurate depth information can be provided by using short pulses and time-of-flight techniques or by using quasi CW radiation with phase-sensitive methods.

Andrea Doria, Gian Piero Gallerano, Emilio Giovenale, Giovanni Messina, Ivan P. Spassovsky
ENEA, Unità Tecnica Sviluppo di Applicazioni delle Radiazioni

Anne Cecile More, Alberto Petralia
ENEA Guests

The Imaging System

A versatile, reflective THz imaging system has been developed at ENEA-Frascati. The system is illuminated by a THz Compact Free Electron Laser operating in the frequency range from 90 to 150 GHz, with an output power of 1.5 kW in 4 μs pulses at a maximum pulse repetition rate of 10 Hz [2]. The imaging set-up is shown in Fig. 1 [3].

The FEL radiation is coupled first into a focusing cone followed by a circular to rectangular waveguide

transition, which matches the cone output to a series of two WR6 directional couplers. A waveguide probe is attached to the second directional coupler directing the FEL radiation to the sample under investigation.
The side outputs of the two directional couplers provide a reference signal (-20 dB) of the FEL radiation incident on the sample and the signal reflected by the sample (-16 dB) respectively. Both signals are detected by Schottky diodes operating at room temperature. A variable attenuator allows for the relative adjustment of the reference signal to the reflected signal within the response range of the Schottky diode during calibration. The sample under investigation is placed on top of a XY translational stage driven by piezo-motors with 50 mm travel range on both axes. To obtain an image, the sample is scanned at a maximum rate of 5 pixel/s with a maximum spatial resolution of about 0.2 mm, the reflected signal is normalized to the reference signal to compensate for any power fluctuation of the source during the scan. Collected data are stored in matrix form to be subsequently analyzed by an image processing software. The distance between the sample and the imaging probe along the z axis can be adjusted by means of a stepper-motor driven stage. It is worth pointing out that this imaging setup can be easily extended to higher frequencies up to about 1 THz by using a combination of both commercial and custom made waveguide components.

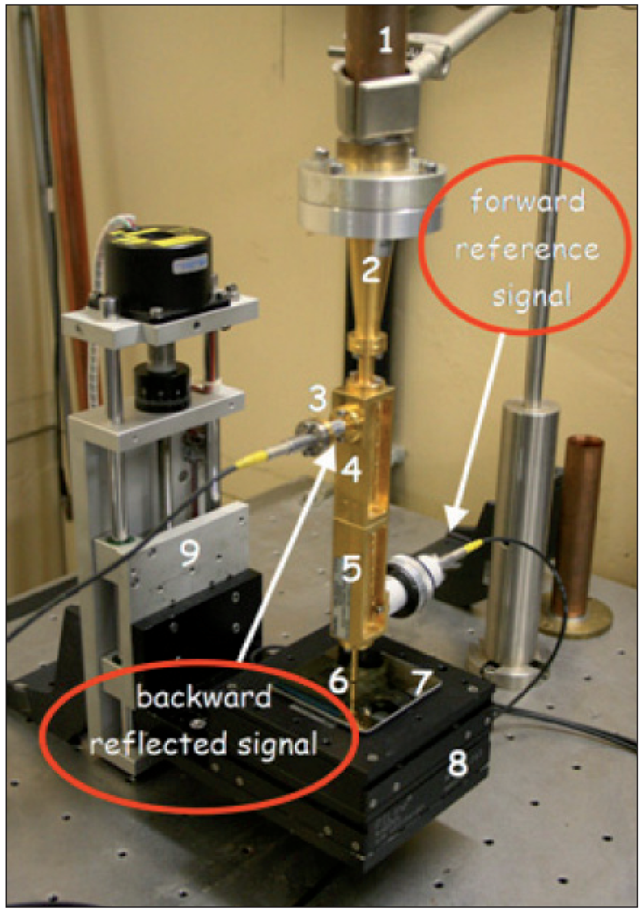


FIGURE 1 Photograph of the imaging setup: 1-Light-pipe; 2-Focusing cone; 3- Schottky diode; 4- 10 dB directional coupler; 5- 20 dB directional coupler;6- WR6 imaging probe; 7- Sample plane; 8- XY axes translational stage; 9-Z axis translational stage
Source: [3]

Experimental Results

Within the framework of a bilateral agreement, signed between the Italian and Japanese foreign offices, and named THz-Arte, we started a collaboration with Dr. Kaori Fukunaga from NICT (National Institute of Information and Communications Technology) about the application of THz radiation for the study of art work, in order to provide a tool for the conservation of cultural heritage. A first test measurement has been taken on a painting made with natural pigments and gold on a wood tablet, and partly covered by a 1.5 mm layer of whitening. This sample has been analysed in the visible (see Fig. 2 a), at THz in transmission using the broad band source at NICT (Fig. 2 b), and finally in reflection at Frascati with the ENEA Compact FEL source (Fig. 2 c). The whitening layer is perfectly transparent in the THz range and, due to the phase contrast control, in ENEA we obtained a clearer image right over the plaster cover: the whitening acted as an antireflection coating [4].
In order to verify the possibility to distinguish the pigments under the coverings, also the painting reported in Fig. 3 has been analysed. This is a tempera representing a Lady Mary's dress. Part of the detail of the dress has been covered by another kind of plaster, the *Gesso di Volterra.* The detail covered is now made

