

Chapter 1

Preliminary Investigations, Condition Assessment, and Mapping of the Deterioration Patterns



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Abstract Although generally assumed as long-lasting and extremely stable materials, natural stones are subjected to complex and interconnected damaging actions over the prolonged exposure time usually associated with heritage sites. Therefore, evaluating and monitoring the state of conservation of the stone surfaces of the built heritage is integral to the design and management of appropriate and effective preservation strategies. This chapter provides a critical overview of different approaches for the condition assessments of the stone surfaces, by examining international standards, guidelines, and methodologies for the identification and mapping of the deterioration patterns. The application of theoretical frameworks to precisely describe and evaluate the actual complex field conditions requires multidisciplinary contributions and an appropriate and sustainable diagnostic support. Selected case studies are also presented to discuss objectives and challenges in applying condition assessment strategies to the long-term evaluation of past conservation treatments, to inform and design suitable conservation strategy for historic façades, and for the preservation of modern architecture.

Keywords Stone conservation · Conditions assessment · Materials mapping · Decay mapping · Damage atlases

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1.1 Introduction

Although stones can be considered one of the most stable materials used in structures and buildings since prehistoric times, it is well known that they are subjected to natural weathering and deterioration phenomena, potentially leading to dangerous, severe, and sometimes rapid consequences.

The deterioration of stones in buildings and heritage sites is a complex phenomenon that can be due to the interconnected action of physical, mechanical, chemical, and biological causes acting simultaneously and over prolonged periods of time. The deterioration effect is, therefore, the result of different synergic phenomena that concur to change the properties of the material, causing a worsening of its “state of conservation” [1]. Deterioration is largely due to natural causes, but after the mid-twentieth century it has been accelerated due to anthropogenic activity.

The level of deterioration is influenced by both the type of material and its intrinsic properties, especially physical, like porosity and pore size distribution, and chemical, like molecular and elemental composition, in addition to the characteristics of the environment, like microclimatic conditions and air quality. The interaction between material and environment determines the type and the kinetics of the deterioration. It is essential to underline how the anthropogenic contribution can change, and sometimes accelerate, the progress of the decay.

Concerning the general durability of stone materials, low-porosity magmatic and metamorphic rocks containing quartz and siliceous minerals are typically more resistant to weathering. In contrast, sedimentary and metamorphic rocks based on carbonate minerals (calcareous rocks, marbles, marls, and sandstones) of medium-high porosity are generally more susceptible to the natural and anthropic deterioration phenomena due to chemical reactions (such as hydrolysis, acid corrosion, and oxidation).

The stone deterioration mechanisms, according to the different reactivity of specific classes of lithotypes, have been elucidated in the literature from the last couple of decades with details and experimental studies [2].

The recession of the stone surfaces due to rain and wind erosion is a combined mechanical and chemical phenomenon activated by the exposure to rainfall. Water can display its ability as a chemical solvent or hydrolysis agent, according to the specific pH, and at the same time is a mechanical force in the runoff, producing the detachment of surface crystallites. This can be typically observed in many historic buildings in urban areas, where the stone’s decorative and architectural elements (columns and capitals, windows and frames, pinnacles and spires, and statues) most exposed to rainfall are subjected to intense erosion. The preservation of the historic fabric in such conditions is particularly challenging. Depending on the specific conservation approach within different cultural environments, the conservation intervention can be targeted towards demanding technical operations, as well as the replacement of the damaged elements with new ones, sometimes with different lithotypes, and relying on not adequate artistic/artisanal level.

Salt crystallization is a particularly dangerous deterioration mechanism that can lead to the disintegration of the microstructure of the stone material, producing patterns like crumbling, flaking, and powdering depending on the mineralogical and micro-structural characteristics of the stone. Even intrusive magmatic rocks, like granites (considered among the most stable stone materials), can indeed suffer from salt crystallization, and the formation of efflorescence and crypto-efflorescence. The crystallization pressure inside the network of small-sized pores can reach hundreds of atmospheres, and disrupt the crystal lattice. The source of salt compounds can be internal or external: they can be dissolved in the rising damp and diffuse into the masonries, derived from the different materials used in the construction, or from runoff and condensation in a polluted atmosphere.

Actually, the most important deteriorating agent is water (liquid, vapor, or ice) [2]. It can penetrate the microstructure of the stone, trigger surface mechanical erosion after rainfall, facilitate the diffusion and crystallization of salts inside the material, and crystallize as ice with increasing volume, resulting in disintegration in cold environments and in the presence of freeze-susceptible substrates. Water is a determinant for the chemical acid attack of pollutants, like CO_2 , SO_2 , and NO_x , and finally, it is the limiting factor for microorganism colonization and biofilm formation. Water is, therefore, the driving force of the most critical deteriorating phenomena of stones in built heritage. Very slow deterioration phenomena generally occur in dry microclimatic environments, where the main weathering processes are due to thermal excursions in different seasons, with consequent thermal dilation in anisotropic materials, and long-term aeolian erosion.

The kinetics of deterioration depends mainly on the micro-climatic conditions and level of pollution to which the stone material is exposed. The impact of pollution is particularly important in urban areas, where built heritage is most present, and depends on the type and concentration of pollutants [3]. The traditional pollutants, such as carbon and sulfur dioxide, have decreased since the mid-twentieth century, while other rising pollutants, including nitrogen oxides and particulate matter, are nowadays acting as catalysts for the formation of different sulfates that tend to accumulate on the sheltered surfaces [4]. Indeed, the concentrations of sulfates have increased two-fold in built heritage across London over the last 50 years, despite the continuous decrease of gaseous SO_2 in the atmosphere [3]. The same authors report a careful study of the impact of climate and pollution change in the urban environment of London [3], with the progressive build-up of atmospheric nitrogen oxides, describing the possible synergic effects according to different classes of lithotypes. The role of the formation and action of nitric acid (HNO_3) in heavy traffic urban areas was also thoroughly studied in Munich and Mainz, and the recession rate of Portland stone (limestone) has been calculated through the use of dose-response functions, referred to traffic hot-spots and urban background in those cities. The differences in limestone recession rate (micron/year) between hot-spots and the urban background are due to higher concentrations of NO_x and PM_{10} (i.e., suspended particulate matter with diameter equal to or smaller than 10 microns) at traffic-rich sites [4].

Concerning the possible impact of climate change on built heritage and particularly on the conservation of stones, in the last decade, many studies have described the possible consequences of changes in the environmental parameters and air pollution [5], especially in Europe, North America, and Australia. The European Union has promoted the publication of reports that focus on this issue. In particular, Bonazza et al. [6] prepared a reference document that collected the main research efforts to identify the possible impact, and to mitigate or manage the consequences on cultural heritage. The range of natural phenomena that are being altered because of the climate change is wide, but there is consensus on the most relevant factors concerning stone decay: changes in the rainfall regime; increased risk of flooding and enhanced soil moisture content; extreme weather events (winds, rainfall, and storms); temperature and relative humidity increase; and enhanced development of microorganisms and pests [5, 7].

In the northern European countries, for instance, the generally accepted scenario predicts shorter and milder winter seasons with increased precipitations spread across the year. Therefore, cultural heritage management will have to face new challenges in conservation [8]. The temperature increase is expected to be determinant and particularly intense in some areas (3–4 °C in arctic areas); the yearly rainfall is expected to increase by about 5–10%, and extreme rainfall events will be more diffused. The impact of increased rainwater and meltwater, together with shorter drying periods, will allow moisture and liquid water to persist longer inside the building materials [8]. This phenomenon will most likely create favorable conditions for biological growth, such as fungi, algae, and mosses.

Within the community of heritage scientists engaged in the conservation of non-renewable resources, it is rather clear that, in the near future, it will be necessary to implement a sustainable maintenance strategy for the adaptation and mitigation of damages, developing innovative methodologies, and best practices.

Firstly, the need for a multidisciplinary approach in the survey of heritage structures and surfaces, along with the assessment of their state of conservation is still not fulfilled. It requires the collaborative interaction of experts and professionals involved in maintenance projects to create truly multidisciplinary teams composed of site managers, architects, engineers, and heritage scientists, such as geologists, chemists, and conservators. Even if this could seem obvious, the actual presence of such teams in the current practice of built heritage study and conservation, unfortunately, is still very rare, despite the continuous progress in the knowledge and standardization of the process [9]. The management and fruition of non-renewable built heritage sites require a systematic effort based on continuous data collection through monitoring activities and diagnostic studies (Fig. 1.1).

Moreover, any reliable conservation and maintenance project should be based on a condition survey carried out by skilled professionals, supported by an appropriate diagnostic phase. In recent years the implementation of the Historic Building Information Modeling (HBIM) approach for the preservation and management of historic buildings showed a continuous, although slow, progression [10]. The efficacy of BIM tools applied to built resources is well acknowledged among the architects' community: it is a powerful method for sharing, storing, and re-using

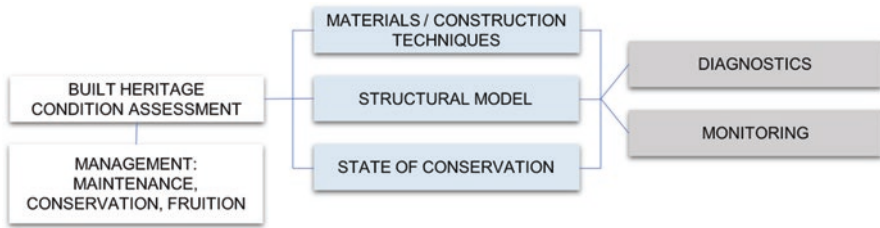


Fig. 1.1 Multidisciplinary approach for built heritage management

information acquired through archival analysis, damage survey, and diagnostic investigation. At the same time, the geometric survey of buildings or archaeological sites (the base for BIM implementation) is becoming more and more sustainable. It can now be achieved with great precision and detail, even in critical conditions, through a wide range of methodologies, including simple and inexpensive technologies [11, 12].

Finally, the conservation practice can rely on more than 30 years of experience and studies on heritage stone materials, including identification and characterization of the material properties, and the assessment of the conservation conditions. At European level, the specific Technical Committee CEN/TC 346/WG 3 – “Porous inorganic materials constituting cultural heritage”¹ is working to draft documents on criteria to select methods and/or products and operating/working conditions concerning the conservation/restoration, repair, maintenance, and preventive conservation work.

