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MULTIDISCIPLINARY PROCESS AIMED AT THE DIAGNOSIS AND TREATMENT OF DAMAGES IN STONY CULTURAL HERITAGE: THE BALUSTRADE OF VILLA CERAMI (CATANIA)

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ABSTRACT

This paper explains how an interdisciplinary study, examined and faced under different points of view (geologists, architects and restorers), can be very useful in planning and performing the apt conservation measures of a monument. As an example, the restoration case of Villa Cerami balustrade (Sicily, Catania) is reported here. This approach, applied preliminarily to the restoration, allowed identifying the materials, the type and the causes of degradation, as well as to plan and perform the necessary conservation measures. The study was planned in three steps: i) anamnesis-prediagnosis (historical analysis; geometric survey; 3D survey; analysis of degradation type; degradation maps; static verification); ii) diagnosis (investigation project and diagnostic analysis); iii) therapy (material restoration; swott analysis, intervention mode and architectural project to fill up the missing parts). Static verification was performed in order to choose whether to save or replace some of the most degraded balusters; during this step, the 3D survey allowed a more accurate assessment of the structural risk. The mineralogical composition and the petrographic features of the constituent materials were determined by X-ray diffraction and optical microscopy, respectively. In order to investigate possible changes in the stone material properties due to degradation, a physical characterization using the distribution of pore access size and pore volume was performed with mercury intrusion porosimeter (MIP). The material knowledge of its degradation state allowed to choose also the protective product by means of a compatibility test (UNI 10921:2001).

KEYWORDS: interdisciplinary, pathologies, material characterization, physical features, protective.

INTRODUCTION

In the field of monumental architecture, the choice of the right project for building restoration must be determined by several factors, such as historical studies, evaluation of the cultural instances, analysis of materials and construction tecniques.

The synergy beetwen experts coming from several disciplinary areas is the key to a complete and conscientious restoration; in particular, as far as interventions on materials are concerned, the cooperation between specific sectors (e.g., architectural, engineering, Earth Sciences) is needed (Boriani et al., 1997). Various applications on stone cultural heritage have been reported regarding petrography, mechanical properties, chemical composition, structural anlysis and conservation (Liritzis et al., 2015; Elyamani, 2018; Elhagrassy & Hakeem, 2018; Samanian et al., 2012; Sabatino et al., 2016).

By doing this interdisciplinarity, the correct strategies can be arranged in order to develop a common cognitive process and identify the rehabilitation therapies, with the aim to perform a restoration without neglecting any details. The common goal is to identify the constituent materials, respect their stratifications and detect any possible traces, even if disguised by weathering, so to program a correct intervention. A multidisciplinary evaluation and systematization of all collected data, represents the correct way for allowing the formulation of critical and creative considerations.

In particular, this paper represents an example of how an interdisciplinary study performed by geologists, architects and restorers may apply to a real case study – namely the restoration of the balaustrade of Villa Cerami, performed in 2015 and commissioned to the University of Catania. A similar method of study could be applied to other severely degraded architectural elements, in order to evaluate their residual cultural (aesthetic and material) and functional (degree of structural risk) content and, therefore, to decide whether to perform or not some project choices. The adopted scientific approach was applied primarily to the restoration and allowed to identify the materials, the type of degradation and the related causes, with the aim to plan and perform the conservation interventions.

The complexity of the restoration project requires a logical organisation of the available data. The critical judgement (Brandi, 1963) should be consciously guided not only by the scientific data, inferred by the preliminary investigations, but also by their systematisation and evaluation. Therefore, as in company policies for management and planning, even in the Cultural Heritage the methodological rigor of the assessment of opportunities and threats, as well as the strengths and weaknesses of all factors involved, could be of great use (Della Torre 2006).

The analized balustrade adorns and protects the steps of the Villa Cerami garden, which is a suggestive example of an 18th century ‘urban villa’, located in the centre of the Baroque Catania. Sadly enough, these stunning steps, whose magnificence and placement characterise the out-door environment of the building, at present suffer from bad degrading conditions, and the decorative details adorning the baluster are affected by irreversible damage.

The iter followed for the restoration project of the Villa Cerami balustrade was divided in three different steps, performed during different times and involving highly qualified professionals (as shown in Table 1).

Table 1. The steps of restoration project

STEP 1	STEP 2	STEP 3
ANAMNESIS - PREDIAGNOSIS	**DIAGNOSIS**	**TERAPY**
HISTORICAL ANALISIS	INVESTIGATION PROJECT	MATERIAL RESTORATION
GEOMETRIC RELIEF	ANALYSIS AND RESULTS	SWOTT ANALYSIS INTERVENTION MODE
ANALYSIS OF THE MATERIAL AND DECADY		ARCHITECTURAL PROJECT TO FILL UP THE LACUNA
DEGRADATION MAPS		
STATIC VERIFICATION		

Step 1 was already described detail in a previous paper by Sanfilippo et al. (2015); here, however, the main data were reported, in order to show the potentiality of such a scientific approach.

The collected results, listed in step 2, validated the hypotheses formulated in the pre-diagnostic phase; the interdisciplinary study was useful to identify the strengths and weaknesses of the damaged balaustrade and to assess the consequences of design choices with awareness. In fact, the results obtained from the performed surveys were applied for cleaning, plastering and consolidations strategies; the figurative solutions were evaluated, in addition to critical considerations, on the base of a swot analysis (Strengths Weaknesses Opportunities Threats) derived from the cognitive path and related with the cultural requirements related to lacunes intervention.

2. MATERIALS AND METHODS

2.1. *Materials*

For this study, three balusters (Fig. 1), affected by different weathering forms (biological colonization, black crust and granular disintegration), were selected (Sanfilippo et al., 2015). The sampling of the degraded material was performed according to the law (NORMAL 3/80, 1980), in order to identify the lithotype, the nature and the intensity of the main forms of degradation, the changes in the materials due to degradation and the operative strategies to be adopted for the restoration of the monument (Sanfilippo et al., 2015, pp. 79-83).