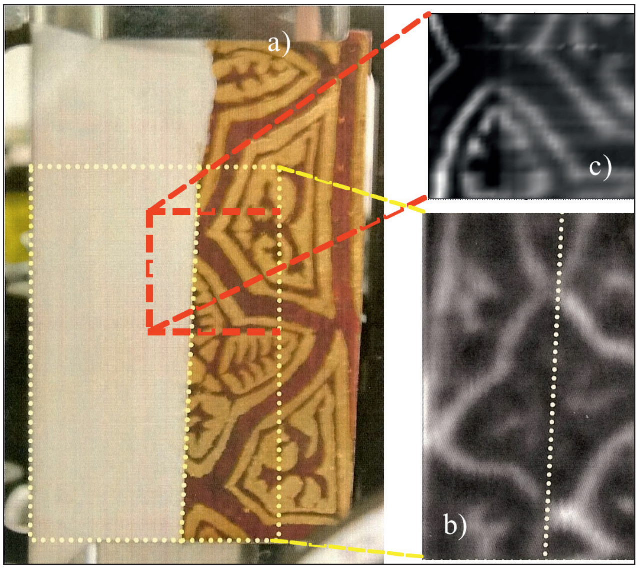


FIGURE 2 a) Visible image of a tempera painting partly covered by plaster; b) THz image in transmission @ 0.6-2.6 THz of the detail shown in the dotted area of the visible image (NICT Japan); c) ENEA THz image in reflection @ 0.15 THz of the detail shown in the dashed square of the visible image
Source: [4]

of two different pigments: indigo and cinnabar over gold. The THz image shows how the experimental apparatus is capable to distinguish not only the painting covered as being completely uncovered, but also the two different pigments demonstrating that they also have two different refractive indices at the ENEA FEL frequencies.

Another example is reported in Fig. 4 where the image represents a saint with a halo made of gold dotted; the painting has partly been covered with lampblack and white plaster. The resulting image demonstrates that the radiation can pass through these materials also.

The phase sensitivity of our imaging system has been exploited to distinguish the different refractive index of the different materials. The basic principle is based on the fact that the radiation, travelling along the waveguide of the probe (element 6 in Fig. 1), splits in two waves at the exit boundary; the transmitted part is attenuated by a factor and carries a phase term to which we must add a phase term related to the complex reflectivity of the sample. The reflected signal then interferes with the reflection from the open end of the waveguide, providing phase information, which can be used to enhance the image contrast and to monitor topological features of the sample surface. The amplitude of the maxima and minima interferences decreases as distance increases due to the radiation diffraction. For a metallic sample, the expected phase shift is π whereas for any other material the phase is a function of the complex refractive index. A proper mathematical model has been set up to match the experimental data with the free parameters. In Table 1 we have reported some results, obtained with the described method, about the optical characteristics of some materials used in cultural heritage and art conservation.

The phase-sensitivity method offers a powerful tool with which we can optimise the contrast among

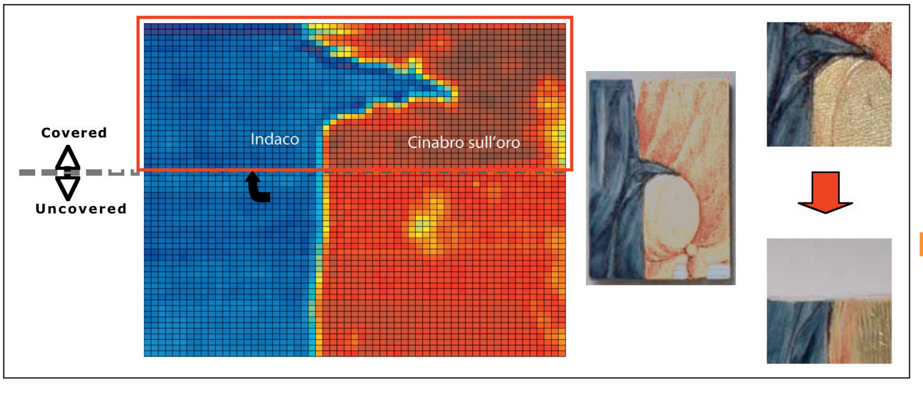


FIGURE 3 Tempera paint partially covered with plaster. Detail of the dress of the Virgin Mary. THz image and comparison with the visible image
Source: [4]

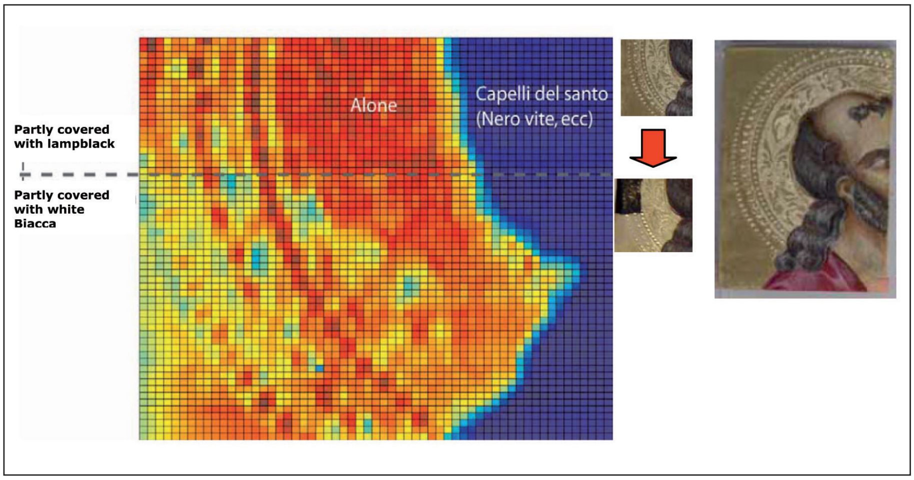


FIGURE 4 Tempera paint partially covered with carbon black and lead white. THz image and comparison with the visible image
Source: ENEA

	Re (n)	Im (n)	α [cm^{-1}]
Cyclo-Olefin Polymer (COP) base	1.04	0.81	25.01
Blue Cobalt Oil on COP	1.46	0.06	1.81
Blue Cobalt Acrylic on COP	1.30	0.26	8.06
Oil	1.15	0.36	11.36
Wax	1.32	0.28	8.35
Balm	1.42	0.11	3.10