Many diagnostic and monitoring methodologies are available to characterize and investigate porous materials of the built heritage. Traditional and more sophisticated or innovative methods have been employed to characterize the materials, according to the relevance and value of the case study. The research on this topic is particularly fertile, although a gap still exists between the number of laboratory techniques available and the still rather limited portable and Non-Destructive Testing (NDT) methods for field application. Recently, a thorough literature review [13] reported a systematic analysis of the instrumental methods applied in the field of architectural heritage conservation, elucidating destructiveness, portability, and typical applications.

¹CEN/TC 346/WG 3 – Porous inorganic materials constituting cultural heritage https://standards.cen.eu/dyn/www/f?p=CENWEB:7:0:::FSP_ORG_ID:411505&cs=11466D45DFF63DD425BA5D9657E4415

1.2 Condition Assessment and Mapping of Deterioration

1.2.1 *Objectives of the Condition Assessment and Implications for Conservation*

Dealing with stone weathering at historic sites means dealing with complexity. The built heritage surfaces are characterized by the presence of heterogeneous materials, as for the typical compositions and the inherent composite-like nature of the historic masonries' fabric, exposed outdoor for considerably long periods of time. The environmental conditions they are subjected to, and interact with can significantly change over time. The equilibrium between materials and the environment will be modified accordingly, in a continuous process of adaptation. In many cases, change in the activities and human functions hosted in heritage structures, and the deleterious effects linked to periods of disuse and abandonment can also be important drivers of change for materials. Lastly, the actions conducted as part of the regular maintenance of historic sites and the sequence of conservation operations carried out on heritage materials play a crucial role. In particular, cleaning, consolidation, materials integration, and surface protection profoundly affect the overall conditions of a site and, most of the time, further alter the pre-existing equilibrium (or lack thereof, if active damaging mechanisms are at play).

These preliminary considerations have a twofold implication on the condition assessment survey. On the one hand, the materials of historical sites must be considered as complex and layered "palimpsests," for which the existing conditions at a given moment testify the cumulative stratification of changes occurred over time. The recording and interpretation of deterioration patterns, therefore, can improve the understanding of long-term deterioration mechanisms and effects of previous treatments, and ultimately allow for better conservation [14]. On the other hand, any condition assessment is bound to be representative of a specific period in time and, therefore, is necessary that it is updated and revised. This does not diminish the fundamental role of condition assessment in the framework of the conservation practice but, on the contrary, highlights its additional potential as a monitoring tool for tracking and recording changes over time.

As part of the preliminary phases of the conservation activity, the condition assessment of heritage surfaces is integral to the overall documentation process, aiming to increase the level of knowledge and understanding of historic structures (Fig. 1.2), according to the international recommendations and standards [9, 15]. Its primary objective is to accurately record the weathering effects through the alteration and deterioration patterns developed by exposed substrates. Although such effects result from the synergic action of multifactor deterioration mechanisms, the condition assessment focuses only on the observation and documentation of their physical evidence. The information gathered in this phase will, on the one hand, inform on the visible extent and nature of the damage and, therefore, guide the field- and lab-based diagnostic; on the other hand, it will contribute to the preliminary identification of potentially critical areas requiring treatment. It is worth noting that

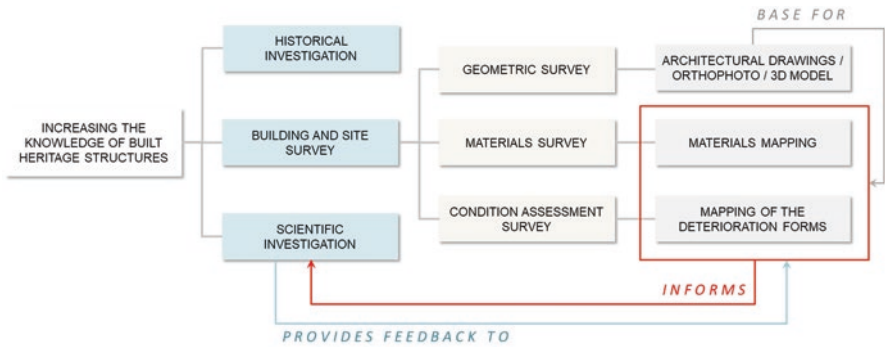


Fig. 1.2 Relationships and outputs (right column) of the condition assessment within the overall process aiming to increase the level of knowledge of the built heritage structures. (Elaborated from Ref. [18])

the precise characterization of the physicochemical deterioration processes belongs to the diagnostic investigation. The qualitative and quantitative data resulting from this further phase will eventually provide feedback to refine the initial interpretation of the damage, following an iterative process. Therefore, according to the medical analogy often employed in conservation studies [16, 17], the condition assessment can be associated with the *anamnesis* phase, as it exploits symptomatic descriptive recording to support the definition of an updated case history, and provides a contribution to reaching an accurate diagnosis [14].

The operative implementation of the condition assessment typically includes a preliminary phase of observation and documentation of the surface conditions onsite, followed by the interpretation and classification of the alteration and deterioration patterns, and a final phase of elaboration and visualization of the weathering effects. One of the most common final outputs of the assessment consists of thematic mappings designed to display all the relevant data on the location and spatial distribution of the different surface conditions documented. Such maps are particularly powerful tools for the broader interpretation of the weathering phenomena when integrated with the information on geometry, exposure, and orientation of the substrates – from the architectural survey – and on materials – from the materials mapping. The overall process, starting from the onsite identification of complex and often intertwined weathering effects, leading to their breaking down into a discreet number of deterioration forms that can be represented effectively on a map, requires a robust and consistent conceptual framework for deterioration classification based on detailed and unambiguous definitions of the physical patterns observed [19].

1.2.2 *Methodological Frameworks and Glossaries for the Classification of Deterioration*

The Italian Recommendation NorMaL 1/88 represents one of the earliest attempts at defining a shared glossary for the identification of alteration and deterioration patterns of stone materials [20]. The collaborative work between the Italian National Research Council and the former ICR – Institute for Conservation and Restoration (now ISCR) gave rise to a lexicon of 24 terms describing the most typical deterioration forms observed on natural stones, ceramics, and plasters. Each term is associated with a brief description of the main features to support the identification onsite and some representative pictures from real case studies. The list is ordered alphabetically, with neither systematic correlations between the different terms nor grouping according to possible common features. The effort towards a more standardized and operative methodological approach is also testified by the presence of graphic reference patterns associated with each term, to be used for consistent mapping operations. The suggested graphic coding for the thematic mapping theoretically allowed for a better comparison of conservation conditions recorded at different times or sites. On the other hand, such a system suffered from intrinsically limited flexibility that prevented the broad adaptation to the built heritage's highly heterogeneous stone substrates.

The systematic work conducted in the framework of the NorMaL commission, as well as the field experiences in the application of the lexicon, eventually converged into a national standard in 2006 (UNI EN 11182:2006) [21]. The new standard document inherits the overall structure and methodological approach of the former recommendation, as well as most of the terms describing the deterioration patterns. The updated list introduces an additional definition for biologically-induced damage, namely *biological colonization*, and a new term for *graffiti*. The photographic documentation is expanded and illustrates the occurrence of the deterioration patterns on stone, ceramic, plasters, and multi-material masonry surfaces. Still, relevant limitations remain and are related to the absence of logical correlation between weathering patterns according to similarities in the type of damage they cause (e.g., soiling and accumulation of exogeneous materials on the surfaces vs. features induced by loss of materials and/or elements). Consequently, navigating the list of terms is not always straightforward, as they are still ordered only alphabetically. Moreover, the practical usage of the lexicon as a working tool in the field requires a certain familiarity with the specific terminology and field experience. The terms are generally very concisely defined and not always unambiguous. For example, the distinction between *biological colonization*, which involves the visible presence of micro- and macro-organisms, and *biological patina*, which can be interpreted as a thin biofilm, is quite subtle and not entirely immune from a certain degree of subjectivity. Similar considerations apply to *erosion*, one of the main deterioration patterns that can be extensively observed in very different environmental conditions, which is defined as a general loss of material from a relatively sound substrate, irrespectively to the size and features of the detaching particles.

The pioneering work conducted by the “Natural stones and weathering” research group of the University of Aachen starting from the early 1990s provided a more systematic framework for the classification and mapping of weathering forms. The role of onsite observation, identification of the weathering patterns, and mapping is recognized once again as fundamental for the definition of appropriate conservation intervention, as well as for the correct interpretation of the damage mechanisms at play. The methodology is designed to record the weathering conditions according to an objective and consistent approach [22]. The identification of the weathering forms relies on a 4-level hierarchical scheme, corresponding to increasing levels of detail in the damage description: 4 groups of weathering forms (level I), defined with respect to the type of damage displayed by the stone substrate; 29 main weathering forms belonging to the different group (level II); 60 individual weathering forms to define precisely the specific deterioration pattern (level III); a final level (level IV) corresponding to damage categories, allowing to differentiate the type of damage, based on a qualitative scale of intensity ranging from very slight to very severe damage conditions. As weathering is recognized as the final result of a complex and multifactor interaction between the environmental and geo-lithological aspects, any genetically-oriented classification of stone decay is deemed inappropriate. Thus, weathering forms are categorized only according to geometric factors and phenomenological criteria [22]. The role of the documentation of the surface conditions in the overall identification and mapping process is emphasized. Also, the methodology suggests that an integrated assessment of the information on the weathering forms with the lithological mapping can provide insights into possible correlations between stone substrates and specific decay susceptibility.

This approach is developed further by introducing *damage indexes*, integrating the concept of damage quantification into the previously defined weathering categories [23]. Indexes are based on the quantitative evaluation of the damage extent, in terms of the amount of material loss, depth of the surface recession, thickness of detaching scales, etc., balanced against the scale of the building blocks or elements on which it occurs. Their actual applicability is therefore linked to the possibility of executing simple measurements on the exposed surfaces and on the detaching fragments onsite and, ultimately, to the site accessibility. The application of the indexes can potentially extend the capability of prioritizing needs for intervention through risk assessment, from the scale of building façades up to architectural complexes. The methodology has been applied and tested in several case studies to investigate the role of exposure and orientation on the weathering distribution, deterioration “zonation” effects, the differential susceptibility of heritage materials to weathering, and the durability and efficacy of conservation materials and treatments. Large-scale experimentations of the methodology have been conducted at significant monuments and archaeological sites, including ancient monuments in Petra in Jordan, and the Luxor and Karnak temples in Egypt [24, 25]. The translation of the weathering forms into damage indexes is highly site-specific and requires an expert approach, as well as collaborative multidisciplinary contributions. The overall procedure can be considered quite time-demanding, and this may have prevented a

more diffused percolation within the conservation professionals working on built heritage complexes and vernacular heritage.

