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A PROPOSAL FOR A NEW STANDARD QUANTIFICATION OF DAMAGES OF CULTURAL HERITAGES, BASED ON 3D SCANNING

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Abstract

In the field of Architectural Restoration, conservation is a fundamental matter to ensure the durability of a built heritage, with historical and artistic values. The process of Conservation consists in the planning of series of interventions, preceded by an accurate phase of investigation about all the main aspects characterizing the artefact. Therefore, it is necessary to perform a preliminary assessment of the general conditions and, eventually, to appraise the presence of pathologies, according to the recommendations contained in the International and European Standards. However, the limit of the major existing legislations is the lack of quantitative criteria to identify and classify alterations. This work aims to make a proposal for an integration of the existing standards, with the identification of meaningful parameters in correspondence of damages. The example application of the study is conducted on Palazzo Palmieri (Monopoli – Italy), through the analysis of photogrammetric 3D models.

Keywords

Architectural Restoration, Cultural Heritage, Condition assessment, Conservation, International and European Standards, Digital Photogrammetry, 3D models' analysis

1. *Introduction*

Restoration and Conservation of Architectural Heritages are complex matters, which are difficult to deal with. Therefore, when intervening on degraded historical buildings, to ensure their durability and the preservation of their significance, it is essential to start from an accurate design of the diagnostic plan, including investigations and analysis, for a complete knowledge of the artefacts.

All the kinds of non-invasive or invasive diagnostic techniques should carry to a complete survey and mapping of the decay, according to the regulations contained in sectorial norms, which define alterations and pathologies.

Existing European and Italian standards, such as EN 16096, EN 15898 or UNI 11182, provide definitions, terms and guidelines useful to approach to a cultural heritage. Nonetheless, they do not consider the possibility to create a classification of damages, not only based on qualitative information, but also on quantitative data about their geometry and extension, to which a level of severity could be related (Delgado Rodrigues, 2015; Oliverira & Lobato Correia, 2013). Therefore, the objective is to research meaningful criteria, including geometrical parameters, for the evaluation of the deterioration of buildings (through the analysis of photogrammetric 3D models), in order to propose a possible integration of the existing Standards.

In recent years, Reverse Engineering, especially Photogrammetry, acquired a fundamental role in the field of Preservation and Maintenance of Cultural Heritages. Some researches showed the great suitability of these techniques to diagnostic investigations, because they are non-invasive and contactless survey methods, avoiding the risk of accidental damages, which could undermine the durability of the artefact (Alshawabkeh & El-Khalili, 2013; Arias, Roca, & Lorenzo, 2008; Hallermann, 2015; Nishiyama, Minakata, Kikuchi, & Yano, 2015)

One of the principal characteristics of photogrammetry is the availability of low-cost equipment, composed by: standard-level cameras, without specific requirements; other elements like telescopic rod in carbon fibre, tripod, tablet, laser distance meter, flexometer, callipers. The instrumentation is quite simple to use and does not need the contribution of specialized technicians. Furthermore, the amount of time needed for the scans and the post-production is shorter than the time that would be used with traditional survey or with other Reverse Engineering techniques, such as the Laser Scanner (Segreto et al., 2017).

The models resulting from photogrammetric acquisitions, like dense point clouds, polygonal meshes and high-resolution ortho-photos, are plenty of information about the object. Especially 3D models are particularly useful in the field of Architecture and Restoration because they represent detailed virtual models of the buildings. Until now, they have been largely exploited for geometrical surveys (Remondino, 2011; Scopigno et al., 2011). However, they represent the opportunity to get a complete knowledge and comprehension of the heritage, and the planning and management of interventions.

2. *Application of digital photogrammetry and 3D model reconstruction techniques to a case study*

Within this research, the photogrammetric technique was applied to a case study: Palazzo Palmieri in Monopoli (Puglia, Italy), an example of late-Baroque architecture, dating to the 18th century. There have been three survey campaigns, during a period of eighteen months, involving the entire external front and part of the internal areas, in order to obtain high-resolution ortho-photos, dense point clouds and polygonal meshes (Fig. 1, Fig. 2). The ground and height resolutions[1] vary according to the size and the distance from the scanned object. For example, the resolution of models of the entire front are of 1-2 mm/pixel, in the parallel direction, and of 2-5 mm/pixel, in the orthogonal direction. For the models of restricted areas, the size and the distance are inferior, so both the resolutions are better (0,3-0,7 and 1-1,5 mm/pixel). The scans of the entire façade took 3-4 hours for each time, and the corresponding processing time was about one hour at most.