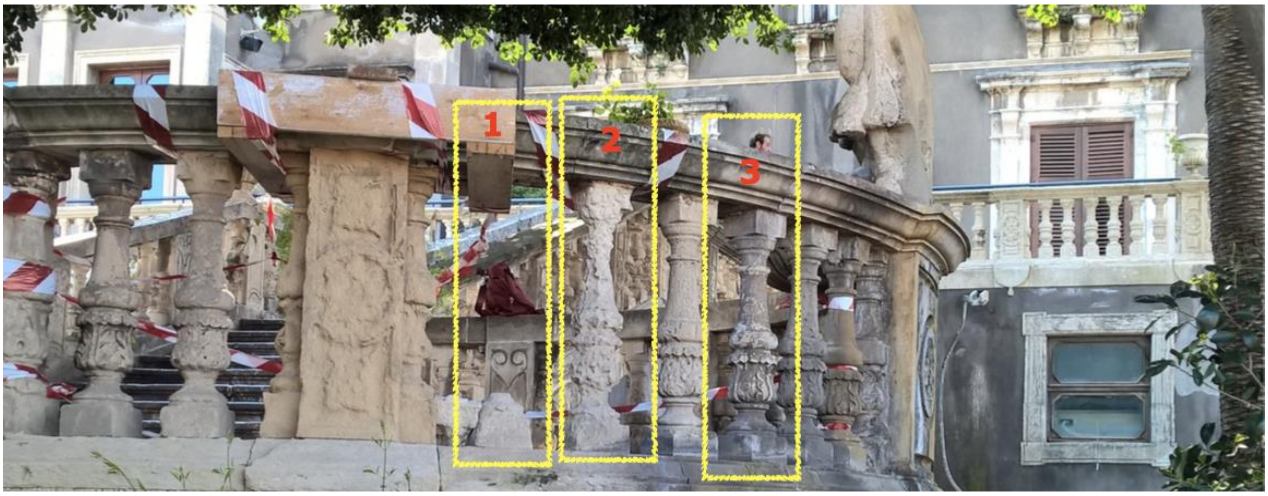

Figure 1. The three investigated balausters

2.2. *Methods*

The forms of decay were qualitatively and quantitatively evaluated using the widely used Italian norm UNI 11182, together with the Fitzner formalism (Fitzner et al., 2002, 2003; Fitzner, 2004).

The petrographic features of the materials were analyzed by using a Zeiss polarized optical microscope. Thin section analyses were carried out by optical microscopy (OM), using a polarized transmitted light microscope Nikon Eclipse E400POL.

The mineralogical composition was determined by means of X-ray diffraction, using a SIEMENS D5000 diffractometer, with Cu-kα radiation and Ni-filter. Randomly oriented powders were scanned from 2 to 45° 2θ degrees, with a 0.02° step size and a count time of 2 s per step. The tube current and the voltage were 30 mA and 40 kV, respectively.

SEM-EDS analyses were prformed by using a Tescan Vega LMU scanning electron microscope, coupled with an EDAX Neptune XM4-60 micro-analyzer, with an ultra-thin Be window. Data were collected with a 20-kV accelerating voltage and 0.2-nA beam current. Measurements were performed on the small chips drawn from the samples and attached to an aluminium stub with double-sided tape and coated in carbon.

Mercury intrusion porosimetric analyses were carried out with a Thermoquest Pascal 240 macropore unit, in order to explore a porosity range ~ 0.0074 μm < r < ~ 15 μm (pore radius), and by a Thermoquest Pascal 140 porosimeter instrument in order to investigate a porosity ranging from ~ 3.8 mm to 116 mm.

The equipment used for the 3D approach is the ToF laser scanner model HDS300 of Leica Geosystems belonging to the Laboratory RDA (Survey and Diagnostics for Architecture) of the Department of Civil Engineering and Architecture, University of Catania. The technical characteristics of the Laser Scanner are the following: Accuracy: position 6 mm, distance 4 mm; Scan rate: 4,000 point/sec; Field of view: 360°x270°; Range: 300 m; Spot size: from 0B50 m, 4 mm (FWHH based), 6 mm (Gaussian based); Laser class: 3R (IEC 60825B 1). The software used for the restitution is the following:

- Cyclone 6.0 (Leica Geosystem), for the phases of acquisition and alignment;
- CloudWorx (Leica Geosystem) and Autocad (Autodesk), for the processing in CAD environment;
- MeshLab (Visual Computing Lab, ISTI B CNR), used for the steps of cleaning, filtering, editing and rendering the mesh model, in order to calculate the volume and lateral surface of the studied balustrades.

Water absorption by capillarity and total immersion tests were performed, according to UNI 10859:2000, on 8 cubic samples (4x4x4 cm^3) before and after tratment with the protective product, stored in desiccators at 25°C for 24 h before application of the coating. The amount of applied product

(≈ 0.74 g) was calculated by weighing each sample before and after application. All samples underwent laboratory procedures to determine interactions between substrate and applied products and the hydrophobic properties of the protective product were tested. These tests included: i) capillary water absorption (UNI 10859:2000), to obtain capillary absorption curves and the relative absorption index (ICrel). The latter is defined as the ratio between the area under the capillary absorption curve of treated (Q_t) and untreated (Q_u) samples, calculated from the beginning (t_0) to the end (t_f) of the test; ii) mass of absorbed water by total immersion (NORMAL 7/81), in order to determine the absorption capacity. For the test of capillarity water absorption (UNI 10859:2000), dried samples were weighed and separately placed in vessels containing a pile of filter papers immersed in water up to half of their depth, with one face of the sample lying on the paper. Absorption occurred only through the base, by vertical suction. The containing vessels were sealed and kept constantly at 20 °C. At regular intervals, samples were extracted and weighed, after sponging with a damp cloth to eliminate excess water. For total immersion test (Normal 7/81), performed after the capillary test, dried samples were weighed and separately placed in vessels containing a pile of paper filters, totaly immersed in water, one face of the sample lying on the paper. Absorption occurred through all the faces. The containing vessels were sealed and kept at a constant 20°C temperature. At regular intervals, samples were extracted and weighed, after sponging with a damp cloth to eliminate excess water.