The theoretical approach for investigating, identifying, and mapping the deterioration patterns of the research group of the University of Aachen resonates in the following research and international efforts towards the definition of standardized nomenclatures. In particular, the rationale for the classification criteria of the main weathering groups is reflected in the International Council on Monuments and Sites (ICOMOS) glossary.

In the early 2000s, the International Committee for Stone of ICOMOS (ISCS) stated that the absence of a clear and shared language in stone deterioration and conservation was a limiting factor for effective communication between practitioners and scientific experts, especially considering the inherently multidisciplinary nature of the research in the field. The group focused its activity on the deterioration patterns identification, with the underlying assumption being that a less ambiguous identification and description of the types of damage would also facilitate a broader comparison of conditions between the sites and support the investigation. Based on the examination and revision of existing glossaries and documents, the ISCS working group first published the Illustrated Glossary on Stone Deterioration Patterns in 2008 as a bilingual English/French document 26. Although the preface clearly states that the glossary “does not aim at replacing [pre-existing glossaries], often set up originally in a language other than English, and for most of them done to a high standard”, the impact of the document grew significantly over time making it a popular tool for the assessment of deterioration and supporting mapping operation. Besides the advantages resulting from a clearly structured conceptual framework and practice-oriented approach, the diffusion of the glossary has also been promoted by the number of international translations made available over time. Since its first publication, the document is currently published in ten bilingual translations (from English), including Arabic, Czech, Georgian, German, Japanese, Korean, Persian, Portuguese, and Spanish.

The glossary first clarifies a series of general terms associated with stone deterioration, which are often employed in the conservation field as interchangeable. Following the guidelines already reported in the UNI 11182 standard, a distinction is drawn between alteration, i.e., a modification that is not associated with an actual worsening of the material’s characteristics, and decay, which describes a chemical or physical change of the material’s characteristics to the detriment of its value or leading to an impairment of use. The concept of loss of value is also associated with weathering, which, differently from decay, is defined according to the processes – of different nature – responsible for the modification of the material’s properties upon environmental exposure. The perceived evidence of decay, i.e., the physical effects of weathering on the exposed materials, is identified as damage.

The list of deterioration patterns follows a 4-level hierarchical structure, corresponding to an increasing detail in the description of the specific phenomenon (Fig. 1.3). The broader and more general level is organized in families (level 1), which in turn contains the deterioration terms (level 2) with sub-types (level 3), and sometimes additional specific terms (level 4). Such a structure supports the operator

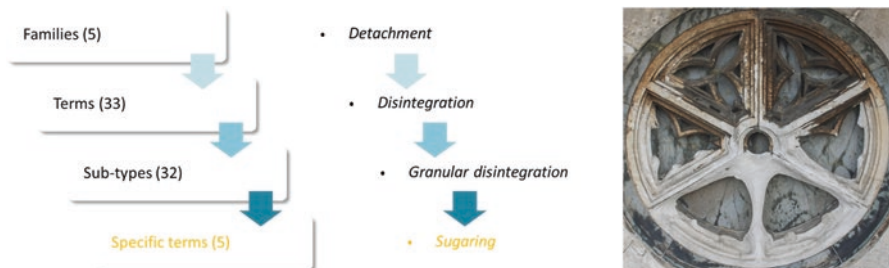


Fig. 1.3 The general structure of the glossary (left, in boxes) and example of one of the hierarchically-defined deterioration pattern identification for sugaring (middle) of a decorative marble element (right, Monza Cathedral, Italy). Specific term definitions (in yellow) are only present in a limited number of sub-types

in navigating the glossary following a logical workflow and allows for progressively in-depth classification of the type of deterioration.

The deterioration patterns are grouped into families according to the main characteristics that can be observed by the naked eye or experienced by limited and simple interactions with the surface (e.g., assessing the superficial cohesion by touching or tapping to detect loss of adhesion or areas of blistering). Therefore, the rationale for classification is entirely phenomenological, as the actual identification of the deterioration processes, as well as the quantitative assessment of the change in the material's properties, is left to the diagnostic. The five families include *crack and deformation*, *detachment*, *features induced by material loss*, *discoloration and deposit*, and *biological colonization*. Each family contains a brief definition of the related terms, describing the main features of the specific pattern to support its correct identification. For the same reason, the glossary points out possible relationships between some of the deterioration patterns and specific substrate's characteristics, such as the centimetric depth that *granular disintegration* can reach in marbles, or to the generally poor adhesion of *efflorescences* to the substrate. To limit the potential uncertainty associated with this task, a list of alternative terms from other glossaries referring to the same pattern follows the definition. Besides contributing to reducing any potential terminological uncertainty, this is a valuable set of information for establishing correlations between surveys executed with damage atlases and stone deterioration lexicons other than ICOMOS. The supporting photographic documentation for each term provides a visual description of the occurrence of the patterns on different substrates and in various exposure environments, using the scale of observation and level of detail to highlight the specific surface changes induced by the decay.

The *crack and deformation* family collects the corresponding deterioration patterns ranging in size and extension from major fractures – crossing entire stone elements – to hair-cracks of sub-millimetric thickness. The term *craquele* is specifically introduced to describe the characteristic presence of diffused networks of micro-cracks. This family also includes a general definition for *deformation*, which applies to a broad range of changes in the overall shape of a stone element (e.g., the

typical bowing of slender marble slabs subjected to prolonged thermal stress) in which the structural integrity is still not lost.

Detachment groups all the deterioration patterns associated with an ongoing process of loss of material, which generally involves a reduced mechanical resistance of the substrate. The definitions included in this family are particularly comprehensive and cover a wide range of deterioration patterns in terms of extent, size, and shape of the detaching materials. References are made to some lithological features of the substrate, which are linked to characteristic weathering forms. Such references, for example, clarify the distinction between *delamination* and *scaling*, the former being associated with the presence of oriented layers in some laminated stone, while the latter describes a type of detachment that is not stone-structure related. The glossary also emphasizes the existing connections between some damage mechanisms and the visible formation of specific patterns. Thus, the occurrence of air-filled, hemispherical, and sub-surface loss of adhesion, defined as *blistering*, points to the action of soluble salts. Similarly, the typical shape and location of the loss of material resulting from *bursting* are linked to the development of internal mechanical stresses. These notes included in the definition also inform on the continually evolving nature of weathering. Typically, the onsite progression of salt-induced *blistering* results in the development of cracks once the surface deformation gets close to – and ultimately overcomes – the substrate's flexural strength. A surface loss will then occur, either as *scaling*, *flaking*, or *delamination*, followed by the exposure of the internal material and, possibly, of the previously concealed salt crystallization. Regarding *bursting*, the glossary highlights that star-shaped face-fracturing formation could sometimes signal the early stage of the formation of this deterioration pattern.

The *features induced by material loss* family differs from the *detachment* one primarily because it describes changes in the substrate's morphological features that are not necessarily related to an ongoing process of loss of material. In such a way, it allows for the identification of a wide range of surface deteriorations even when the primary damage mechanisms are no longer active. This is particularly useful when dealing with substrates characterized by extensive voids, discontinuities (as in the case of *alveolization*), or increased roughness. All these changes are known to increase the potential for further development of additional patterns, including, but not limited to, *soiling* and *biological colonization*. Therefore, the precise identification of deterioration through this family can contribute to the early detection of critical areas where secondary damage development can be expected.

Discoloration and deposit contains terms describing the deterioration patterns due to the accumulation of deposit from exogenous sources (including soot, dust, and materials of anthropogenic origin), the aesthetic alterations, and the secondary formation of by-products triggered by the substrate reactivity in specific environmental conditions. The latter case is characteristic of *black crust* formation, included as a sub-type of the general term *crust*. The impact of this deterioration pattern on the fabric of carbonate substrates and its potential for damage has been extensively investigated by the scientific literature. Its worldwide occurrence in urban and highly-polluted sites still makes it a significant cause of loss of value for the built

heritage. The proper identification of *black crust* is therefore crucial, and the glossary provides additional details on the factors required for its activation and progression. Unfortunately, the definition is not entirely exempt from ambiguity, as it does not take into account neither the inherent layered structure of typical black crusts in polluted environments [19] nor the peculiar nature of the damage mechanism that involves a chemical alteration of the outermost substrate. This family also includes terms to describe the different types of *patina*, such as *oxalate patina*, which are defined as the result of natural and artificial alteration processes. The surface formation of soluble salts in the form of *efflorescences* is also listed among deposits. The glossary contains remarks about the crystallization process, as well as the different nature – and related solubility – of the most common salts found on architectural surfaces influencing their adhesion and permanence on the substrate.

All the effects resulting from the activity of living organisms are collected in the *biological colonization* family. This family expands the range of deterioration patterns from previous glossaries offering specific terms to describe precisely the different morphologies of subaerial biological formations. Areas of spot-like colonization or more extensive biological growths are covered with terms ranging from *alga* or *lichen*, up to the identification of actual vegetation, defined as *plant*. This accounts for the variable extent and impact of colonization, including the particularly highly damaging mechanical actions of growing roots within porous matrixes.

To highlight further the potential of the ICOMOS glossary, it is worth exploring in detail the term *erosion*, corresponding to one of the most common patterns affecting stone surfaces exposed outdoors and belonging to the *features induced by material loss* family. This pattern is defined quite broadly as the “*loss of original surface, leading to smoothed shapes.*” Such a definition clearly focuses on the ultimate effect on the stone substrate rather than on the mechanisms responsible for it. It can describe a range of macroscopically altered surface conditions as a result of natural or anthropogenic actions, as well as by the synergic effect of both of them. Depending on the nature of the substrate, geometric features, and surface finishing, this pattern can be observed either as a loss of material from border areas, edges, and sculpted details, as in the case of *rounding*, or as an increase of the surface irregularity resulting in *roughening*. The presence of these two sub-types allows for a detailed identification that takes into account some peculiar substrate characteristics. *Rounding* is typically associated with stone suffering from granular disintegration, whereas *roughening* is due to the removal of superficial grains or clusters of particles, and it is therefore emphasized in medium- to coarse-grained substrates. Examples of both subtypes are reported in Fig. 1.4.