The 3D-2D models (dense point clouds, polygonal meshes, high-resolution ortho-photos) were reconstructed through the help of the software Agisoft Photoscan, on a computer, with dual Intel Xeon processor (128 GB of RAM, 64-bit operating system).

Three dimensional models are particularly interesting, because they provide the possibility to create virtual representations (Valzano, Negro, & Foschi, 2018); 3D printed models of the artefact (Clini, Mehtedi, Nespeca, Ruggeri, & Raffaelli, 2018); or web systems to collect information about the cultural contents of the heritage (Trigilia, Valenti, Gatto, Paternò, & Mariniello, 2018). In the specific case, the creation of tangible models of the artefact, first of all, allowed a better comprehension of the artefact itself, but also a spreading of the fruition (Polishape 3D srl; Politecnico di Bari; Building Refurbishment and Diagnostics srl; Università degli studi di Napoli Federico II, 2013).

As shown by the 3D models in Fig. 1, the principal elements of the main façade are a rusticated base and a cornice at the top, with smoothed stones. A pair of Ionic columns and semi-columns in limestone, supporting the entablature and the upper floor balcony, adorns the entrance. There, as the central point of the façade, there is the family emblem, sculpted in the stones. In addition, the cornices of the windows of the three floors are in limestone. The interiors are divided into three apartments set around a central courtyard. The family emblem decorates the upper floor balcony. Through the portal, it is possible to reach an atrium or internal courtyard, where there is the access to the stone - staircases, leading to the upper floor and to the solar roof. On the ground floor, near to the main door, there were stalls for horses, the coach depots and the stocks.

The fabrication includes in its foundations some of the oldest structures, characterized by large buried compartments, now occluded by more recent walls. In 1767, Giuseppe Palmieri, the designer architect of the building, refers to a new plan that he would have designed "in place of the demolished one". Those locations have a considerable archaeological value, whose oldest roots date back to the Bronze Age.

The raised ground floor was partially occupied by servants and by the wood and food storage. At the main floor, there was the apartment of Palmieri family, which consisted of a series of

[1] Ground resolution: minimum distance on the ground between two closely located objects distinguishable as separate objects (parallel to the plane of the façade) Height resolution: difference in height of the intersection of two homologous beams from adjacent photographs, when one of the two rays moves a pixel along the line connecting the two projection centres (perpendicular to the plane of the façade)

rooms, developed around the atrium, covered by frescoed false vaults. The most important room is the "gallery", intended to host art collections of ancient artifacts such as amphorae, coins and paintings. Near the gallery there was the private chapel, typical element of the eighteenth-century buildings, with a decorated altar. The top floor, instead, was dedicated to guests, friends or relatives.

The identification of the architect is uncertain, but some researchers thought at the Apulian architect Vincenzo Ruffo (1749-1794), Vanvitelli's pupil and designer of other local buildings, such as Palazzo Alberotanza in Mola and Castle Marchionne in Conversano. This hypothesis was contested by the researcher Michele Pirelli, who stated that Vincenzo Ruffo was too young at the time of the construction. Instead Mimma Pasculli Ferrara attributes the project to Giuseppe Palmieri (1725-1792), who participated to the construction of the Cathedral, the Episcopal Palace and the "Muraglione" in Monopoli. Besides, he designed also another palace in Ostuni, for the same family (Palmieri, 2002; Todaro, 2002).

The actual general conditions and organization of the artefact are the result of several changes during the late centuries. After the death of the first owner, Francesco Paolo Palmieri, in 1797, the property ran into long periods of abandonment, until the early years of the 1900. In 1907, the top floor of the building became a male orphanage; instead, in 1921 the whole building turned in a School of Arts and Crafts. The years of neglect put the artefact in critical conditions: the roof and the façade required interventions. Consequently, the first structural works, by Eng. Sant'Erchia, consisted in the application of the "sew-unsew" to substitute degraded stones of the piers, in the facade of the internal atrium, collapsed because of compression stresses. In 1950, further works were carried out, including a series of changes in the third floor, including the elevator. After an earthquake, in 60's, the existing school was evacuated and then completely abandoned. The last restoration works date back to the 80s (Todaro, 2002).