TABLE 1 Optical parameters of some materials
Source: ENEA

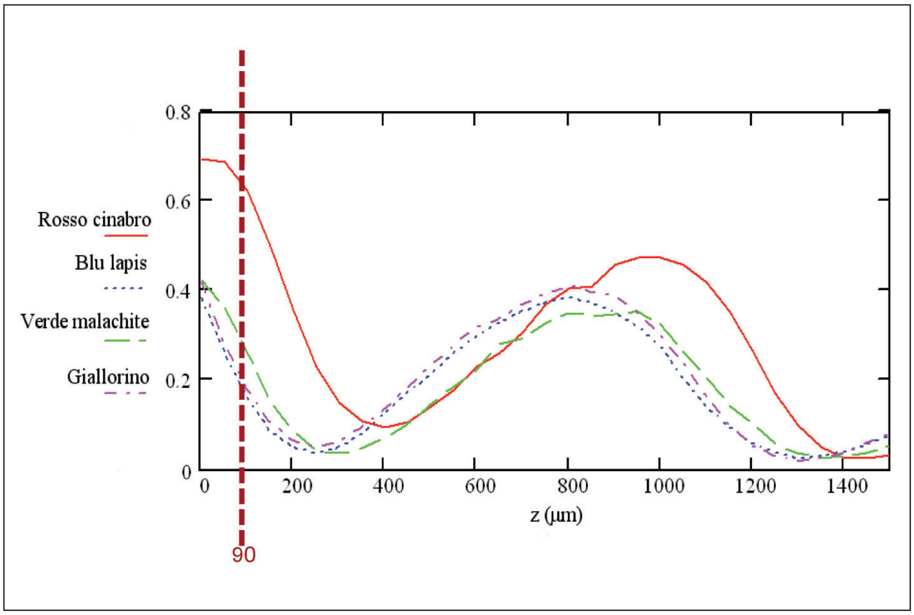


FIGURE 5 Phase scanning for different pigments. Highlighted in red is the distance for which the maximum contrast is obtained
Source: ENEA

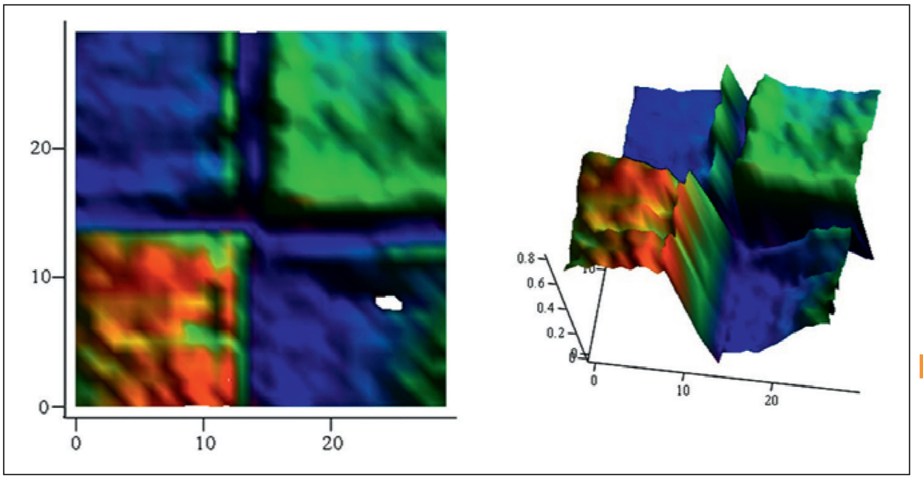


FIGURE 6 THz images of 4 pigments measured at the optimum distance obtained with the phase measurements
Source: ENEA

pigment responses in reflection. To proof the technique, a mosaic composed by four different pigments, was prepared (see Fig. 6); a phase profile scan, just moving the z-linear stage and thus changing the distance between the tip of the probe and the sample, has been performed for each pigment (see Fig. 5). A detailed analysis of the figure tells us that at a distance of 90 µm we have a maximum phase contrast for at least three pigments out of four. Setting the probe distance to that specific value, a 2D scan was performed.
A new activity recently started in Frascati on a complete series of samples provided by CISA3 (University of California, San Diego, USA) and prepared in 1983 at Editech, Florence (see Fig. 7). All samples reproduce typical material preparation for painting pigments, used for realising works of art over the centuries. The combination of 26 different pigments, painted with 5 different thicknesses over 3 different substrates, using 2 different binders, results in a total of 780 samples, covering most of the experimental situations [5].
Since THz radiation penetrates dielectrics, we expect to be able to identify the response from pigments, binders and substrates: by comparing the optical behaviour of the same pigments with different substrates and binders we will be able to determine the contribution of each component. Four different

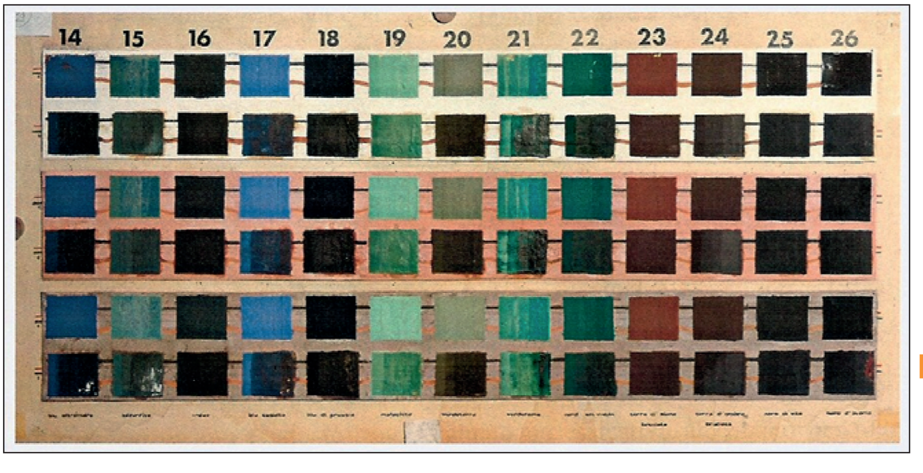


FIGURE 7 Panels with pigments prepared by Editech for THz measurements
Source: [5]