The third sub-type within the *erosion* term is *differential erosion*. It describes deterioration patterns observed as a non-homogenous loss of material from the surface due to marked compositional or microstructural variability of the substrate. Therefore, *differential erosion* is typically encountered on sedimentary stones characterized by a layered or composite-like structure (e.g., conglomerates), and mineralogically heterogeneous volcanic stones. The additional sub-division into the



Fig. 1.4 Left, rounding along the edges of blocks of fine-grained Crevoladossola marble (dolomitic marble, Monza Cathedral, Italy) due to the erosive effect of water runoff. Right, roughening of the sculpted decorative element of Candoglia marble (medium- to coarse-grained calcitic marble, Milan Cathedral, Italy) due to the combined action of rain and thermal dilation

specific terms *loss of component* and *loss of matrix* is available for specifying which part of the stone is mostly affected by the weathering effect.

The ICOMOS glossary methodological framework has found vast application on real case studies of built heritage and conservation projects. The classification of the deterioration patterns according to this glossary has been integrated with the historical data, lithological mapping, and the geometric reconstruction of the building phases, as part of the investigation activity and prior to the conservation intervention [27–29]. The additional contribution of portable NDTs and field-based diagnostic has also been explored for characterizing the actual damage extent and monitoring its evolution over time, mostly in cases of deterioration patterns associated with depleted mechanical strength, crusts development, and biocolonization [29–31].

The potential limitations in the use of the glossary include the need for well-trained and experienced operators, as the reliable interpretation of the complexity of the weathering conditions onsite and their classification still represents a difficult task, and its time-demanding nature. Also, although the process of detailed identification of the deterioration patterns according to the ICOMOS framework can effectively inform the scientific investigation activity and, ultimately, support the understanding of the deterioration processes, its integration into the actual conservation practice can be challenging. Delgado Rodrigues [19] pointed out that the breaking-down of the surface conditions into individual mapping units, following the deterioration pattern definitions, may not be an efficient approach in practice, as it cannot be translated directly into specific sets of conservation actions. He proposed the introduction of a new methodology to support the conservation professionals and contractors, possibly complementary to the traditional deterioration mapping, based on the identification of surface units sharing common conservation needs, and therefore requiring a similar set of conservation operations. Sanmartin et al. [32] discuss some potential ambiguities in the use of the ICOMOS definitions when applied to less diffused and low-porous substrates, such as granites. The authors focus on the mismatches between some of the glossary definitions, namely

those belonging to the *discoloration and deposit* family, and the investigations conducted on real substrates with stratified covering layers. In conclusion, they suggest opening a discussion to revise and assess the opportunity of redefining some of the terms, to expand the applicability of the glossary to a broader range of materials and conditions.

Other researchers explored alternative approaches for concise and lower time-demanding identification and classification of decay. Thornbush and Viles [33] tested the use of close-range photography and digital image analysis to monitor temporal changes in the deterioration patterns of replaced stone blocks over a 5-year interval. Thornbush [34] later proposed a site-specific stone weathering classification system for limestone surfaces exploiting a high-resolution digital photographic survey. Such a system is meant to be more easily accessible to non-experts with respect to traditional glossaries. It applies to selected weathering forms ranging from the micro- to visible-scale that are classified according to a size-extent index. Inkpen and colleagues [35] proposed the integration of the data on the weathering forms acquired at a range of scales into a spatially referenced information system, as a complementary method to field surveys. They investigated the feasibility of the methodology by using high-resolution photography and historic series of photographic documentation for mapping the surface conditions and the relative change in the deterioration extent, according to a simplified classification scheme.

Recent contributions in the field have been targeting aspects related to the acquisition, visualization, and recognition phases of the weathering forms, exploiting the remarkable advancements of digital technologies. In particular, the potential for remote and rapid field-based recording and mapping of the surface conditions has been explored by close-range Unmanned Aerial Vehicle (UAV) photogrammetry [12] and the use of 360° cameras acquiring spherical images [36]. As the overall process for patterns recognition and classification still represents the most time-consuming phase of the condition assessment survey, innovative approaches have been proposed exploiting digitally-assisted damage detection of surface data from 3D models [37], and machine learning for supervised and fully automated recognition of specific weathering forms [38, 39].

Most of the glossaries and classification methods currently available are oriented towards the comprehensive coverage of the most diffused deterioration patterns, thus aiming for broad applicability in terms of types of substrates and surface conditions. It is worth noting that additional resources have been created to tackle specific conservation issues and damaging phenomena. The thematic glossary for the classification of salt-related damage developed in the framework of the Saltwiki online information structure [40] belongs to this group of resources. The bilingual English/German glossary comprises a list of terms and photographic descriptors of the different deterioration patterns associated with salt efflorescences, defined according to the crystallization features (size, shape, preferential location). Some additional terms are also provided to describe salt-related damage effects on building materials and wall paintings. The “European Illustrated Glossary of Conservation Terms for Wall Paintings and Architectural Surfaces” has been developed in the framework of the EwaGlos project [41]. This multilingual document – originally elaborated in

English with translations to ten European languages – addresses topics related to conditions assessment and provides a brief list of definitions of deterioration patterns focused on decorated surfaces.

1.3 Diagnostic Approaches to Assess the Deterioration of Stone Surfaces

The visual inspection and mapping of the state of conservation of stone surfaces should be complemented with the diagnostic investigation aimed to understand the major causes of decay and support the development of a sustainable conservation strategy.

The diagnostic investigation of the stone surfaces will have, therefore, the following aims:

- knowledge of details of constructive and decorative techniques;
- knowledge of the causes and mechanisms of deterioration;
- assessment of the level of damage;
- prioritization of the conservation actions; and
- identification and development of adequate methodologies for the intervention.

As reported in Fig. 1.5, the diagnostic approach [1] can be composed of three different levels of investigation: *in situ*, when the equipment can be used directly on the built surfaces in a non-invasive or micro-invasive way; in the laboratory, with equipment that requires samples from the stone surfaces; and “monitoring”, using non-invasive or micro-invasive equipment, generally *in situ*, for repeated sets of measurements at established time intervals.

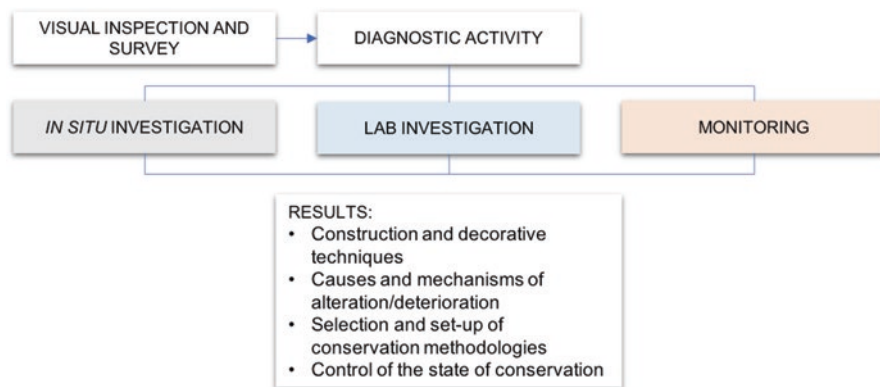


Fig. 1.5 Diagnostic approach for built heritage: three different levels of investigation can be exploited to study stone surfaces

For what concerns the study of the materials, of the details of surface decoration, of the surface stratigraphy due to specific anthropic interventions, etc., the best practice and the current literature indicate that a mix of *in situ* and *laboratory* investigation techniques should be applied to get a comprehensive and satisfactory understanding. In principle, acquiring information with non-destructive methods and avoiding sampling is highly desirable, but it is clear that onsite measurements are often affected by several constraints, including non-standard environmental conditions and surface anomalies, and deposits of extraneous materials. In actuality, physical, chemical, and mechanical characterization of the stone materials should be carried out in standard conditions, according to standard protocols and methods, in order to assess the properties of the material onsite, and sometimes it is necessary to perform a comparative evaluation with similar fresh materials.

A large variety of portable and laboratory investigation techniques are available for the characterization of materials and the study of their state of conservation. All the instrumental techniques have been transferred from materials science and analytical chemistry to the field of cultural heritage diagnostics. They can be differentiated by the technology, sensitivity, precision, and repeatability they offer. Therefore, to get an accurate and affordable diagnostic plan, it is necessary to utilise a variety of techniques, tailoring them to an analytical objective of achieving a sustainable and reliable result. The diagnostic plan is an important part of the survey of built heritage that should be carried out by expert researchers (heritage scientists) in collaboration with architects and heritage managers.

In Table 1.1, the most common instrumental techniques (non-invasive and invasive) are listed according to the materials' properties that they can explore and elucidate. Chemical and mineralogical characterization allows for assessing the composition of stones and materials of neo-formation due to the deterioration processes: the compositional features of the materials are particularly interesting when they are correlated with morphological changes at the visual or microscopic level [13]. Some of the traditional spectroscopic measurements that were previously only done on powdered samples can now be performed directly on the surface of interest (XRD, XRF, FTIR, Raman). Some of the spectroscopic techniques have been coupled with microscopy, and it is possible to localize compositional changes also at the micro and nano-scale (micro-FTIR and Raman, SEM-EDS). The study of neo-formation layers, like deposits, black crusts, and intentionally applied materials, and the knowledge of their origin and causes, is very important to set-up appropriate conservation measures or to design the cleaning strategy of the surfaces [42]. In the last decade, the progress in the application of these techniques allowed for new perspectives and enabled outstanding conservation work.

The development of imaging spectroscopic techniques (Laser-induced spectroscopies; UV-VIS Multispectral Imaging) has delivered a powerful tool to examine stones and decorative elements [43], particularly in the case of polychrome surfaces or remains of polychromies. Infrared thermography applications became a fundamental tool to examine masonries, assess discontinuity in the building structure, and evaluate the water sources and capillary rise inside the stone materials [44]. Numerous recent examples of applications deserve attention [45].