At present the building is abandoned, and both the internal and the external components are deteriorated, and they required interventions.

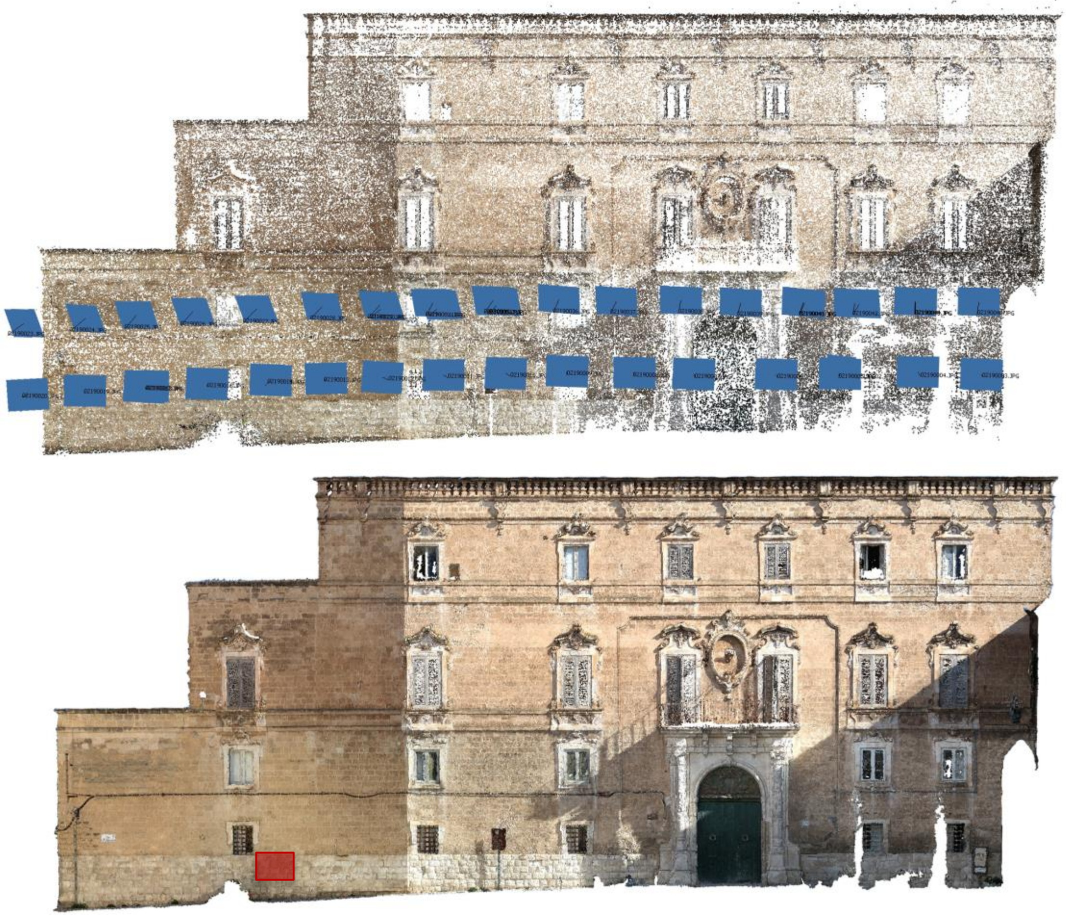


Fig. 1: Sparse point cloud of Palazzo Palmieri's façade, with the position of the cameras used for the shootings; Polygonal mesh of the same façade, with the indication of the analysed particular.

Fig. 2: Polygonal meshes (with textures) of the portal, the right ionic capital, and the internal atrium and courtyard; 3D printed models of the same elements

Fig. 3: 3D printed model of the internal courtyard

3. European and Italian Standard Framework

In Europe, the European Standard regulates Cultural Heritages and assimilates European and International conventions, charters, and declarations. It provides good practices and examples to follow in matters of Conservation and Maintenance of the built heritage. Particularly, there are three norms (EN15898, 2012; EN16096, 2012; EN16853, 2017), dealing with the main aspects of Architectural Restoration.

First, they define the principal terms about Conservation. They supply useful guidelines for conservation professionals, who must manage and preserve a cultural property. There are recommendations on how to record all the information and the documentation, which are fundamental to understand the significance and the values of the object. The adopted terminology, relatively to stone deterioration patterns, is defined by the "Illustrated Glossary on stone deterioration patterns"(ICOMOS XV, 2010).