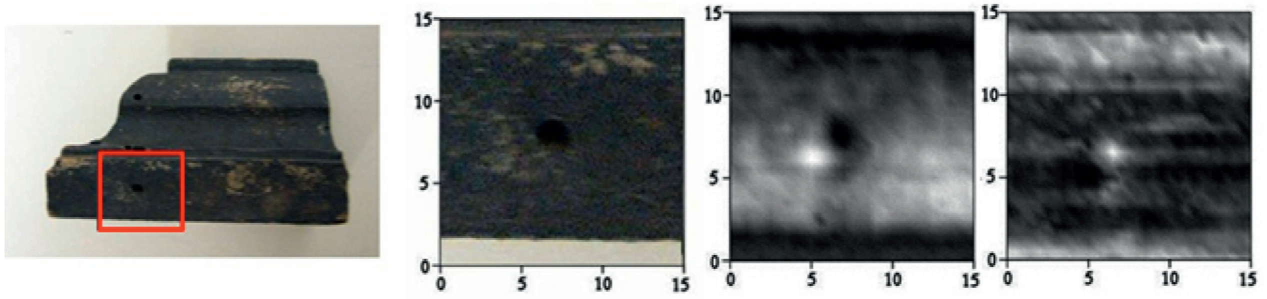


FIGURE 8 Fragment from a wooden altar dated 1774. From left: visible image, a magnifying of a particular and two THz images in reflection, measured at different tip-surface distances
Source: [6]

"wire patterns" were deposited between the substrate and the painted samples using the following materials: carbon, lead, silver and yellow ochre. It's important to verify if those materials can be detected under the painting, because these are the main components used for the preparatory drawings, usually underlying the final painting.
The three degree of freedom associated with the ENEA THz imaging system allow for tomographic imaging. This technique has been applied to detect damages induced by parasites, like worms, in wood samples. Reflectivity of wood is low, but it is sufficient to perform the measurements, if polarization of the Compact FEL radiation is chosen to be parallel to the wood fibres. The investigated samples are wooden objects from an altar dated 1774 of the Church S. Maria Maggiore, Piedimonte Matese (Caserta, Italy) [6]. The phase-contrast capabilities of the imaging system allows to perform a tomography scan, revealing internal properties of the sample and thus Fig. 8 reports visible and THz images, taken at different z-values, of the wood sample. It is quite evident how the hole changes its position in the image while changing the tip-sample distance, giving us evidence of how the tunnel develops beneath the surface.

Due to the capability of THz radiation to have a high contrast in reflection with respect to water content in samples, THz imaging techniques have been proposed to study the biodegradation of the mosaics in the "Villa del Casale" (Piazza Armerina, Italy). This will be a joint research activity between ENEA Frascati Reserch Centre and Centro Regionale per la Progettazione e il Restauro (CRPR) in Palermo. The reflection of the watery content of the biomaterials can be used to make a map over an area of the mosaic floor and to control its preservation state over time. A preliminary phase of the study will be carried out in laboratory to typify the material present in the mosaic works in order to plan the diagnostic operations on *in situ* mosaics at best and in a more targeted way. In particular, it is important to determine the transmission coefficients, reflectivity and the refractive index of the different materials, the characteristics of the different infiltrated microorganisms, in order to recognize them in the subsequent diagnostic interventions on the original mosaic. The second step concerns the diagnostic intervention *in situ* to map the infiltrate materials (such as algae, lichens, green patinas, etc…) under the mosaic "tesserae" without removing them and without deteriorating the mosaic themselves.

References

[1] K. Fukunaga, Y. Ogawa, S. Hayashi, I. Hosako, *IEICE Electronic Express,* 4, pp. 258-263, (2007).

[2] F. Ciocci, R. Bartolini, A. Doria, G.P. Gallerano, E. Giovenale, M.F. Kimmitt, G. Messina, A. Renieri, *Phys.* Rev. Lett. 70, pp. 928-931, (1993).

[3] G.P. Gallerano, A. Doria,M. Germini, E. Giovenale, G. Messina,I. Spassovsky; J. *Infrared Millimeter Terahertz Waves 30,* pp. 1351–1361, (2009).

[4] G.P. Gallerano, A. Doria, E. Giovenale, G. Messina, A. Petralia, I. Spassovsky, K. Fukunaga, I. Hosako; *33rd International Conference on Infrared, Millimeter and Terahertz Waves, 2008.* IRMMW-THz 2008. 15-19 Sept. 2008. pp. 1-2 - DOI: 10.1109/ICIMW.2008.4665511.

[5] G.P. Gallerano, A. Doria, E. Giovenale, G. Messina, I. Spassovsky, A.C. More, M. Seracini, *36th International Conference on Infrared,* Millimeter and Terahertz Waves, 2011.

[6] A. Doria, G.P. Gallerano, E. Giovenale, L. Gupta, G. Messina, A. Petralia, I. Spassovsky, and B. Bisceglia; *BIOEM 2009,* Davos (CH) June 14-19; P-185, (2009).

[7] G. Miceli, L.M. Vinci, E. Guarneri, A. Doria, G.P. Gallerano, E. Giovenale, G. Messina, A. Petralia, I. Spassovsky, V. Surrenti; *Atti del XVI Colloquio AISCOM, Palermo 17-19 marzo 2010 – Piazza Armerina 20 marzo 2010.*

Is this Artwork Original or Is it a Copy? The Answer by a New Anti-Counterfeiting Tag

We present a patented apparatus which consists of an extreme ultraviolet radiation source writing invisible patterns on thin tags of alkali halides. The tags written using this method are almost impossible to counterfeit, and offer a much better protection against fakes than the available anti-counterfeiting techniques. So far, we have used this invisible marking to tag electrical components, credit cards and containers of radioactive wastes. However, the protection level, the cost and the production yield associated with our technique suggest that the ideal field of application is the traceability and the protection of artworks against fakes

Sarah Bollanti, Paolo Di Lazzaro, Francesco Flora, Luca Mezi, Daniele Murra, Amalia Torre, Francesca Bonfigli, Rosa Maria Montereali, Maria Aurora Vincenti

Introduction

Counterfeiting is a global problem that has major social and economic consequences [1]. The spread, number and kind of counterfeit goods has greatly increased in recent years. In a recent update [2] the Organization for Economic Co-operation and Development has estimated in USD 250 billion in 2007 the worldwide value of international trade in counterfeit goods, with an impressive growth rate of USD 25 billion/year. The above estimate does not include counterfeit and pirated products that are produced and consumed domestically, nor does include the significant volume of pirated digital products that are being distributed in the Internet.