Table 1.1 Most common laboratory and portable instrumental techniques to characterize stone materials

| | Field based (portable instruments) | Laboratory based |
|--|--|--|
| Chemical characterization | | |
| Elemental composition | X-ray fluorescence (XRF); laser induced breakdown spectroscopy (LIBS) | Energy dispersive spectrometer (EDS); micro-XRF; atomic absorption spectroscopy (AAS); inductively coupled plasma atomic emission spectroscopy (ICP-AES); inductively coupled plasma mass spectrometry (ICP-MS); neutron activation analysis (NAA), LIBS |
| Molecular composition; functional groups | Fourier-transform infrared (FTIR) spectroscopy; Raman spectroscopy | UV-VIS spectroscopy; micro-FTIR; micro-Raman; FT-Raman; thermogravimetric analysis (TGA, DTA, DSC); chromatography (GC-MS, PyrGC-MS, HPLC, IC) |
| Physical characterization | | |
| Interaction with electromagnetic radiation – photography and imaging | IR, UV, VIS photography; UV-VIS reflectance spectroscopy; UV-VIS-NIR multi-spectral imaging; IR Thermography | |
| Microstructural characterization | | |
| Crystalline matrix and surface properties | Water absorption coefficient: “pipette” method at atm. pressure; contact sponge method; contact angle test | Mercury porosimetry; Brunauer-Emmett-Teller (BET) surface area determination; thermal dilatometry; surface roughness, profilometry; water absorption coefficient: capillary, total immersion, evaporation; contact angle |
| Mineralogical and petrographic characterization | | |
| Minerals composition and characteristics | X-ray Diffraction (portable XRD) | XRD; optical microscopy in VIS polarized light |
| Morphological characterization | | |
| Surface morphology and microstructure study | Digital microscopy; video-endoscopy | Stereomicroscopy; VIS-UV optical microscopy; confocal microscopy; scanning electron microscopy (SEM); transmission electron microscopy (TEM); atomic force microscopy (AFM); micro computed tomography (μ -CT) |
| Mechanical characterization | | |
| Mechanical properties, cohesion | Ultrasonic testing (portable); drilling resistance measurement (DRMS) | Laboratory mechanical testing: compressive, tensile, flexural strength |

Although methods for the characterization of the crystalline structure, pore size distribution, and mechanical properties provide critical information on the state of conservation of stones of the built heritage, they are used and applied less often. In

general, these testing methods require several samples of a given mass and geometry that rarely can be collected from a real case study and are, therefore, carried out on reference sound samples from the quarry.

These tests are used to assess the conservation methods (surface consolidants and protectives) in the framework of standardized testing procedures, but so far, only the application of DRMS is rather diffused and performed *in situ*, and it has found increasing application in the diagnostic of stone surfaces [29, 46, 47]. The test can be used in a comparative way, both to assess the state of conservation of a given surface, and to test the performance of treatments.

Finally, the field investigation of the morphology of stone surfaces at the microscopic level is gaining increasing popularity thanks to the diffusion of video-assisted microscopy and endoscopy that allows studying surface defects, discontinuity, layers, surface treatments and finishing directly onsite. At the same time, laboratory microscopy techniques underwent major development, particularly on digital acquisition and elaboration of images (SEM, TEM and μ -CT), and currently offer a large variety of tools for analyzing, measuring and mapping [48]. Environmental scanning electron microscopy (ESEM) technology for studying construction materials and stones has been extensively developed in the last decades, with particular attention to the interpretation of morphological features [49].

In any case, the diagnostic approach requires extensive experience in the specific field of application, in material science and in the instrumental tools. The diagnostic results, both to address the problem of deterioration and to select and assess the methods for conservation, should be carefully elaborated, and interpreted in the light of the data published in the literature.

1.4 Case Studies

1.4.1 *Conditions Assessment Survey as Part of Monitoring and Long-Term Assessment Strategies*

The foundation of The Ca' Granda complex in 1456 represents a significant event for the historical, urban, and social development of Milan (Italy), being the first example of a hospital specifically intended for the general population. The construction works spread across three centuries, and the original function of the complex changed over time. Starting from the late 1950s, it has hosted the *Universita' degli Studi di Milano* (University of Milan). The central courtyard's current design is due to Francesco Maria Richini and dates back to the seventeenth century. A continuous columned *portico* frames the four sides of the courtyard. Half-columns are alternated to decorated windows on the two lateral sides on the upper level, while the entrance and opposite ones are designed as an open *loggia* with columns that replicate the alignment and spacing at the ground level (Fig. 1.6a–b). A remarkable sculpted decoration enriches all the architectural elements, in striking contrast with

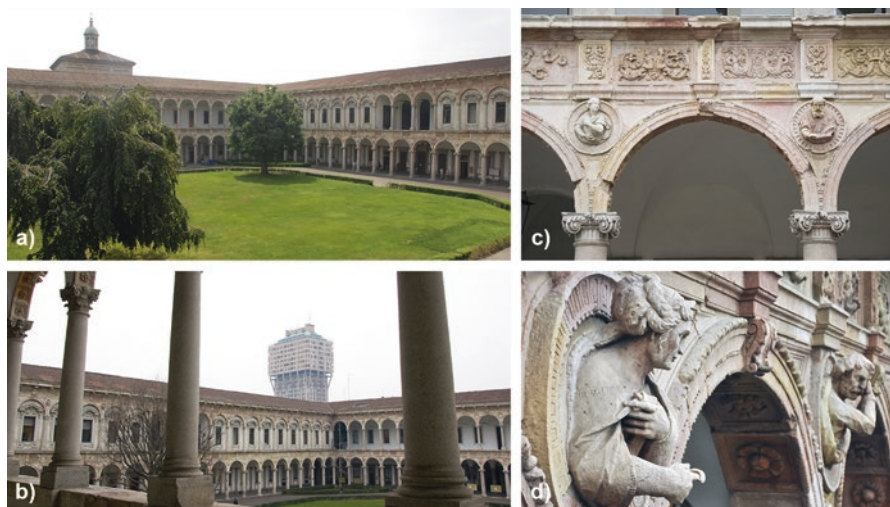


Fig. 1.6 General views of the courtyard showing the NW and NE-facing façades (a), and the NE and SE-facing ones (b) from the upper loggias; (c) the sculpted apparatus made of Angera stone decorating the lower level; (d) detail of the high-relief sculpted figures emerging from the spandrels

the sober volumes of the granitic columns. Floreal tiles cover the intrados of the arches, highly detailed bas-reliefs decorate the continuous parapet between the two levels, and high-reliefs with human figures emerge from the spandrels (Fig. 1.6c–d). Except for the columns and capitals, all the sculpted elements are made of *Angera stone*, a local dolostone with a typical color that varies, even within the same block or element, between white, yellow, and pink-orange hues [50]. The *Angera stone* is also a rather soft and porous lithotype, which makes it particularly suitable for sculpted and carved decoration. On the other hand, its characteristic microstructure and mineralogical composition are responsible for its generally low durability. The exposure to urban and highly polluted conditions, in particular, increases the stone reactivity, thus promoting erosive, corrosive, and sulfation processes [51].

The cumulative effects of the problematic conservation history of the site also added up to the intrinsic fragility of the decorative stone apparatus. The World War II bombing of Milan in 1943 caused extensive structural damage, with partial destruction and displacement of the stone elements. A challenging restoration intervention was performed in the aftermath, involving the partial rebuilding of the courtyard's structure and the reconstruction of the decoration by anastylosis. In the 90s, the critical state of conservation of the stone surfaces after decades of worsening of the air quality and increasing pollutant concentration called for a new conservation intervention. A comprehensive supporting diagnostic focused on materials characterization, identification of the deterioration mechanisms, and set-up and control of the conservation methodologies. The full integration of the scientific investigation within the overall conservation activity led to a model conservation project [52].

In 2010, after almost 20 years since the last intervention, a new project was designed with the aim of assessing the long-term performance of conservation methodologies and materials, providing an updated condition assessment of the stone surface, and investigating the new environmental threats. The working team included conservation scientists, chemists, physicists, geologists, biologists, architects, IT engineers, and art historians. The ultimate goal of such a multidisciplinary team was to define guidelines for the monitoring and preventive conservation of the courtyard, and to integrate them into an operative maintenance plan.

The entire courtyard was initially laser-scanned to create a 3D model, and the main architectural views (floor plans, cross-sections, and front views) were extracted. The project required an extremely high level of detail to track the changes in the surface conditions and investigate the weathering evolution. A comprehensive close-range photographic documentation was acquired for every single decorative element (bas-reliefs, arches voussoirs, keystones, and high-reliefs) on a pilot area on each side of the courtyard. The photo-rectified data were then assembled into a high-resolution and metrically correct orthophoto, which constituted the basic cartography for the subsequent operations.

The classification of the deterioration patterns followed the Italian national standard [21]. The type, location, and extent of the weathering forms were studied onsite during several surveys, and mapped on the orthophoto. The condition assessment survey pointed out that the weathering effects were strongly influenced by the overall orientation and local exposure conditions. The North-facing pilot areas generally showed the worst conservation conditions, being affected by diffused efflorescences and salt-related damage, scaling, and crust formation. The deterioration mapping confirmed the correlation between the local geometric features and the occurrence of weathering forms associated with the rain runoff and the accumulation of solid pollutants [51].

Consistent combinations of deterioration patterns were identified and mapped on surfaces directly exposed to the rain – mainly erosion, pitting, bleaching, and encrustation – which differed significantly from those observed on sheltered areas – mainly crust, deposit, disintegration, exfoliation and scaling (Fig. 1.7).

The condition survey was meant to provide the baseline data for future monitoring by non-expert personnel. Therefore, the mapping was integrated by a site-specific atlas of the deterioration forms, structured as a series of single-paged, two-sided working sheets for easy onsite consultation during the periodic surveys. For each deterioration pattern, the atlas provided the general standard definition, a description of the specific features characterizing their occurrence on the four sides of the courtyard, and explanatory notes for the identification, such as possible relationships with correlated damages.

An additional step to further streamline the monitoring process was implementing all the project data on a web-GIS platform specifically developed for built heritage applications [53]. The available historical data from the 1990–1993 intervention were also uploaded, including the deterioration mapping and the precise location of the different conservation treatments. The platform employed the orthophoto of the pilot areas as a spatially referenced base (a local positioning system was defined to



Fig. 1.7 Photographic documentation of characteristic deterioration patterns in sheltered conditions (a, crust; b, deposit; c, exfoliation) and in areas subjected to the rain runoff (d, erosion and encrustation; e, pitting; f, bleaching)

manage the x, z coordinates deriving from the use of a frontal view). The different sets of information were structured as single informative layers that could be selectively visualized (Fig. 1.8). A database section was also present to collect all the alphanumeric data, such as the historical and archival information, the diagnostic results, and the detailed photographic documentation.