In Italy, further legislations integrate European and International Standards, with specific descriptions of decay and pathologies of a Cultural Heritage. In fact, in 1977 the Central Institute for Restoration (ICR) created the NorMaL Commission (Normalization of stone materials). The purpose was "establishing unified methods for the study of alterations on stone materials" but also "controlling the effectiveness of conservative treatments on artefacts of historical-artistic interest" through the creation of interdisciplinary working groups (Santopuoli, 1979).

The NorMaL code that referred to macroscopic alterations of stone materials, was NorMaL 1/88[2] (ICR Instituto Centrale per il Restauro CNR, 1988). It consisted of a first classification of the kinds of alteration on stone materials, with specific attention on the terminology, the definitions of the causes and the corresponding graphical representations (Faccio, 1990).

Today the NorMaL 1/88 has been replaced by the UNI 11182:2006, an Italian Standard elaborated by the UNI – Cultural Heritages - Normal technical commission (UNI 11182:2006, 2006). The norm describes the form of macroscopic alterations, to which stone materials[3] are subjected. There are also prescriptions about the indication of the distribution of these forms on the artefact, which must be recorded with the help of graphic illustrations and photographical documentation.

The standard distinguishes:

- Alteration: Modification of a material that does not necessarily imply a deterioration of its characteristics.
- Degradation: Modification of a material that leads to a deterioration of its characteristics.

There are 27 types of alterations, with a complete description, and various pictures, representing the same pathology insisting on different materials.

[2] Lexicon for the description of alterations and macroscopic degradations of stone materials

[3] Stone materials are divided in natural stone materials such as rocks, and artificial stone materials such as mortars, stuccos, ceramic products, etc.

4. *Proposal for an integration of the existing standards*

In a previous work (R. A. Galantucci & Fatiguso, 2018) it was created by the authors a possible approach of analysis on three-dimensional models, deriving from photogrammetric scans, but also applicable to 3D models obtained from other Reverse Engineering techniques. The aim was to create a semi-automatic protocol to provide a thematic map of the decay of historical buildings.

Therefore, series of elaborations were performed on 3D models of small areas of the main façade, using software for three-dimensional microscopy, like Talymap 3D (TaylorHobson-Ltd 2016).

For example, maps in false colours (Fig. 4) or morphological filters[4] to eliminate useless information for the detection of alterations; threshold operators (Fig. 5 a), to identify only the regions of the surface within a selected depth threshold value (corresponding to cavities, missing parts, alveolizations); binarization (Fig. 5 b), to segment the detected regions into grains (each is indicated in a different colour) within certain depth threshold values and then to calculate its 2D geometric characteristics. (area, perimeter, medium, minimum, maximum diameter).

The *studiables*[5] were further elaborated through the motifs' analysis (Fig. 6), obtaining, for each detected motif, quantitative measures like area, volume, depth, coplanarity, minimum, maximum diameter, orientation, aspect ratio, roundness, compactness.

The adopted software provides tools that allow also direct measurements (distances, areas and volumes), for the monitoring of alterations over time. In fact, the progression of defects can be observed automatically, measuring the same points and distances on 3D models acquired at different times.

The established protocol distinguishes separate methods, depending on the object of the analysis (cracks or features induced by material loss), from which it is possible to quantify the damages. 4.1 Standards from other fields - Integration of the standard UNI 11182

From the European and Italian framework, it emerged that there are not specific rules for the quantitative analysis of alterations and surface profiles. Therefore, it could be interesting to study norms and legislations deriving from other fields (reinforced concrete constructions, welding mechanical works) which contain detailed quantitative requirements and limits (R. A. Galantucci, 2017).

In Building Engineering there are some standards about characterization of paving textures through the analysis of profiles. They present methods to determine the average depth of macro and mega-surface textures of a pavement, regardless of the micro-texture and the irregularities of the pavement (UNI 1347301:2002, 2002). They illustrate the data acquisition process and operations[6]; but also, how to use instruments; to vary the resolution parameters, calibration, acquisition speed (UNI1347305:2010, 2010).

Another norm describes surface defects quantitatively, and defines the general structure of contact instruments for measuring surface roughness and ripple (UNI327400:1998, 1998).