Sarah Bollanti, Francesca Bonfigli, Paolo Di Lazzaro, Francesco Flora, Luca Mezi, Rosa Maria Montereali, Daniele Murra, Amalia Torre, Maria Aurora Vincenti
ENEA, Unità Tecnica Sviluppo di Applicazioni delle Radiazioni

The range of products has broadened from luxury objects to products directly impacting on health and safety, like food, pharmaceutical products and automotive/aerospace spare parts. Consequently, anti-counterfeiting (AC) technologies are continuously evolving, extending their applications to identification of the origin of documents or objects, copyright protection systems, traceability and identification of paper currency, identity/credit/debit cards, forensic documents, critical/strategic components, dangerous wastes, pharmaceutical products.
Concerning artworks, 4,222 faked works of art have been found in Italy by the 'Comando dei Carabinieri Cultural Heritage Protection' just during the first six months in 2012. The value of the counterfeited artworks discovered in the last four years was 250 million euro [3], but a conservative estimate of the market of counterfeit artworks was about 1,5 billion euro during the year 2011.
Many AC techniques based on high-tech tagging have been developed, like fluorescent inks (currently used, e.g., in banknotes), thermo-chromic inks (used,

e.g., for tickets of events and lottery), demetallized hot stamping foils, holograms, diffractive foils, laser engraving (writing inside glasses) and radiofrequency identifiers. However, each of these techniques has its own effectiveness and lifetime limited by a variety of factors, including the ability of counterfeiters to replicate the technique, so that a continuous innovation of AC technologies is needed. Most important, none of the above techniques contemporarily matches a demanding way for a difficult-to-replicate marking and a simple control reading, being at the same time respectful of the privacy issue.
We propose here a new invisible marking technology to tag critical and/or expensive goods, which is effective to fight counterfeiting using a technology whose complexity and cost can be tailored to the value of the good to be protected and leaving, on the other hand, the specific reading technique straightforward.

Technology Background

At the ENEA Research Centre in Frascati we have developed expertise in the field of extreme ultraviolet (EUV) radiation and soft X-rays generation and applications [4]. A plasma source driven by two different XeCl excimer lasers is operative and its short-wavelength radiation is used in different fields, ranging from microscopy to radiobiology, from micro-radiography to photonics. Based on our laser-plasma source, we have developed an apparatus for EUV projection lithography that was recently put in operation, printing a sub-100-nm-resolution pattern on polymethylmethacrylate (PMMA) resist [5, 6].
More recently, we operated a discharge-produced-plasma source (DPP) which can deliver EUV pulses with energy/solid angle of 20 mJ/ster in the 10-20 nm wavelength spectrum and 60 mJ/sr/shot in the full EUV range, working up to 20 Hz repetition rate [7]. The DPP is particularly suitable to irradiate large-sized targets in the near field with a higher yield vs. laser-plasma source, thus showing its superiority in the EUV contact lithography irradiations. As an example of typical space resolution attainable by EUV contact lithography, Fig. 1a shows a luminescent pattern based on stable color centers locally written on a lithium fluoride (LiF) crystal.

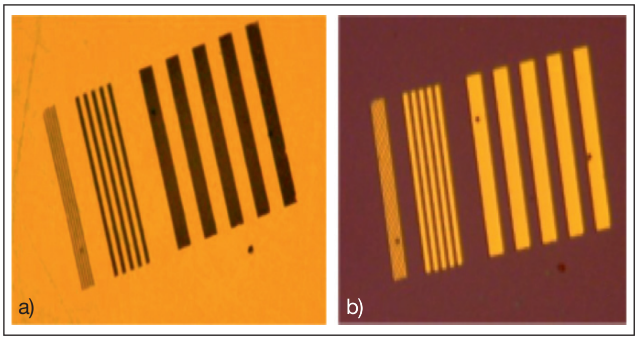


FIGURE 1 a) Luminescent patterns on a LiF crystal obtained by placing a mask in contact with the crystal surface and exposed to EUV radiation in vacuum. b) The mask, here observed in reflection mode, is a silicon nitride membrane patterned by sequences of 100-nm-thick gold zones with 2, 6 and 20 μm periods
Source: ENEA

The Invisible Marking Technique

Besides affecting the chain bonds of polymers like PMMA, the EUV radiation also alters the electronic structure of a class of dielectric materials, like alkali halides. Depending on the EUV irradiation conditions, a permanent visible pattern on alkali halides can be obtained, see Fig. 1 However, in particular conditions the radiation can locally produce a controlled density of color centers, thus printing a trace which is invisible to the naked eye and also at the microscope observation.
Thanks to the atomic-scale interaction and to the short EUV wavelengths, the writing process allows to achieve an extremely high spatial resolution of the stored image, down to the sub-micrometer scale [8] which is not attainable, e.g., using fluorescent inks deposited by the current ink-jet printer technology.
The invisible mark created by EUV radiation on the alkali halide can be detected by a proper reading system, suitable for the specific luminescent material. Figure 2 shows a pattern printed on a LiF film by contact EUV lithography (namely, an hexagonal-holes mask in contact with the material), as observed by an