There are several advantages in using such an approach. Tracking the evolution of the surface conditions before the previous intervention and after the prolonged exposure could be easily done by visually overlaying the related maps. This highlighted, for example, the presence of thick deposits and crusts on areas that suffered from massive black crust formation in the past, thus suggesting the permanence – and potentially still active role – of the related damage mechanisms. The same applies to the recurrent development of efflorescences and exfoliation issues in previously affected locations. Cross-referencing the data about the past intervention and the updated condition survey is an additional way to support the investigation of the treatments' durability and long term-effects. This sort of information is of great importance not only for the ex-post evaluation, but also when planning for future conservation actions.

As part of the overall preventive conservation and monitoring strategy, the combined application of the atlas and the web-GIS mapping was meant to offer a valuable option to manage and collect the results of the surveys in a time-effective manner. The results of the monitoring activity, as well as the maintenance operation, can be theoretically recorded in real-time using different electronic interfaces and uploaded to a remote server.

The main drawbacks of the platform – and similar systems later proposed – are linked to the use of proprietary software and the reliability of the storage servers. The potential risk of low flexibility and rapid obsolescence deriving from closed source codes cannot be ignored, especially if the actual percolation of the adopted

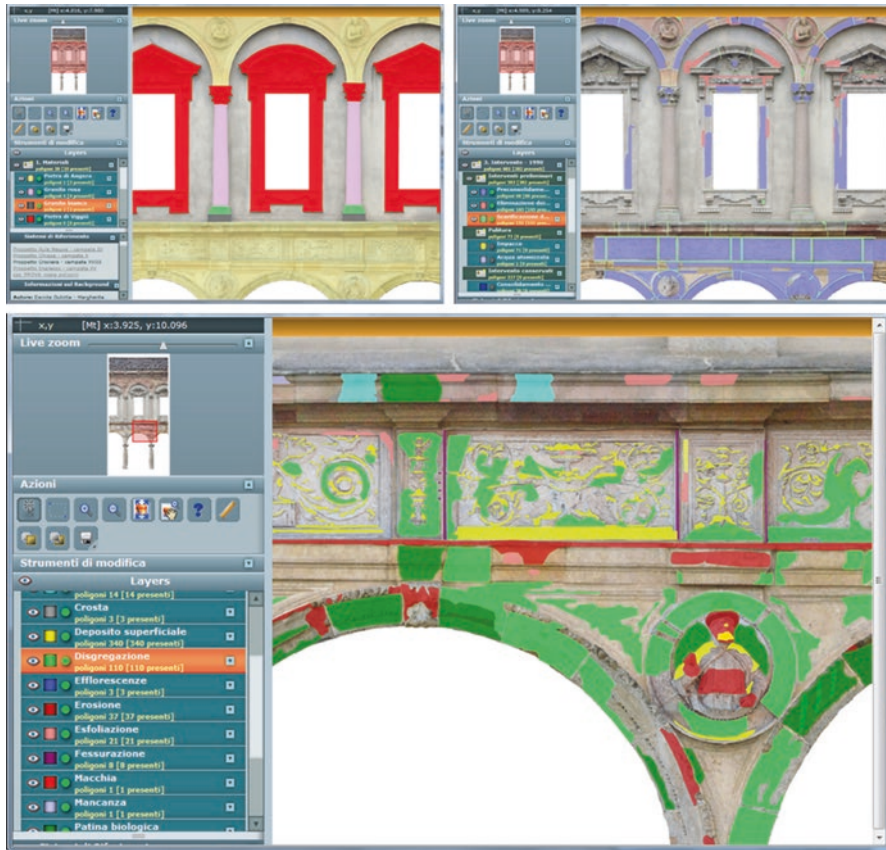


Fig. 1.8 Screenshot of the web-GIS platform for the management of the project’s information. Lithological mapping (top left), mapping of the 1990–1993 conservation intervention (top right), and 2010 mapping of the deterioration patterns (bottom). In each panel, the navigation tool and the content manager (controlling the visibility option of the informative layers) are displayed on the left side

systems in the community of conservation professionals is limited. The data management is an additional issue, considering the vast amount of information usually generated during the conservation, monitoring, and maintenance operations. While the uploading process is becoming of lesser concern, as the technological advancements are continually expanding the bandwidth and pushing the data transfer speed, robust and long-lasting data centers or cloud infrastructures are key to the safe storage of the data.

1.4.2 Condition Survey Informing the Overall Conservation Strategy of Historic Façades

The Monza cathedral is a renowned heritage site in Northern Italy, which dates back to the fourteenth century. The main façade was built during several construction phases, following the floor plan configuration changes until its completion in the early twentieth century [54]. The wide range of local stones employed for the architectural and decorative elements, as well as for the sculpted figures of the upper spires, is a unique feature of the site. The lithotypes include different types of marbles, calcitic sandstones, a dolostone, and serpentinites. The local microclimate and the severe pollution conditions characterizing the Padan plain – in particular the highly-developed area centered around Milan and encompassing the city of Monza – provided an extremely challenging environment for the stone materials of the façade. The remarkable materials heterogeneity has been a critical factor influencing the overall site management and the conservation operations, because of the differential response of the various substrates to the prolonged exposure and, consequently, their rather diverse decay evolution. As a result, the historical records report a series of restoration activities conducted starting from the seventeenth century in response to the rapidly evolving weathering of the most reactive substrates. Such activities have profoundly impacted the overall aesthetic configuration. For example, they included a substantial intervention of removal and substitution of the dark slabs of the cladding, made initially of a low-durable black limestone, with a dark-green serpentinite. The last documented intervention dates back to the 1980s, during which cleaning and consolidation targeted the central sector of the façade and the large rose-window.

In 2016, the highly critical state of conservation of the exposed stone substrates pointed out the urgent need for a new conservation intervention. One of the primary and most evident concerns was the extensive soiling of the cladding elements, which significantly impaired the original aesthetic contrast between dark and white-colored rows of blocks. A general loss of mechanical cohesion of several decorative and sculpted elements was also reported, which posed safety issues due to the risk of detachment and falling of stone fragments on the cathedral parvise.

The preliminary assessment was conducted using an aerial work platform, which allowed for the rapid exploration of the stone surfaces of the whole façade up to the spire level, located roughly 36 meters above ground level. The information acquired during this phase, supported by the photographic documentation, provided the baseline data for the first identification of the weathering effects, their location and relationship with the architectural surfaces, and the areas displaying particularly critical conditions (Fig. 1.9b–d).

The site constraints were also identified. These included the overall accessibility for the metric survey and the condition assessment, and the request to minimize the cost and impact of the scaffolding on the Cathedral visitation, at least during the preliminary investigation. The resulting conservation plan was designed and managed in phases: (i) historical investigation of the whole complex, identification of

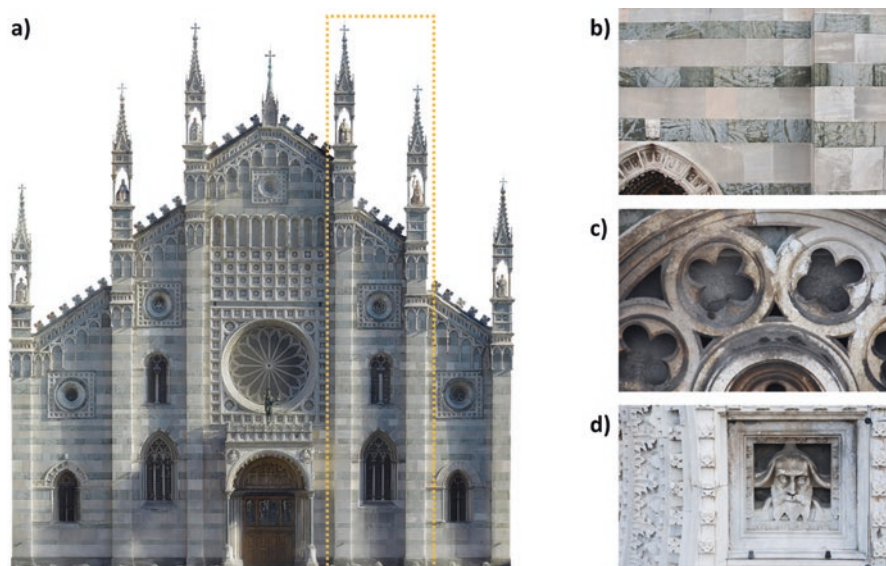


Fig. 1.9 (a) Orthophotographic documentation of the façade with the location of the pilot site area (yellow frame) and preliminary documentation of the weathering effects with aerial work platform: (b) diffused darkening of the stone cladding, (c) areas of crust formation, disintegration and loss of material, (d) detail of the intense soiling of the sculpted decorative elements framing the rose-window

the construction phases and past conservation interventions, and geometric survey of the façade; (ii) selection of a highly representative area (as for the various types of materials, geometrical features, exposure conditions, and weathering forms) for the implementation of a pilot site for materials' identification, deterioration patterns mapping, and set-up of the trial conservation methodologies; (iii) scale-up of the lithological mapping and condition assessment to the entire façade; (iv) revision and scale-up of the conservation methodologies to the entire façade (according to the corpus of information from phase iii), identification of the areas requiring specific sets of treatments, and cost estimation; (v) elaboration of the final conservation project [18].

Given the specific site requirements, the geometric survey followed a photogrammetric approach by UAV. The main architectural views were then derived from the orthophoto (Fig. 1.9a) and used as a highly-detailed cartographic base (up to 1:20 scale) for all the subsequent mapping operations. The pilot site area was established in the left sector of the façade, roughly 3.5 meters wide and encompassing the total height. In this area, a metal scaffolding was set-up for the documentation and onsite investigation. The close-range observation of the surfaces, supported by digital microscopy, allowed for the identification of the different lithotypes. Some recurrent correlations were found between materials' usage and architectural features. The dolomitic marble from *Crevaladossola* is consistently employed as slabs for the light-colored rows of the cladding, with some *Candoglia* marble elements (a

local calcitic, medium- to coarse-grained marble) occasionally used for replacements (Fig. 1.10). Similarly, the dark-colored rows are made of a single type of dark-green serpentinite (*Oira stone*). Additional correlations were also identified with the building evolution, such as the prevailing use of *Candoglia* marble for the spires and top decorative elements, which all belong to the latest construction phase. Such correlations proved extremely important during the scale-up of the lithological mapping from the pilot area to the whole site, providing an additional set of information to support, and confirm the photographic- and photogrammetric-based identification of the materials used at the scale of the façade.