Other standards, for example, in the field of welding, aim to identify and classify geometric imperfections resulting from the process of welding of metals. The defects are similar to the alterations found on the surfaces of buildings, such as longitudinal, diagonal, radial cracks, cavities and porosity (UNI1391902:2005, 2005; UNI652002:2013, 2013). Therefore, some parameters could be used for the quantitative determination of alterations in Cultural Heritages:

- L: distance between two imperfections (pore, cavity)
- d: maximum size of an imperfection (pore, cavity)
- f: projected areas of pores or cavities
- h: dimension of imperfection (height, width)
- l: length of imperfection (measured in each direction)
- Lc: length of combined porosity.

According to these parameters, for each detectable imperfection, some limits are established, in order to maintain pre-determined levels of quality, as can be seen in Table 1 (UNI1391902:2005, 2005).

[4] Removal of the median noise, extraction of the contours

[5] All types of measurement data files that it is possible to study on TalyMap 3D

[6] Handling of invalid readings, high-pass filtering, low-pass filtering, slope suppression, peak determination

Tab. 1: Examples of imperfections limits for quality levels, according to UNI1391902:2005

N°	Alteration	Observations	Limits of imperfections for quality levels		
			moderate	**intermediate**	**stringent**
1	**Cracks**	All types of cracks except micro cracks (less than 1 mm² crack area)	not permitted	not permitted	not permitted
2	**Crater cracks**		local crater cracks permitted	not permitted	not permitted
3	**Porosity**	The following conditions and limits for imperfections shall be fulfilled: - Maximum dimension l (l_1,l_2 or h) for single pore - Maximum dimension of the summation of the projected area of the imperfections	l or h<= 0,5 t or 6 mm, whichever is the smaller f <= 10 %	l or h <=S 0,4 t or 5 mm, whichever is the smaller f <=6 %	l or h <= 0,3 t or 4 mm, whichever is the smaller f <=3 %

a)

b)