3. RESULTS AND DISCUSSION

3.1 Anamnesis and pre-diagnosis

The anamnesis and pre-diagnosis phases in the proposed cognitive process include: i) the historical study, by means of archival and historical research, aimed to acquire and evaluate the existing information about the studied monument; ii) the geometric survey, carried out with direct and instrumental methods (in particular, the method of 3D survey by means of a laser scanner, with the aim to obtain the dimensions of most degraded surfaces, the real amount of the lost material because of erosion, and information about the current granular disintegration); iii) analyses of building techniques (materials, problems concerning building issues, etc.), performed with macroscopic analyses; iv) analysis of damage, carried out by means of traditional and non-destructive surveys and mapping of damaged areas. In particular, the lithological nature and the weathering forms were defined based on the situ investigation, using respectively the comparison of materials, to identify the calcarenite varieties, and the Italian norm UNI 11182 along with the Fitzner formalism, to classify the degradation forms (Fitzner et al., 2002, 2003; Fitzner, 2004).

3.1.1 Geometric survey

The historical analysis and the study of the stylistic, geometric and proportional balustrade components allowed to define the different formal types existing in the staircase. The balusters were made with tender limestone; they consist of a succession of small columns, alternated by small pilasters decorated with flower motifs and engraved jars. Three different kinds of columns were identified, apparently identical, but showing typical forms and decorations (labelled ‘a’, ‘b’ and ‘c’ in Fig. 2). These three types of balusters are distributed along the stairs without a precise pattern, with only an element (‘b’) defining a common theme; these columns are located into the apse and they are likely to be remains of the original balusters. The identification of the degraded areas and the related casues have not been performed with traditional survey methods, because of the complexity of the eroded surface. A thorough understanding of the three-dimensional features of these elements were further complicated by the disgregating action of pathogens, which gradually transformed some of the balustrades into shapes not attributable to any Euclidean geometrical figure. For this reason, the geometric study was performed by means of a 3D laser scanner, which provided the volumetric data on the amount of degradation (Sanfilippo et al., 2015).

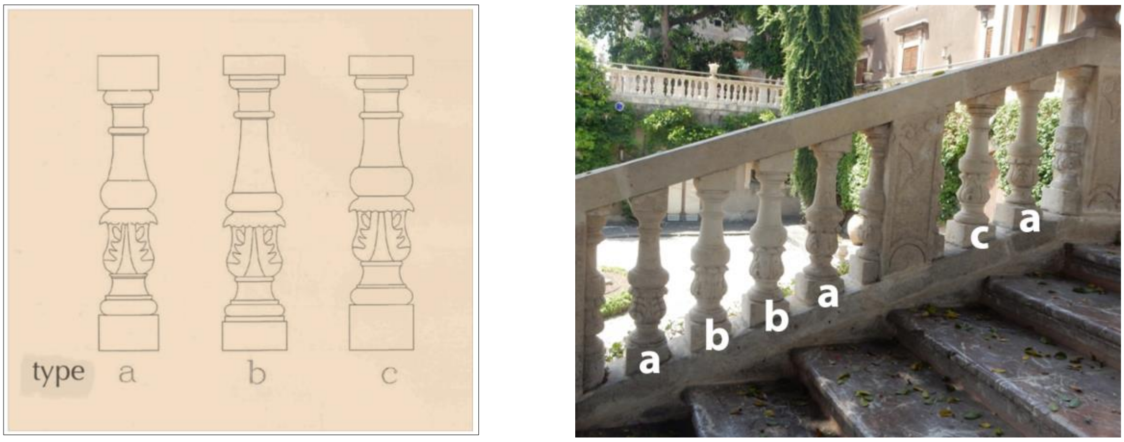

Figure 2. The three balausters typologies, labelled 'a', 'b' and 'c' (from Sanfilippo et al., 2015, modified)

A volumetric study was performed on the three selected balustrades. The collected spatial and material data were acquired with the aim of creating a 3D model, useful for the reconstruction and the geological survey. At Villa Cerami, we tested an integrated approach, involving two survey methods: i) 3D Laser Scanner, for the survey of the involved areas and volume determination about the erosion and loss of material; ii) 3D photo modelling, for the survey of the patinas and the black crust.
Baluster no. 3 was first selected to perform the surface survey on the biological patina and the black crust. The area affected by the black crust was calculated by using 3D photo modelling. Since the model contains the real colour textures, the yet non-degraded parts of the baluster have been lifted through physical elimination of mesh parts, with the software MashLab and the subsequent remaining area calculation.

3.1.2 Analysis of the material and decay

On the basis of the macroscopic observations, several materials have been recognized as those used to build the Villa Cerami balustrade, affected by different degradation forms. In particular, two main lithotypes were identified, which characterized the entire balauster: calcarenites of Carrubba Formation, probably used in the oldest balustrades and, more widely, calcarenites of Palazzolo Formation (Noto Stone). The limestone of Carrubba Formation is a whitish-gray oosparite, with "lumachella" levels from the iblean area and widely used in the historical buildings of Catania. These calcarenites have a low porosity and rare microcavities, filled with a spatic cement of secondary recrystallization. With regard to the limestone attributable to the Palazzolo Formation, namely ''Pietra di Noto'', it is a yellowish-white calcarenite that extensively outcrops in the Hyblean Plateau and was widely used as a building stone in the Baroque monuments of Catania. This formation was described by Rigo and Barbieri (1959) as a limestone and bioclastic limestone series, stacked in accordance with the marls of the Tellaro Formation. It is divided into two Members, Gaetanì and the Buscemi Members, which are the lower and the upper part of the Formation respectively (Di Grande et al., 1992). In particular, the Gaetanì Member consists of an alternation of marly and yellowish limestones, while the Buscemi Member, shows a different colour, which might be described as yellowish-grey. Other authors (Carbone et al., 1987) identified two different lithofacies within the Palazzolo Formation: "*fine-grained grey limestones and soft marly limestones alternating in layers of 20 – 40 cm; yellowish-white limestones outcropping in large bank levels*". The calcarenites of the Palazzolo Formation have high open porosity with small pores, causing circulation of rainwater and capillary water rise and favoring a widespread pulverisation. In fact, in this stone, loss of cohesion in the carbonate granules is frequent because of the chemical dissolution of the micritic portion (Sanfilippo et al., 2015). In particular, the three examined balausters are made with yellowish Pietra di Noto.