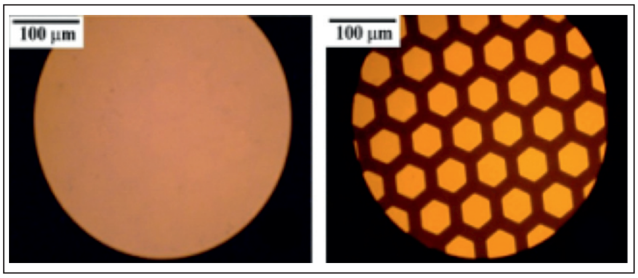


FIGURE 2 Hexagonal-hole pattern obtained by contact EUV lithography and observed at an optical microscope by white light (left) and by using the dedicated reading technique (right)
Source: [11]

optical microscope using a conventional illumination and when using the dedicated optical device. The LiF film was thermally evaporated on a glass substrate at the ENEA Research Centre in Frascati [9].
Figure 2 shows the color centers patterned by EUV radiation and a contact mask, which becomes visible only by the specific optical excitation and spectrally selected fluorescence spectra. The apparent similarity with the behavior of some fluorescent inks fails at a deeper analysis, thanks to the very low absorption of color centers in the ultraviolet, which, on the contrary, is strongly absorbed by inks, see Fig. 3. A simple, differential spectral reading system can thus definitely distinguish between a mark written by our technique and the same mark written by fluorescent ink.
The security level of our technology can be further increased by the digital encoding of the image, applying the current state-of-the-art cryptography techniques. In this case, the control relies not only on the physical reading of the image, but also on its decoding with the appropriate digital key/algorithm.
A prototype of a portable device able to read the invisible marks through a PC interface is shown in Fig. 4. In this case an encoding technique has been applied to crypt the invisible pattern. The PC screen shows the hidden raw data matrix (an array of tiny squares as a 2-D barcode) written on the film as read by the device, and the corresponding pattern "WATER MARKING" decoded by a dedicated software.
We can further increase the security level of our technology by structuring the crystalline film in a series of thin layers, each separated by non-luminescent materials, with a variable tapered thickness. By so doing, after irradiation by ionizing radiation, the energy of the ionizing radiation affects the luminescence ratio of the different layers, and therefore a mark imprinted with an ionizing radiation having a different spectral energy with respect to a pre-determined one can be identified.
ENEA has filed two patents about the invisible marking system [10].

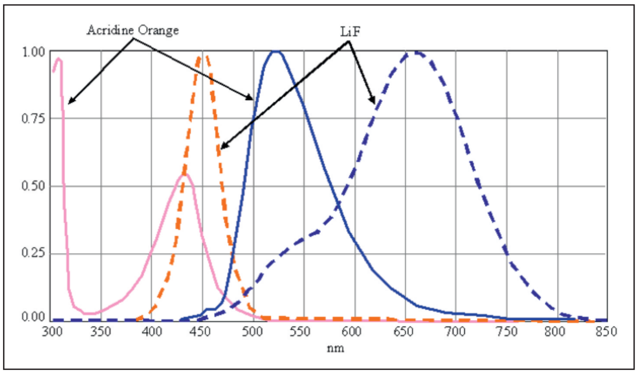


FIGURE 3 Optical absorption and emission spectra of LiF color centers (dashed lines) and of Acridine orange (continuous lines) in the range 300 nm - 850 nm. Acridine orange is the dye having the most similar absorption and emission spectra vs. LiF
Source: ENEA

Application to Artworks

In the past, we tested our invisible writing technique to produce tags able to track radioactive wastes, and to protect cards and electronic components [11]. To test the possible exploitation of our technology for AC purpose on artworks, we need adhesive and transparent tags. To this end, we have deposited a LiF film on transparent and adhesive plastic substrates. We printed the schematic picture of a Li atom on these tags in advance with respect to the LiF film deposition on the "nucleus" of the atom picture. Then, we irradiated the tags to write the invisible letter "E" within the pictured nucleus of the Li atom. The results, shown in Fig. 5, demonstrate the capability to produce flexible and adhesive AC tags that can be applied to every surface, independently of its roughness.

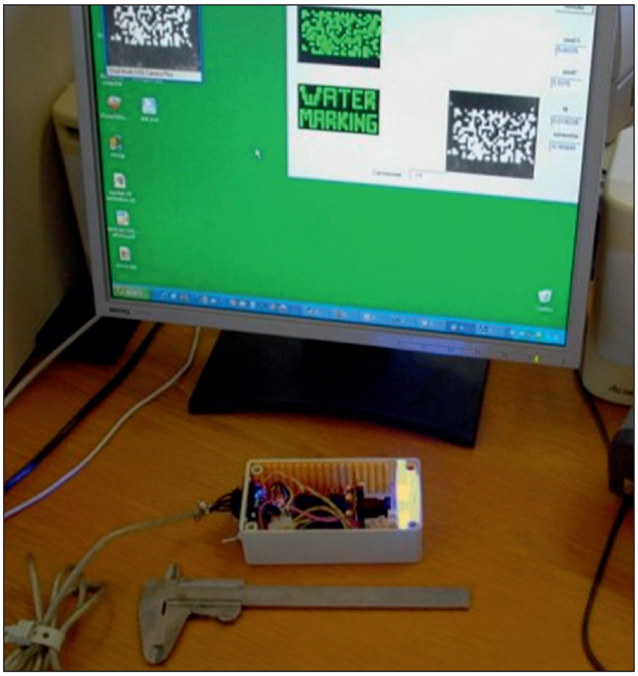


FIGURE 4 Prototype of a portable reading device able to detect the invisible images placed on a desk. On the PC screen there is the coded data matrix (a 2D binary array) transmitted by the ENEA device as read on the irradiated film, and below the corresponding sign "WATERMARKING" as decoded by a specific software
Source: ENEA

Obviously, a good anti-counterfeiting tag should change its status/ pattern-visibility when it is torn off the original object, in order to easily recognize if it has been moved to a faked object. We have checked what happens when slowly and carefully pulling off the adhesive tag of Fig. 5 and attaching it to another surface. The result, shown in Fig. 6, shows that the letter "E" patterned by EUV radiation becomes visible when observed at ambient light after the tag was pulled off the original surface.
As a test to check the applicability of our AC tags to archaeological objects, we stuck a tag like that of Fig. 5 to a copy of a bronze statue, known as "hero four-eyes and four-arms", see Fig. 7. The original statue was found in the Nuraghe Village at Abini (Nuoro, Sardinia) and dated back to the tenth century B.C.
Figure 7 provides evidence that the patterned letter E is absolutely invisible to the naked eye, while it is easily detected by a proper illumination and filtering.