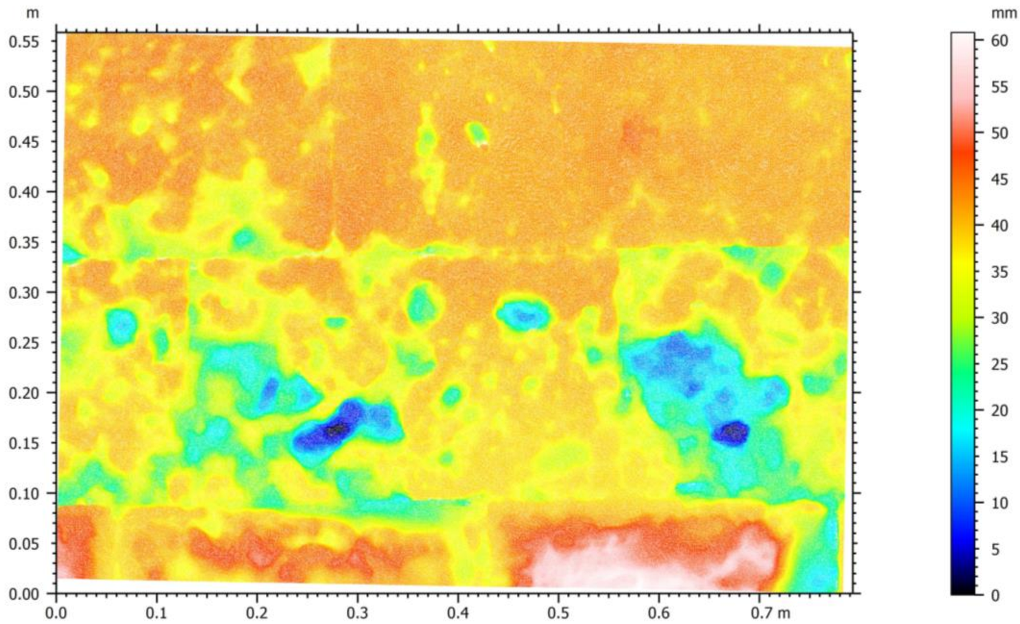
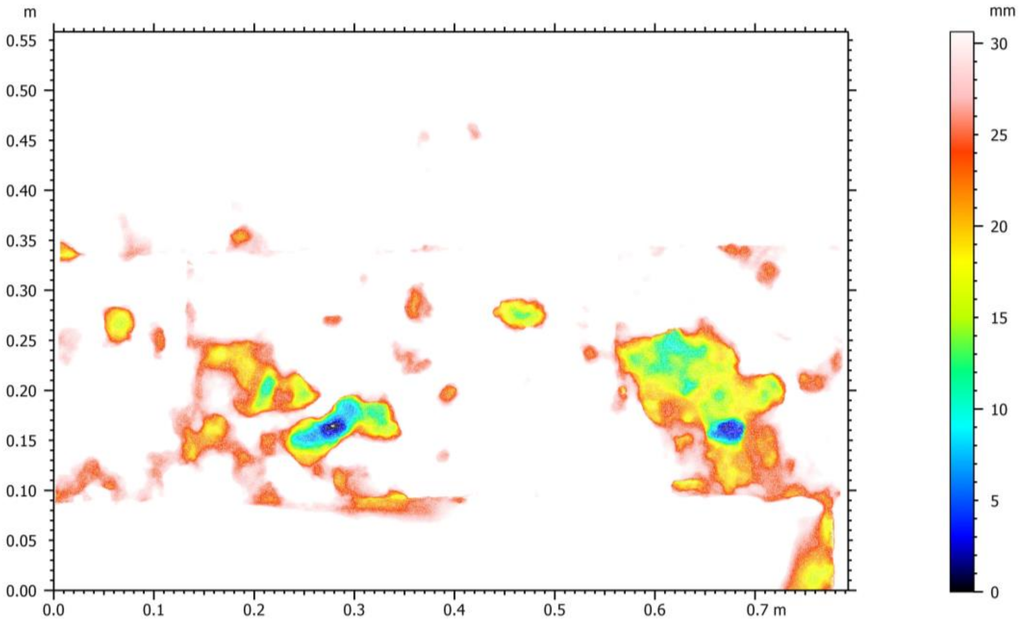
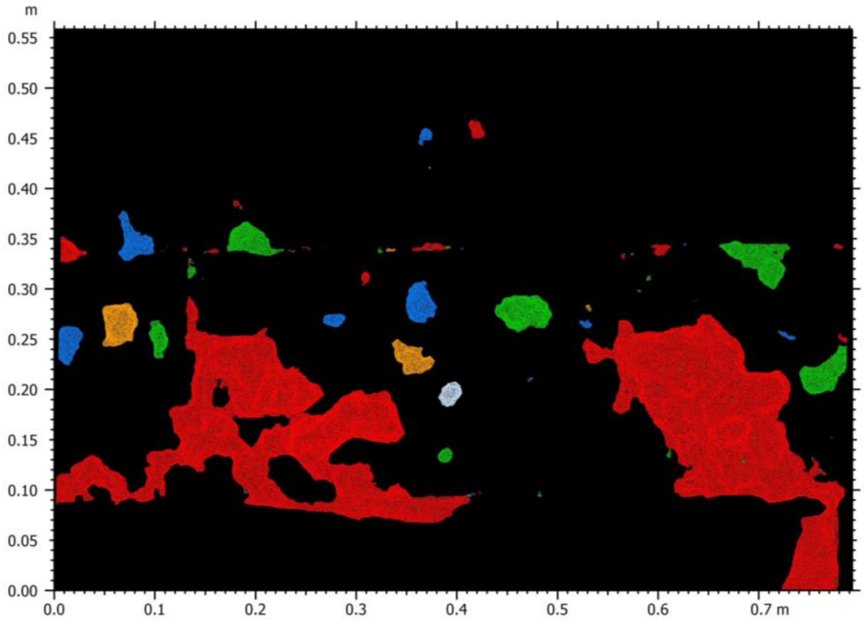


Fig. 4: a) Ortho-photo of the analysed portion of the main façade, made by limestone blocks, affected mostly by lacks and cavities; **b)** Pseudo-colour view of the surface, calculated automatically by the software, while importing a dense point cloud (the scale bar at right indicates the variation of Z-coordinates, corresponding to the variation of depths)

a)



b)