The macroscopic observations confirmed the hypothesis according to which Villa Cerami balausters were manufactured by the same workers who built the balustrade of the Benedictine monastery (Catania). In fact, both balusters show the same motifs and follow the same inter-axe fuse cadence (20 cm). Moreover, the elements characterising each baluster are almost identical. In one of the inner courtyards of the monastery, some remains of the original balusters were found. Thanks to an accurate compared analysis, coupled with a metric and photographic survey, we could understand how these architectural elements had been made. Both at the base and at the abacus of the baluster the stone is moulded to the central part, in order to ensure a link between the base and the handrail stone. They were then assembled by a male-female joining technique. There is also a correspondence between the lithotypes used in the Villa Cerami balustrade and those used by the Benedictines (Punturo et al., 2006). In particular, the lithotypes used in 'b' type balusters are the same as the Benedectine ones. It is therefore possible to state that the balustrades corresponding to the 'b' type belong to the original XVII century staircase and that probably, contrary to what the sources say, might have been made by the same author. Conversely, the 'a' and 'c' types are probably successive inserts that occurred after the date of construction, unfortunately not distinguishable from the original.

3.1.3 Damage and static verification

During the semiological phase, several degradation forms were examined and reported on both 2 and 3-D geometric survey. The main recognised pathologies were: i) presence of a black crust and ii) erosion. Material detachment and loss are instead concentrated on a few elements of the stair, such as the small pilaster on the left side of the first flight, the small columns of the balusters and the exedra at the level of the first half space. The extent and intensity of the decay are linked to the material features, exposure and shape of the balusters. For example, the deposit of polluting substances is cumulated in the areas that are not reached by atmospheric agents, i.e. below the overhang and inside the bas-survey. For a Baroque balustrade, the riskier zones are then the top of the small columns, protected by the upper overhang of the handrail stone, and especially, the inner parts of the central fountain elaborated engravings, the front sides of the small pilasters and their decoration jars. Villa Cerami is heavily exposed to an urban environment, rich in carbon monoxide and other polluting agents, especially exhaust fumes from local traffic. The decay becomes worse in the northern face of the building, due to the effect of the ascending humidity coming up from the roof garden, which has caused chromatic alteration of the stone material, spreading of vegetal micro-organisms and partial detachments over time. In particular, in the portion of balustrade on the first landing (exedra shaped and located under a big ficus), the part facing west appears more degraded. These degradation forms occur even on the investigated balaustrade, particularly intense where the large tree that frames the staircase. The biological aspect can be considered as a concurrent factor, aggravating the conditions favoring the action of other degradation agents.

In situ observations identified the main causes of wheathering as follows:

- circulation of aqueous solutions;
- crystallization of soluble salts, with consequent removal of materials;
- formation of crusts.

Two types of crusts were identified, characterized by a coerent brownish layer and by superficial brownish deposits, with different thickness and adhesion to the substrate. Those crusts located on the balustrade portion placed below the tree show higher thickness and tenacity, coupled to an increased adhesion to the substrate.

According to the Fitzner formalism, the weathering forms recognised in the balusters belong to the following classes: loss of stone material (group 1); discolouration/deposits (group 2); detachment (group 3); fissures deformation (group 4). The surfaces affected by black crusts were obtained by means of an image modelling technique. Data were used to calculate the damage indicated through equations proposed by Fitzner and the limit at break for crushing. Static verification was performed to choose whether to preserve or replace some of the more degraded balusters. In particular, the 3D survey allowed a more accurate assessment of the degree of structural risk. The total damage index, calculated by the Fitzner method, is very high for the third baluster, high for the second and moderate for the first one.

The structural function was monitored in the baluster portion that shows loss of material and shape. Laser scanner survey provided the volumetric data and the 3D image of the baluster, thus allowing to check whether the element might resist the compressive stresses due to its own weight and that of the above handrail. Once the resistant section (DD=12,63 cm^2) and the volume of the imposed elements (8.520cm^2) had been determined, the weight P and σ_{am} (23kg/12,63 = 1,82) were calculated. The result, despite serious reduction in the section (from 35,15 to 12,63cm^2), shows values quite lower than the minimum resistance to compression, in dry state, for the Palazzolo Formation limestone (Fig. 3; Sanfilippo et al., 2015 pp.88-90).

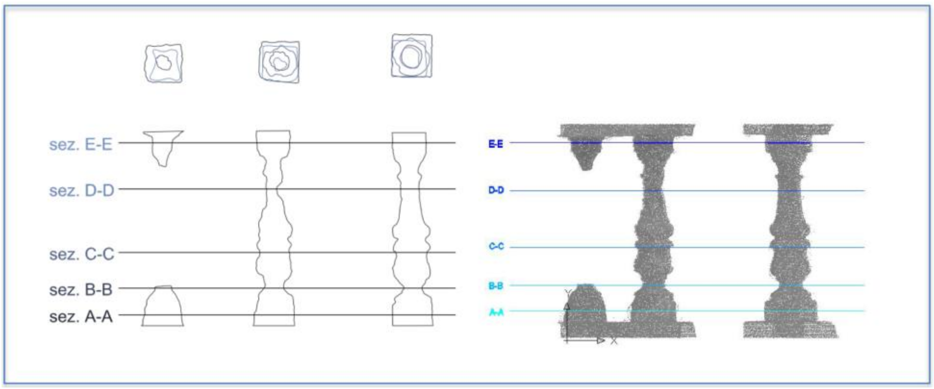

Figure 3. Scheme of sections and planes of balusters 1-2-3. (from Sanfilippo et al., 2015, modified).

3.2 *Diagnosis: investigation project aimed at evaluating protective materials for stone conservation*

To understand better the degradation causes of the most compromised balustrades, a diagnostic study of the building materials and their decay was requested by the 'Apsema' (the technical office of the University of Catania). In particular, the building materials from the investigated balustrade were studied with the following approaches: i) a petrographic, mineralogical and porosimetric characterization, in order to define their structure/texture, composition and physical properties; ii) a micro-morphological and chemical analysis of the black crusts; iii) an analysis of the conservation state. Furthermore, in order to verify the efficiency of the selected protective product and evaluate the interactions between protective and substrate, specific tests according to the UNI 10921: 2001 Cultural Heritage - Natural and artificial stone materials - Water repellent products - were performed. The porosimetric procedure was carried out to observe the porous structure of stones and a possible change due to degradation; their knowledge is fundamental for predicting the behavior of stones and the effectiveness of conservative treatments.

Figure 4. Black crusts sampling points.