The onsite condition assessment was firstly conducted in the pilot area and then extended to the whole surface exploiting the highly-detailed photogrammetric

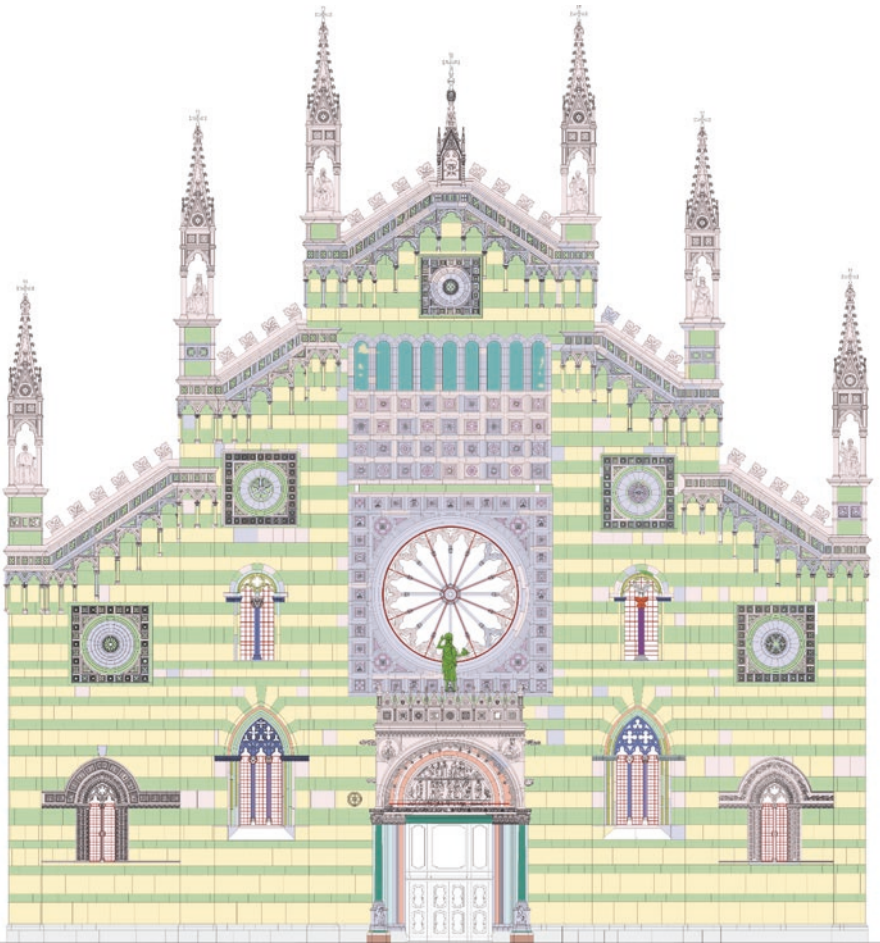


Fig. 1.10 Lithological mapping, showing the consistent usage of dolomitic marble and serpentinite for the cladding (yellow and green areas, respectively), and *Candoglia* marble for the spires and top elements (pink areas). Original scale 1:50

documentation. The standard Italian terminology was employed for the classification of the deterioration forms [21],² after naked-eye and microscopy observations. As expected, the type of exposure played a crucial role in the damage development. Crust formation and surface accumulation of deposits of different nature and variable degrees of adhesion to the substrate were diffused on the stone element in sheltered conditions. By contrast, erosion and all the patterns involving loss of material were generally observed in areas affected by rain runoff. The subsequent phase of mapping the deterioration patterns confirmed the strong location-dependency in the distribution and extent of the damage effects and provided preliminary input on the most likely weathering mechanisms at play. Extensive biocolonization and biofilm formation were concentrated on the top elements of the façade and the spires [55]. Such a preferential distribution is linked to the particularly favorable humidity conditions due to the direct exposure to the rain. The prolonged water runoff and the related chemical and mechanical erosive actions are also responsible for enhanced roughness of the substrate, which is a known factor further promoting biological growth.

The correct interpretation of what was initially labeled as soiling of the cladding proved challenging, as the survey clearly showed that its features did not entirely match the standard definition. According to the UNI-EN 11182:2006 standard [21], soiling consists of deposited material having exogenous origin (including dust, soot, and soil), variable thickness, and, generally, low adhesion to the substrate. On the contrary, the close observation of the surface indicated that the darkening effect was deeply embedded into the stone matrix. A reduction in the cohesion was also associated with the surface change, with loss of material as sanding, which was not consistent with a deposition phenomenon. The final classification was achieved through the integration of lithology, geometric data, and mapping of the weathering effects on the façade. The darkening was only concentrated on the white marble slabs, whereas the serpentinite ones were not affected. Its distribution was uneven, with increasing intensity towards the lower sector of the façade (Fig. 1.11). This pattern was ultimately defined as a discoloration, thus focusing on the main physical evidence of the weathering action, in association with erosion, where the loss of material and increase surface roughness was particularly noticeable. The damage mechanism involving inter- and intra-granular chemical corrosion of the stone matrix and soiling of the newly formed micro-cracks was later unveiled by the diagnostic investigation, which confirmed the role of the substrate mineralogy and rain-water percolation linked to the exposure conditions.

The thematic mappings were integral to the design of the final conservation plan and, in particular, informed the selection of the operative approaches and treatment procedures. The complexity of the overall condition assessment – laid out in the mapping of the weathering forms – required a clear graphic representation to become an effective working tool for conservators and contractors. To this end, the deterioration patterns were grouped according to their characteristic distribution on

²Here translated according to the most similar terms available in the ICOMOS glossary.



Fig. 1.11 Mapping of the deterioration patterns, showing the preferential distribution of the discoloration pattern on the with marble rows of the cladding (see Fig. 1.9 for reference) and its increasing extent towards the lower sector of the façade. Color key: discoloration, grey areas; erosion, orange areas; differential erosion, yellow areas; crack, purple areas; fracture, red lines. Original scale 1:50

the façade (localized vs. widespread patterns) and similarities in the set of conservation actions they required (e.g., stabilization > cleaning > consolidation; mechanical removal > biocide treatment > cleaning > surface protection). The condition survey was graphically represented at a 1:20 scale, breaking down the deterioration patterns information into four executive drawings: (i) disintegration, scaling, exfoliation, staining; (ii) discoloration, erosion, differential erosion, crack, fracture (Fig. 1.11); (iii) crust, black crust, efflorescence, patina, oxalate patina; (iv) biological colonization, deposit, soiling.

1.4.3 *Condition Assessment for the Preservation of Modern Architecture*

The “new” seat of the “Società Umanitaria” is located in downtown Milan and is an important complex of modern rationalist buildings by Giovanni Romano and Ignazio Gardella architects, built in the post-war years 1947–56, and published on “Casabella” in 1957 [56]. The complex is devoted to the educational aims of the homonym nonprofit organization, hosting a professional school composed of several buildings according to the different functions: classrooms, heavy and light laboratories, school of books, administration, and “convitto” (students’ dorms). In the same squared area, the “Società Umanitaria” is complemented by the Renaissance complex of the Church and Monastery of the Peace.

Recently, the conservation state of the building “Convitto”, which changed function in the last decade as the Milan Prosecutor’s offices, was carefully examined and assessed, aiming to set up a rehabilitation and conservation project of the outstanding architectural evidence, and recover its original function as students’ residence.

The visual examination methodology was transferred from traditional historical buildings to the modern concrete structure, including the use of the ICOMOS lexicon [26] for the identification of the weathering patterns of the reinforced concrete elements: the investigation of the deteriorated reinforced concrete pillars and the assessment of the extent of carbonation and corrosion phenomena were crucial to identify an effective conservation strategy [57, 58].

Concerning the construction materials, the building is based on a very simple reinforced concrete structure (Fig. 1.12), where vertical pillars and floor slabs emerge directly on the façade and have been exposed to the environment for more than 60 years.

These elements show a typical general erosion of the surface due to the rainfall, and diffused detachment and loss of material that can be defined “bursting” due to corrosion and expansion of the steel rebars inside the concrete [26]. In some areas, these lacunas have been integrated with cement mortar patching that looks different (Fig. 1.12, grey areas in the light yellow vertical pillars), and are quite diffused along the pillars, both in the east elevation and in the lower part of the west façade. These patch repairs (Fig. 1.13 shows a comparison of the original and integration concrete where the difference in the homogeneity of the two materials is clearly visible) demonstrate their failure with diffused new cracks, detachment and bursting (Fig. 1.14a); in many areas, the corroded rebar is exposed because of the spalling of the concrete covering due to the expansion of corrosion products (Fig. 1.14b).

Although the visual examination clearly points out that the concrete covering the rebar has been carbonated and the steel rebar is no longer passivated, the whole structure should be carefully examined through a comprehensive diagnostic procedure [57]. The diagnostic should at least include the measurement of the concrete coverings’ thickness, determination of the carbonation level, the possible presence of chlorides in the concrete, and the assessment of the rebar’s generalized corrosion.