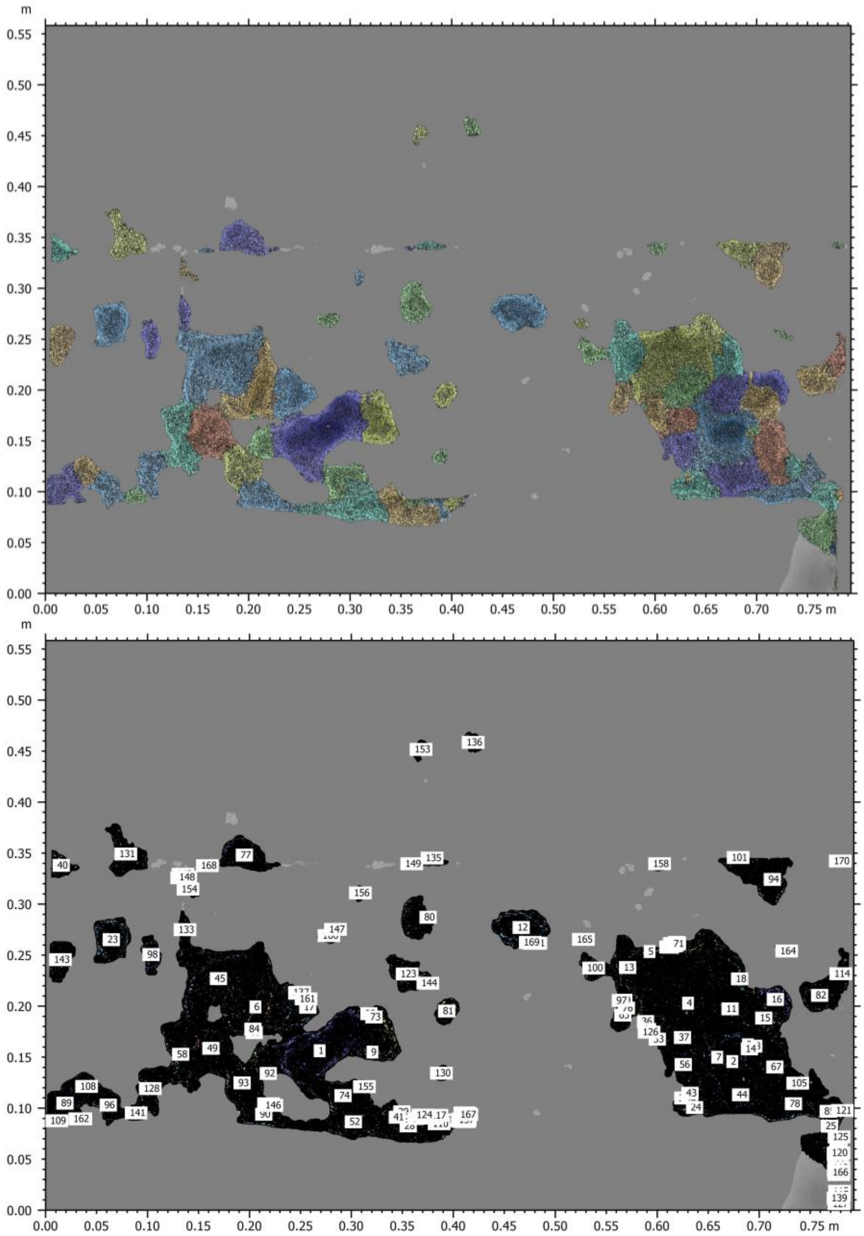
c)

Parameters	Value	Unit
Grain #	1149	
Area	0.000259256	m²
Perimeter	0.958281	m
Equivalent diameter	0.0181685	m
Mean diameter	0.0221708	m
Min diameter	0.0179889	m
Max diameter	0.0262284	m
Form factor	0.00354775	
Aspect ratio	1.45804	
Roundness	0.479838	
Compactness	0.692703	
Orientation	53.9548	°

Fig. 5: a) Application of two thresholds in depth, in order to isolate only those points, whose depths is in the interval; **b)** Binary-segmented view of the surface, through which the software identifies a certain number of grains and calculates 2D parameters (area, perimeter, medium, minimum, maximum diameter); **c)** Table with an example of parameters calculated by the software in correspondence of the single grain

a)

b)