Samples of black crusts show variable morphology, color and thickness, which probably depends on their exposure to rain, deposition time and textural features of the underlying substrate, this latter exhibiting a high degree of damage and extended exfoliation phenomena. Overall, the sampled damaged layers can be divided in two types, from which three samples were extracted (Fig. 4) as follows:

- samples C1 and C3 from the lateral portion of balustrade (sensitive to touch, about 1mm thick);
- sample C2 from below the tree (more tenacious to the touch, about 3 mm thick).

SEM-EDS measurements were performed to study these crusts, allowing to obtain information about their morphology and interaction with the substrate, as well as on their chemistry (major elements).

3.2.1 Optical microscopy

Such an approach allowed a detailed petrographic description of the limestone samples. These samples show a mud-supported texture, with about 70% mud. Allochemical components consist of various small bioclasts, including echinoids, foraminifera, bryozoa and plankton, extensively reworked by tubeworms represented by skolithos (Fig. 5). Sample porosity is about 30%. Pores are regular or irregular and show various sizes, ranging between 0.08 and 1.6 mm. According to these textural features, the stone can be classified as biomicrite (Folk RL., 1959), wackestone (Dunham RJ, 1962, p. 108-21), and calcarenite limestone, belonging to the Palazzolo Formation (Pietra di Noto, yellowish variety; Anania et. al, 2012).

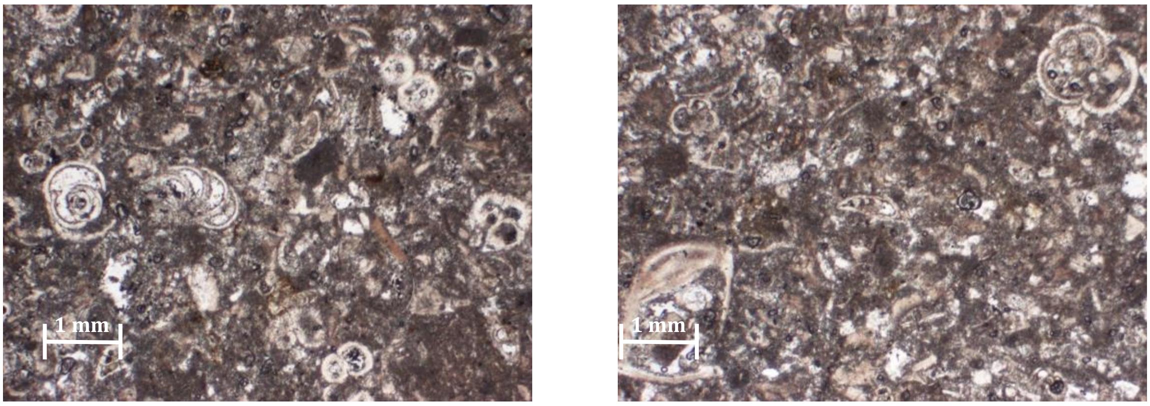

Figure 5. Photomicrograph (plane polars light; 10x) representative of the Noto Stone samples.

3.2.2 Mineralogical analysis

The mineralogical composition of the analysed samples is mainly represented by calcite. The non-carbonated fraction is apparently less than 5%, divided into sandy (quartz, K-feldspar, plagioclase, hematite and fluoroapatite) and silty-clayey phases (illite, kaolinite and smectite). The abundance of the silty-clay fraction is the only discriminating element between the two Noto Stone varieties: in fact, the yellow variety has a more abundant percentage of insoluble residue (~ 3.5%) than the white-cream (~ 2%; Anania et al., 2012).

3.2.3 Morphological and chemical analyses of the black crusts

SEM-EDS data were collected on three samples, selected as representative of the entire suite (C1, C2 and C3). This method allowed obtaining detailed information on the micro-morphology of the crusts and on the chemical composition of the damaged layers. These data confirmed that differences exist beetween the sampled black crusts. Specifically, as regards the crusts from the lateral balustrade portion, samples C1 and C3, show a matrix consisting of a mixture of lamellar and acicular crystals identified as Ca- and Na-sulphates; quartz crystals are incorporated into the gypsum matrix, as well as Fe and Ti oxides (Fig. 6). Quartz may have an eolic or residual origin; frequently, it can be found as an accessory mineral in carbonate rocks, concentrating on the surface as corrosive acids formed by pollutants cannot attack it. Ba-sulphate was also detected, probably a residue of past consolidation attempts, carried out using Ba-hydroxide.

For what concerns the crust sampled from below the tree (C2 sample), this exhibits the recrystallization calcites with a homogeneous matrix consisting of Na- and Ca-sulphates. In addition, the crust displays quartz crystals as well as Fe and Ti oxides, incorporated in the plaster matrix. It is worth noting the presence of carbonated carbon spherules, distributed homogeneously on the surface of the crust, probably due to recrystallization phenomena of calcium carbonate, previously dissolved and then recrystallized in different conditions. Black areas appear in this sample, showing different surface morphologies, shape and size (Fig. 7).

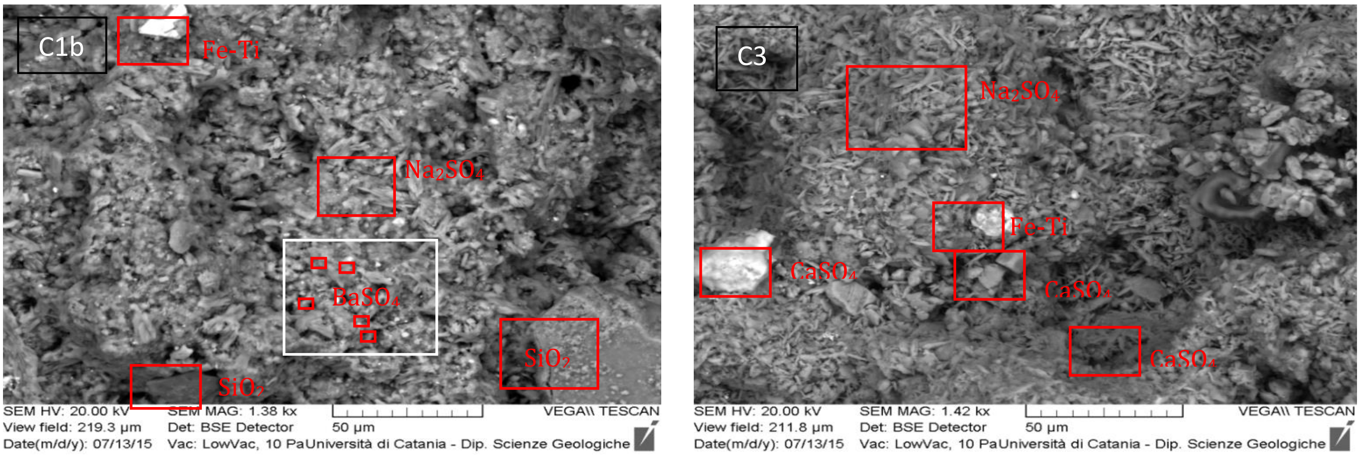

Figure 6. SEM-BSE (Back-scattered electron) images of the black crusts on the samples C1 and C3.