Towards the Market: Durability, Cost and Production Yield

When seeking for practical uses of our technology, an important issue is the durability of the invisible writing on AC tags. In general, LiF is a rugged

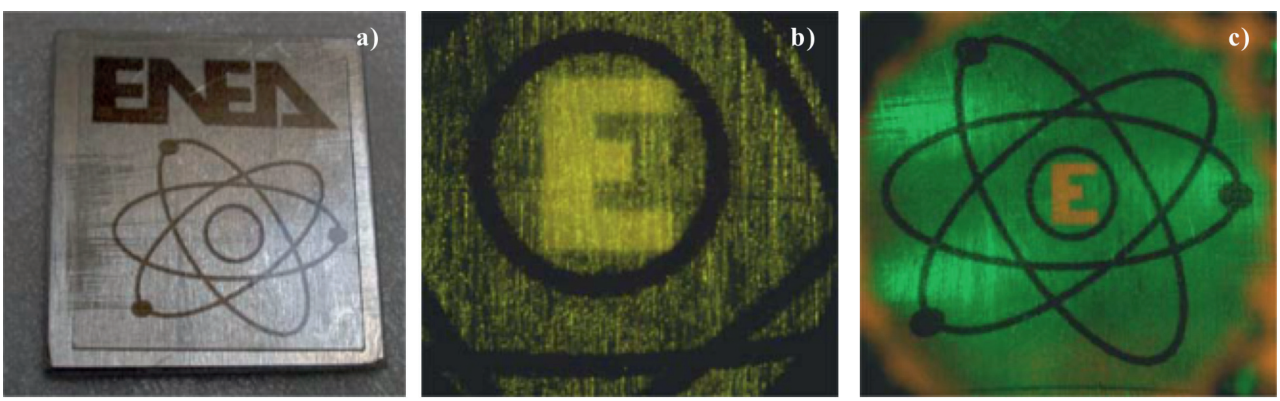


FIGURE 5 Transparent and adhesive plastic tag stuck to a rough metal plate. The LiF film is deposited in the area corresponding to the central "nucleus" of the atom pictured, and then it is exposed through a mask (where the letter "E" was patterned) to the EUV radiation emitted by the ENEA DPP. a) The tag observed at ambient light. b) The tag observed by a microscope at low magnification (2.5× objective) using the appropriate illumination and filtering. Note the rough surface of the metal plate, well visible behind the tag. c) The tag observed by the patented portable reading device
Source: ENEA

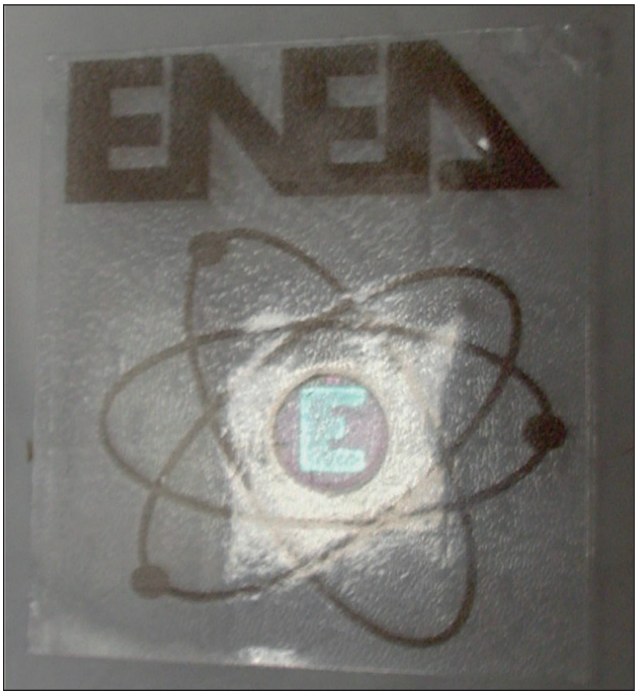


FIGURE 6 The same adhesive tag of Fig. 5a photographed after being pulled off the original metal substrate and re-attached to another surface. The patterned letter E, which was invisible, see Fig. 5a, is now visible at ambient light illumination
Source: ENEA

material, hard and almost non-hygroscopic. Our tests show that the irradiated films can be touched many times without significantly damaging or altering the visibility of the pattern, as detailed in [11]. When the tags are exposed to severe conditions (heavy and uncontrolled scratching or abrasions), a protection film can be applied on the tag.
What does a Company need to build up an industrial prototype producing our AC tags? a) The ENEA patents and the related know-how; b) A 50-W average power EUV source (DPP commercially available); c) A contact mask with the barcode/logo/picture (made, e.g., by lithography, or using a laser, or by chemical erosion); d) A suitable alkali halide film sensitive to EUV deposited on a flexible transparent plastic substrate (commercially available).

There are several parameters that influence the number of tags written per unit time, including the time to accurately align the contact masks on tags, the maximum number of tags that can be irradiated in the same irradiation run, and the area to be irradiated (which depends on the size of the patterns). A conservative estimation, based on a system made by assembling commercially available parts, gives a potential production yield of about 50-100 tags/hour, each tag having a patterned area of 0.4 cm^2.

Summary and Remarks

ENEA has developed and patented a new anti-counterfeiting/tracking technology based on EUV lithography on luminescent materials. An arbitrary pattern can be transferred as an invisible image on thin tags, which in turn can be put on or embedded in any object to be protected or traced. A compact and cheap device can read the luminescent image and check the authenticity of the tags.
In contrast with the use of fluorescent inks, our patterns are obtained by illumination of alkali halides materials with EUV radiation rather than by ink jet writing. Consequently, our patterns can reach a better spatial resolution (down to the sub-micrometer range), and they can be easily distinguished among fluorescent-ink patterns because of the different spectral response to UV light illumination (see Fig. 3).
Our writing tool is complex and expensive (especially in the case of projection imaging, giving sub-micrometer resolution) and it requires an experienced and skilled team to be optimized. As a consequence, it is highly unlikely that a counterfeiter can build up and operate a similar writing tool. On the other hand, the reading system is cheap and simple so that anybody can easily check the presence of watermark patterns to verify if the good is genuine.
The complexity and safety level of our hidden patterns can be further enhanced and adjusted by encoding patterns by cryptography techniques, and/or by structuring the fluorescent film as a series of thin layers, each separated by non-luminescent materials,