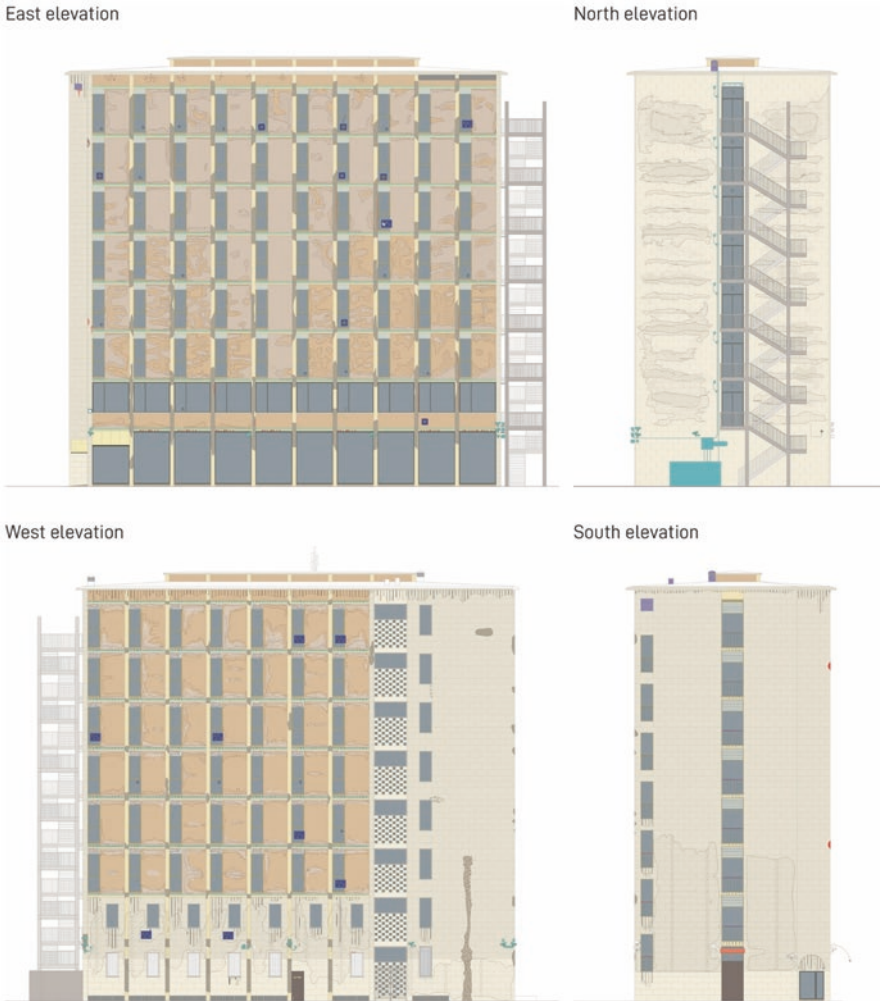


Fig. 1.12 “Convitto” by G. Romano, 1956. Mapping of materials and the deterioration patterns, original scale 1:100. Color key for materials: light yellow-reinforced concrete vertical pillars; light grey- “graniglia martellinata” hammered cement grit plaster; ochre-cement plaster with almond color silicate paint; green-copper water flashings; black and white-glass block. (Courtesy of Dr. Stefano Evangelista, MSc Thesis, Politecnico di Milano 2020)

The plastering of the façade has been carried out with two different materials and finishings that emphasize the partition of the building in the two distinctive volumes hosting the main functions, namely stairs, elevators and services, and students’ rooms (Fig. 1.12, the west elevation’s lower right part; left part with the windows). In the right part of the west elevation, and in the north and south elevations, the masonry is covered with a grey hammered cement grit plaster (*in italian* “graniglia martellinata”, as found in the original notes of the project by Romano). It is a sort

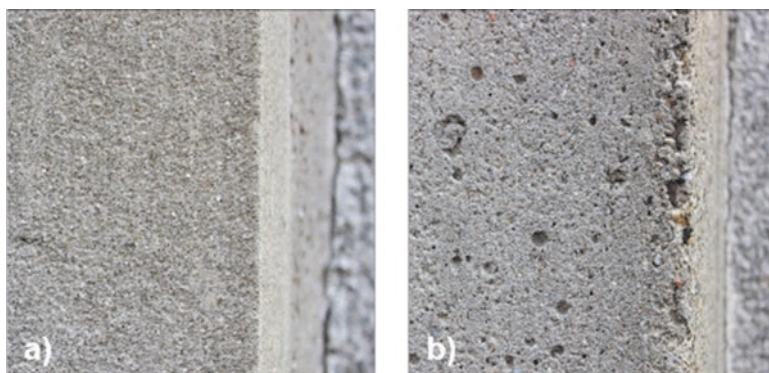


Fig. 1.13 New concrete repairs along the vertical pillars of the structure visible on the façade: comparison between the original compact concrete (a) and the new integration concrete (b)

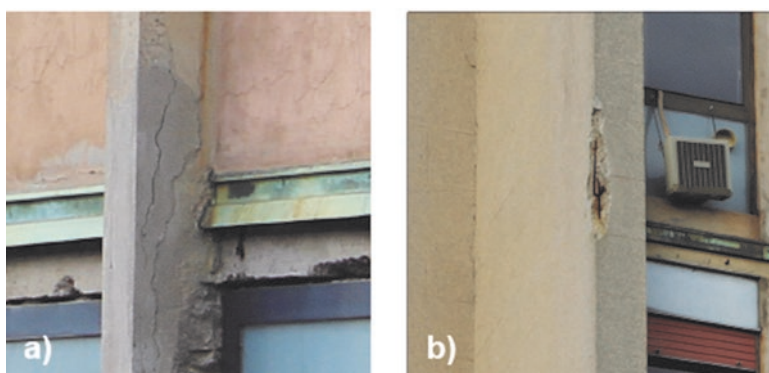


Fig. 1.14 Concrete integration patches along the vertical pillars with new formation cracks (a); areas along the pillars with exposed corroded steel rebar (b)

of artificial stone, a mortar mix using cement as the binder agent and mixed marble fragments as aggregate; the surface was hammered after hardening and smoothing, and underlined with incisions that simulate stone slabs. This surface is in a very good state of conservation and affected by minor alterations: deposit and soiling, mild surface erosion, formation of few micro-cracks, and both erosion and exfoliation of the paint layer applied, most likely, in recent times (Fig. 1.15). The application of this good quality plastering (resembling a stone cladding) proved to be very durable.

The plaster used for the rest of the façade of Convitto is a cement mortar decorated with an almond colored paint for the external render, which is most likely a silicate paint with an additional polymeric binder. Unsurprisingly, after such a long period without any maintenance work, this render is in a rather bad condition, with deep surface erosion of the paint layer, diffused detachments of the plaster and lacunas where the detached parts have fallen down. The characteristic copper flashings,

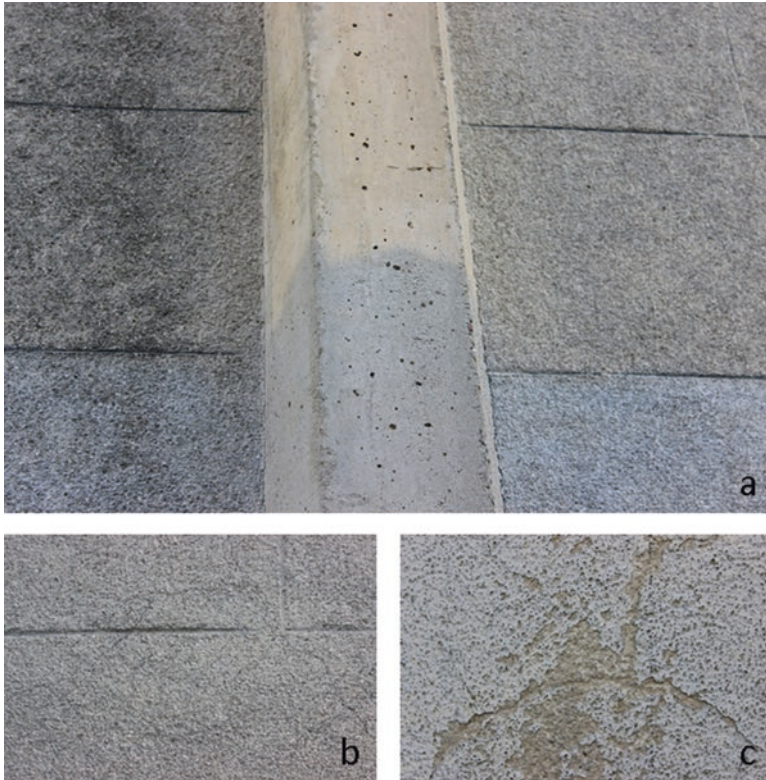


Fig. 1.15 “Graniglia martellinata”: (a) grey hammered cement grit plaster applied around the concrete pillar; (b) evident white marble clasts, intentional incision and a network of hair-cracks; (c) light grey painting layer over the plaster

that mark off the horizontal flooring, have been passivated with a copper-green sulfate patina, although sometimes they have been deteriorated by deep localized corrosion and are covered by a dark black crust.

1.5 Conclusions

Preliminary investigation, condition assessment, and mapping of the deterioration patterns are key to the overall process of understanding and documenting stone heritage sites. Moreover, the information gathered during these phases informs the design of the overall diagnostic and monitoring activity and, in turn, provides positive feedback to strengthen the identification and interpretation of the deterioration processes. As a result, the preliminary investigation becomes dramatically important to develop coherent and effective conservation of monuments and structures.

The knowledge phase can rely on a large corpus of scientific literature built up in decades of research that have extensively elucidated most of the deterioration causes and mechanisms affecting stone substrates. Nevertheless, as the globally-changing climatic scenario is expected to alter the established and known interactions between heritage stones and the environment, the conservation community will face new threats and unprecedented challenges.

The role of the condition assessment will be, once again, fundamental for tracking the physical impact and extent of such changes and monitoring the long-term response of heritage materials. The toolkit of equipment and methodologies available to heritage scientists and conservation professionals has improved significantly in the last years, particularly in regards to the resources for the geometric survey, data visualization, and production of 3D models. New experiences shared among heritage scientists call for a more consistent interdisciplinary dialogue and broader diffusion of the outputs to the extended conservation community. For example, in the framework of the European Community program Horizon 2020, many important projects have developed instruments and advanced technological solutions in close collaboration with conservation institutions and industrial partners. However, the research outputs and the related “good practices” still percolate very slowly to field practices, and the investment for successful innovation and growth is scarce.

The examined case studies have elucidated practical methodologies for the condition assessment of stones and artificial materials like mortars, plasters, and renders. The critical review of the standards and glossaries for the classification of the deterioration patterns has clarified advantages and possible limitations in using these powerful tools.

The research perspectives in this respect may unfold in several directions, including:

- exploring methodological approaches to increase the objectivity of damage identification and weathering quantification, possibly allowing for better cross-site exchange and comparison of the condition survey data;
- expanding the field-based toolkit to increase the potential of *in situ* investigation for condition assessment, and ultimately contributing to model deterioration phenomena based on more robust field datasets; and
- refining existing approaches and investigate innovative solutions (including AI-assisted, digital “twins” and DL-based options) to improve the condition assessment and monitoring sustainability.

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