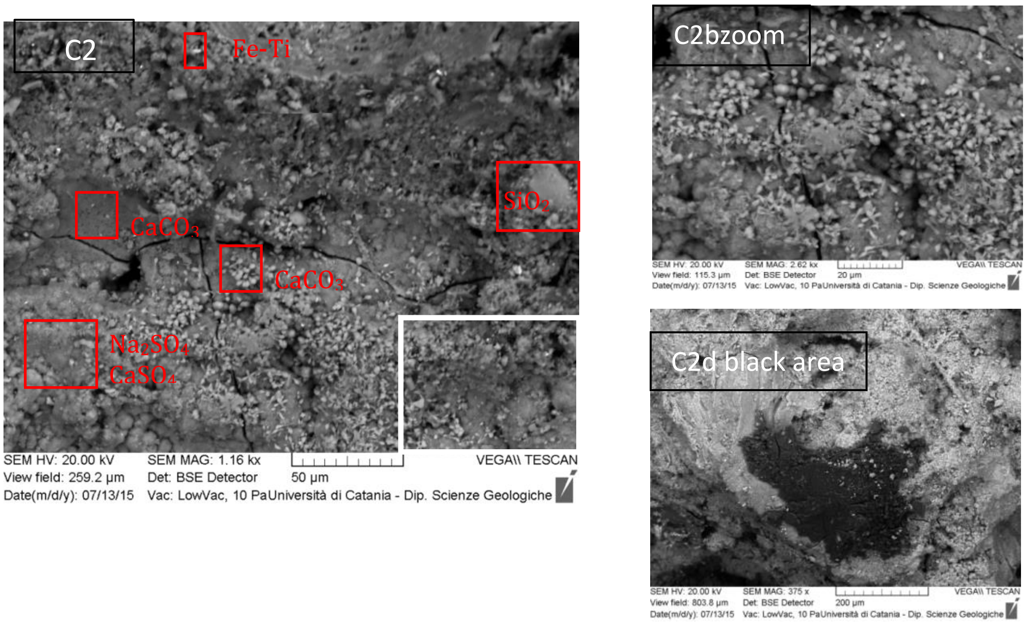

Figure 7. BSE-SEM (Back scattered electron) images of the black crust of the sample C2.

3.2.4. Mercury intrusion porosimetry

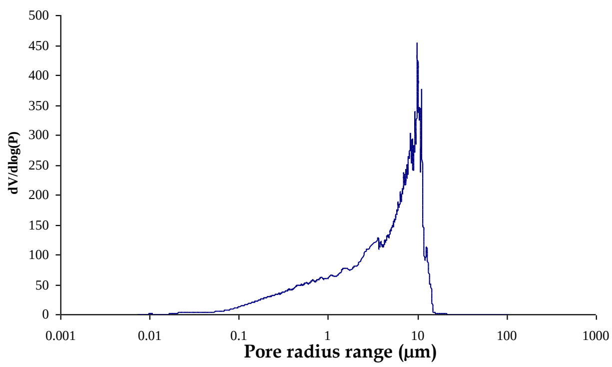

Figure 8. Porosimetric curve of the stone sample from the balustrade.

With the aim to investigate the physical properties of the balustrade stone material, resulting from the degradation process and specifically due to soluble salts, porosimetric analyzes were performed on a rock sample taken from the monument. The obtained results were compared with the literature data reported by Anania et al. (2012), concerning quarry samples (Cava Porcari, located in Villa Vella, Noto and Syracuse). These data show that the weathering processes determined a change in the porous structure as well as in physical and mechanical properties. All degrading agents are responsible of pores enlargement (modal radius ~ 5 µm), probably due to the crystallization of soluble salts within the rock (Fig. 8 and Table 2).

Table 2. Porosimeter data of a stone sample from the balustrade of the Noto Stone (cava Porcari) (Anania et al., 2012)

	Total cumulative volume (cc/g) *(cm³/g)*	**Total specific surface area** *(m²/g)*	**Apparent density** *(g/cm³)*	**Bulk density** *(g/cm³)*	**Average pore radius** *(μm)*	**Total porosity** *(%)*
Sample of balustrade stone	0.2	0.99	2.68	1.74	4.97	35.22
Noto Stone (Porcari quarry)	0.2	1.77	2.68	1.70	2.67	35.58

3.2.5 Efficiency and compatibility test of the water-repellent protector with the Noto Stone, yellow variety

The restoration intervention is aimed at decreasing the main causes of weathering (water circulation and pollution deposition) and consolidating the stone. For these reasons, the choice of the protective product was based on its hydro- repellent, bonding and pre-consolidating properties, which make it suitable for restoring the degraded Noto Stone. The tested product is a polymethylsiloxane reactive oligomer, which acts through evaporation of the solvent, polymerization reaction and adhesion to stone, eliminating small quantities of ethyl alcohol. The results are deep penetration, higher stability to ageing, capacity of not adversely affecting the aesthetic features of the lithotype, non-toxicity, water repellency and minimal permeability alteration. In order to verify the efficiency and compatibility with the substrate, water absorption tests for capillary and total immersion measurements were performed before and after treatment, in accordance with UNI 10921: 2001 (Table 3).

Table 3. Relative absorption index values (IC_{rel}) for untreated (NT) and treated (T) samples with the protective products.