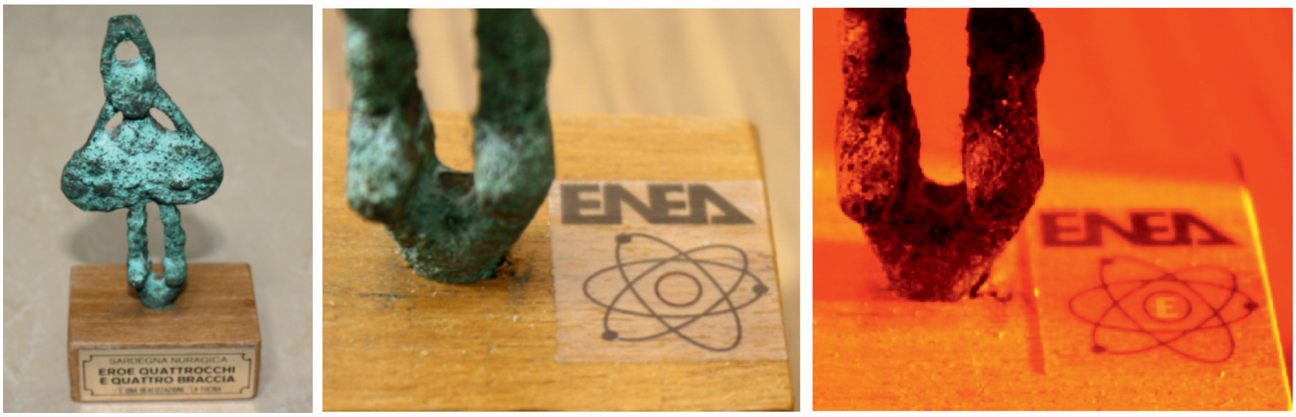


FIGURE 7 Left: copy of an archaeological bronze statue, known as “hero four-eyes and four-arms”. Height: 11 cm. Middle: the transparent and adhesive tag of Fig. 5 stuck on the wood base of the statue. Right: the letter ‘E’ patterned by EUV radiation appears when using the patented reading technique
Source: ENEA

with a variable thickness, as detailed in [10].
The feasibility of the application of this technology to artworks has been demonstrated, see Figs. 5 to 7.
Our anti-counterfeiting tags are resistant to normal conditions of use, and can be protected by a standard thermoplastic film, when exposed to severe conditions.
Our tags cannot be detached from the original object and stuck on another object, because in this case the pattern becomes visible, see Fig. 6.
Conservative estimations show that assembling the writing system by using commercially available parts, a production of about 50-100 tags/hour can be achieved.
The ENEA technology can be used alone or in conjunction with other anti-counterfeiting/tracing methods.
The level of security of our technology can be evaluated by the following standard criteria:
- very high cost to break;
- high probability to detect a clone;
- very low probability of false negatives;
- no privacy risks.

Concerning vulnerabilities, at the moment we are not able to find practical ways to fool the product authentication.
ENEA is presently looking for industrial companies and research partners interested in a joint scientific/engineering development, and/or license agreement, and/or testing new applications.

References

[1] http://www.oecd.org/industry/industryandglobalisation/2090589.pdf

[2] http://www.oecd.org/industry/industryandglobalisation/44088872.pdf

[3] http://www.adnkronos.com/IGN/News/Cronaca/Crisi-frena-larte-ma-corre-il-falso-sequestrati-40-mln-di-euro-in-6-mesi_313699008896.html

[4] Bollanti, S., Bonfigli, F., Burattini, E., Di Lazzaro, P., Flora, F., Grilli, A., Letardi, T., Lisi, N., Marinai, A., Mezi, L., Murra, D., Zheng, C.E., *"High efficiency, clean EUV plasma source at 10-30 nm, driven by a long pulsewidth excimer laser"*, Appl. Phys. B 76, 277-284 (2003).

[5] Bollanti, S., Di Lazzaro, P., Flora, F., Mezi, L., Murra, D., Torre, A., *"First results of high-resolution patterning by the ENEA laboratory-scale extreme ultraviolet projection lithography system"*, European Physics Letters 84 58003 p1-58003 p5 (2008).

[6] Di Lazzaro, P., Bollanti, S., Flora, F., Mezi, L., Murra, D., Torre, A., *"Excimer-laser-driven EUV plasma source for single-shot projection lithography"*, IEEE Transactions of Plasma Science 37, 475-480 (2009).

[7] See 2011 Activity Report. www.frascati.enea.it/UTAPRAD/labs/UTAPRAD/rapporto_attivita.pdf pp. 59-61.

[8] Baldacchini, G., Bonfigli, F., Flora, F., Montereali, R.M., Murra, D., Nichelatti, E., Faenov, A., Pikuz, T., *"High-contrast photoluminescent patterns in lithium fluoride crystals produced by soft X-rays from a laser-plasma source"*, Appl. Phys. Lett. 80, 4810-4812 (2002).

[9] Montereali, R.M., *"Point defects in thin insulating films of lithium fluoride for optical microsystems"*, in Handbook of Thin Film Materials, Nalwa, H.S., ed., Academic Press; Vol.3: Ferroelectric and Dielectric Thin Films, Ch.7, 399-431 (2002).

[10] *"Invisible writing method based on lithography of luminescent materials, relevant reading method and anti-counterfeiting marking system"* EP 09734435.2 – 1232 (2010). "Method for the detection of micrometric and sub-micrometric images obtained by means of ionizing radiations" IT 1.337.672 (2002).

[11] Di Lazzaro, P. Bollanti, S., Flora, F., Mezi, L., Murra, D., Torre, A., Bonfigli, F., Montereali, R.M., Vincenti, M.A.: *"Extreme ultraviolet marking system for anti-counterfeiting tags with adjustable security level"*, Proc. SPIE, in press (2012).