	NT	**T**
IC	0,90	0,48
IC rel		0,54
CA*mg/cm²	22,71	15,66
CA*g/cm²	0,023	0,016

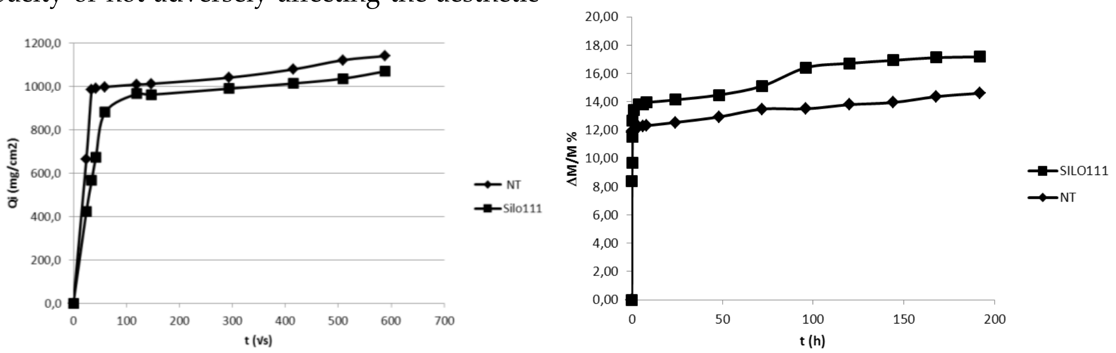

Figure 9. Graphics showing the average water absorption by capillarity of untreated and treated samples, after application of the protective.

The product was applied by brushing at ambient temperature and pressure. Such an operation was repeated three times, waiting about one hour between each application. Water absorption by capillarity and total immersion test are widely used methods for the characterisation of building materials, as they provide information about pore structure. The absorption curves, collected on eight cubic samples (side: 4 cm) before and after tratment with the protective product, are shown in Fig. 9, where the x and y axes represent the square root of time and the Q_i value, respectively. Q_i is the quantity of absorbed water per surface unit, expressed as: $Q_i = (m_t–m_0) /S$, where S is the area of the sample base, and mt and m0 are sample weights measured at times t and 0, respectively (UNI 10859:2000).

Capillary absorption tests resulted in a modest reduction of the related coefficient. With regard to the total immersion tests, a shorter time of absorption is observed in treated samples , whereas on a long period of time, an increase in the specimens ability to be imbibed is evident, probably due to a removal of the water-repellent protective after prolonged immersion in water.

3.3 Restoration

One of the main issues addressed in this restoration project is the lack of some balustrade elements, which may compromise the entirety of the valuable staircase.

In the material apparatus of the historical monument, the "structure and shape" are articulated in several aspects: aesthetic, based on its artistic expression; compositional; functional and static-structural (the shelves of the balconies, balustrades, columns, architraves etc. sustain other horizontal elements and live loads). The reintegration, in this case, becomes a "relative necessity" that is closely related to the role of the element.

The troublesome interpretation of the instances and the critical evaluation makes one wonder whether to keep the fragment (conservative intervention) or replace it. The reconstruction, using a similar but more durable stone material, should be done with simple geometries, with no carving and/or engraving, so as not to be confused with the original balusters. The pure conservation may represent an alternative solution, maintaining the deformated elements, without filling the lacunae. By doing this, the balustrade image, as a whole, would not be compromised but in time, the disintegration would gradually increase until this element collapses . This project aims to stop this degenerative process.

Table 4. The main feature of a restoration project.

OBJECTIVES OF THE RESTORATION PROJECT
1- AUTHENTICITY RESPECT
2- SAVE RESIDUAL MATERIAL
3- ENSURE A CORRECT UNDERSTAND OF CONTENTS
REQUIREMENTS: REVERSIBILITY

Table 5. Integration of the missing portions.

STRENGTHS	WEAKNESSES
Reintegration of the image with artificial stone	Further confusion in the philological reading of the staircase
OPPORTUNITIES	**THREATS**
Customer appreciation	Gradual loss of original material

Table 6. Conservation of matter with support structures (maintenance of the lack).

STRENGTHS	WEAKNESSES
Respecting of the original cultural content	Compromise formal values
OPPORTUNITIES	**THREATS**
- conservation of matter - reversibility - possible future measures	The solution can not be applied repeatedly in the same balustrade

In order to perfom a correct intervention, a systematically scientific approach was applied by means of the SWOT analysis (Strengths Weaknesses Opportunities Threats). This approach is a tool of business economics, now widespreadly used even for strategies tied to both the urban and territorial planning and the management of cultural heritage (archeological sites, museum networks, highly cultural contexts, etc (Sanfilippo et al., 2013). In particular, the SWOT analysis aims at showing the strengths and weaknesses in the case study, so to reveal those aspects favoring or hindering the goals of the project: respect for authenticity, resilience of residual constituent materials, correct use of formalities (perception 'the whole' prevailing over the gap). However, the intervention must be reversible, and so integrations should be completely removable with no (or only minimal) alteration of the original materials. Table 4 summarizes the objectives of the restoration project, while Tables 5 and 6 consider the possible solutions for replacing the missing portions and preserving the original materials, respectively.

Figure 10. Mirror plates, virtually reconstructing the aspect of the balustrades.

Finally, as an alternative further hypothesis, a virtual reconstruction of the missing balustrade could also be considered. In order to do this, two mirror-finished structural slabs could be inserted instead of the lack, with the aim to have a dual function: i) to structurally support the handrail above; *ii)* to visually reassemble the missing element. In fact, the mirror plates, if arranged at a specific angle, would virtually reconstruct the aspect of the balustrades alongside (Fig. 10 and Table 7).

Table 7. Reconstruction of the image by introducing contemporary elements (reflective structural slabs).

STRENGTHS	WEAKNESSES
- image reintegration - authenticity - Adding cultural values of contemporaneity	-No match between image and function - creative protagonism
OPPORTUNITIES	**THREATS**
reversibility	-

Table 8. Interventions on the building materials.

RESTORATION			
BIOLOGICAL PATINE DISINFECTION	**CLEANING OPERATION**	**CONSOLIDATION**	**PROTECTION**
BIOCIDE SOLUTION APPLIED BY BRUSH	WATER SPRAY	ETHYL SILICATE	POLYMETHYLSILOXANE REACTIVE OLIGOMER
	AMMONI CARBONATE IMPACKS	PUTTING WITH MORTAR OF HIDRAULIC LIME AND STONE AGGREGATES	
	CONTROLLED PRESSURE MICRO-SABBIATURE		

The data obtained in the steps 1 and 2 (see Table 1) allowed to plan the different kinds of restoration interventions (Table 8). In the following paragraphs, a detailed description of the global intervention is reported.

3.3.1 *Cleaning*

For what concerns the "intact" balusters, characterised by no longer perceptible carvings and colour (because of the layer of pathogenic substances), the intervention can only be conservative.

The cleaning operation should also be aimed at the legibility of the sculptural relief; therefore black crusts and biodeteriogens must be removed from the stone surface, also because of their damage to the limestone. The natural patina has instead to be identified and maintained.

In the first step, a general cleaning with water spray was carried out; biocide brushes were also applied to the parts affected by biological patina. On the balustrades compromised by black crusts, a compress made of paper pulp and a solution consisting of demineralized water, EDTA, ammonium bicarbonate and sodium bicarbonate was tested on a selected test site (Fig. 11). The solution was tested at several concentrations and in different time steps, i.e., each solution was applied for 1, 2, 4 and 6 hours. However, the wrap did not allow to remove the incrustations.

Figure 11. Cleaning operation with wrap and micro-blasting.

According to the SEM analyses, the thickness of the crust is about 2 mm and consists of recrystallised calcite associated with a homogeneous matrix formed by Na and Ca sulphates, highly resistant to detachement. For this reason, we opted for a variable-pressure micro-blasting with 2-4 atm, at the basis of the crust (Fig. 11). The employed abrasive product was GARNET 200 MESH, having a hardness lower than that of the predominant lithotype (Gasparoli et al, 2002) but slighltly higher than the black crust.

3.3.2 *Consolidations and plastering*

Figure 12. Treatment with micro steel bars and fillings.

The porosimetric analyses show that the stone does not show substantial changes, if compared to its original condition. Therefore, it was sufficient to intervene with cyclical applications of ethyl silicate by means of a brush, until reaching the healthy nucleus.

However, as described before, the surface layer had been severely compromised by the effect of the black crusts. Consequently, some balustrades lost cohesion not only superficially, but also due to alveolization (with loss of a large amount of material). By excluding the hypothesis of replacing the degraded columns with new ones, it was necessary to intervene with fillings, in order to replenish those cavities excavated by the deterioration agents. The mortar used for the partial reconfiguration of the stone surfaces was made of natural marble powders, (60% aggregate), with a binder made of white caolins and limestones mixed with baking powders with white powders (25%) and water (15%).The application of the dough was carried out using metal spatulas, leaving an undercut with respect to the edges of the alveoli of the stone (Fig. 12).

3.3.3 *Protection*

The protection treatments should have the following requirements: i) minimum influence on the optical properties of materials; ii) stability to chemical pollutants and radiation; iii) water resistance, iv) vapor permeability and v) reversibility. The obtained results and the compatibility tests performed by following the UNI 10921: 2001, established that a good aesthetic compatibility has been achieved between the protective and the lithotype, which determines no color variations in the samples after treatment and a reduction of water absorption. For this reason, at the end of the restoration intervention, the tested product was repeatedly applied with a brush on the stone until rejection.

4. CONCLUSION

The damage and deterioration of the historical buildings, due to their prevalently outdoor location, is one of the serious problems that attracts the researchers and conservators efforts from all over the world.

The variability of the rock lithologies used in historical buildings is quite rich, depending on the specific cultural context as well as by local availabilities. However, the choice of the stony materials might also also be influenced by functional roles, such as their structural efficiency and resistance (Musso, 1997).

Therefore, as far as the structural architectural components are concerned (as in the case reported here), the design choices might also depend on both aesthetic and technical-scientific variables, which can be identified only through a multidisciplinary methodological process.

The operative choices necessary to the project development originates from a strictly scientific process, logically organized, in which each element is analyzed both singularly and in relationship to the others. In the studied case, the obtained results were based upon a previous fundamental knowledge of the history, materials and related degradation. Such a knowledge produced solutions that allowed an integrated merging of all the previously evaluated and analysed opportunities.

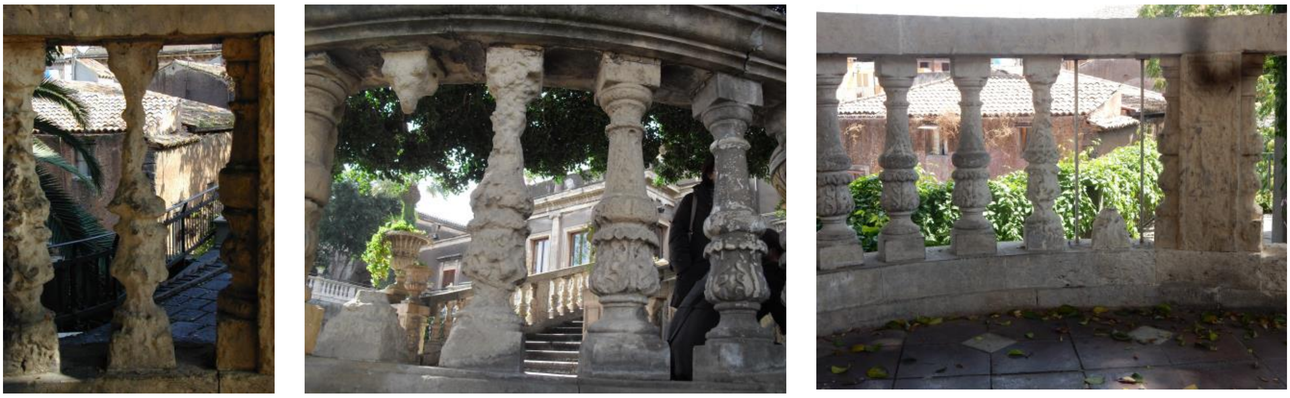

Figure 13. Three stages of decay: on the left photo of 2001; in the centre, the baluster without spindle (February 2015) and on the right, a minimal intervention was chosen, inserting sheets of stainless steel supporting the handrail.

The application of the methodology and operational techniques for cleaning, consolidation and additions were performed by following the fundamental requirements of the restoration, due to the correlation with the results of the diagnostic process. The described methodological approach is a useful example of the importance of new technologies and cooperation between interdisciplinary competences in the restoration project. The aim is to extend the proposed method to the other case studies in architecture and in archaeology, showing similar technical and cultural issues.

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