Number of motifs	168

Parameters	Unit	Grain #1	Grain #2	Grain #3	Grain #4	Grain #5	Grain #6	Grain...
Type of motif		Interior motif	Interior motif	Interior motif	Interior motif	Interior motif	Interior motif	Interio...
Height	mm	13.3674	7.43910	2.06410	4.02881	3.76548	11.3693	1.84529
Area	mm²	0.00368909	0.00248616	2.74656e-06	0.00103388	0.00337539	0.00180573	1.6348...
Volume	mm³	7489.23	1719.10	0.490651	220.756	1183.93	3415.54	0.1592...
Nb of neighbors		4	12	2	5	15	5	1
Coflatness	m	0.0222013	0.0180667	0.00531044	0.00784362	0.010510	0.0111318	0.0087...
Perimeter	m	10.2334	7.92675	0.00759985	3.51393	11.1917	5.47598	0.0064...
Mean diameter	m	0.070963	0.062249	0.00159581	0.0402076	0.0698284	0.0495371	*****
Min diameter	m	0.0403141	0.0444331	0.000989658	0.0252235	0.0347713	0.0244382	*****
Max diameter	m	0.0973171	0.0811207	0.00255727	0.0518803	0.110474	0.0811335	*****
Form factor		0.00035415	0.000370457	0.398380	0.000759365	0.000248665	0.000582969	0.2566...
Aspect ratio		2.41397	1.82568	2.58399	2.05682	3.17716	3.31995	*****
Roundness		0.396781	0.358397	0.356497	0.352965	0.258575	0.269072	*****
Compactness		0.629906	0.598662	0.597074	0.594109	0.508503	0.518721	*****
Orientation	°	33.3363	108.792	63.8967	42.4267	33.0600	60.1823	83.0626

Fig. 6: a) Analysis of the motifs identified by the software, after the definition of two thresholds in depth and area; **b)** Motifs with labels associated to their number; Table with the calculation of all the parameters

4.2 Example of integration through the definition of specific criteria

The photogrammetric survey provides measurements on three-dimensional surfaces, through the reconstruction of profiles, sections and surface textures. Besides, through the analysis illustrated in this paragraph, it is possible to acquire specific information about the geometry, the size and the distribution of certain elements on the studied surface. These data allow detecting and measuring different types of alterations.

In fact, studies like binarization (fig. 5), for 2D parameters and motifs' analysis (fig. 6), for 3D parameters, give information about depth, area, volume, shape, orientation of each motif. In table 2 (DigitalSurf, 2016) there are all the parameters taken into consideration in this research. They concern important geometrical characteristics, which could help understanding, identifying and classifying a pathology. In fact, for example the depth (height) of a grain is useful to understand if a defect is superficial or deep. Area, maximum and minimum diameter are useful to know precisely the flat dimensions of the defect. Parameters like aspect ratio, roundness and compactness allow to classify the motifs according to their form.

Therefore, some of the alterations (as defined by UNI 11182:2006), were considered, in order to elaborate a quantitative detection approach, based on these parameters. In Table 3, there is a suggestion to correlate the geometric characteristics, based on the analysis of 3D photogrammetric models, to each alteration.

The proposed method wishes to determine a severity index for each pathology(Ayres & Smyth, 2010). It consists in finding four suitable criteria, in correspondence of which establishing three thresholds, to obtain a classification of the motif/grain (Table 4).

The criteria are:

- *Form f*: a combination of aspect ratio, roundness and compactness, expressing the shape of a grain;
- *Depth (d)*: the medium height of a grain, calculated as the ratio between volume and area;
- *Uniformity (u)*: calculated as the ratio between the maximum height and the medium height;
- *Volume (v)*: the three-dimensional size of the grain.

Tab. 2: Significant parameters deriving from the Motifs' analysis (on TalyMap 3D)

Parameter	Description
Height	Height between pit and lowest saddle point
Area	Horizontal area enclosed inside the ridge line
Volume	Void volume of the motif, below the lowest saddle point
Co-flatness	Maximum vertical distance between the central pit and the pits of adjacent motifs
Min diameter	Smallest diameter of the grain measured from its centre of gravity
Max diameter	Biggest diameter of the grain measured from its centre of gravity
Aspect ratio	Ratio between the maximum diameter and the minimum diameter. If the value is close to 1, the form of the grain is close to the form of a disk. If the value is high, the grain is oblong $Aspect\ Ratio = \frac{Dmax}{Dmin}$
Roundness	Ratio between the area of the grain and the area of the disk having as diameter the maximum diameter of the grain. This value is close to 1 for a circular grain, and smaller than 0.5 for an oblong grain $Roundness = \frac{4Area}{\pi(Dmax)^2}$
Compactness	Ratio between the equivalent diameter and the maximum diameter. This ratio is close to 1 for a grain with the form of a disk, or smaller than 0.5 for an oblong grain. $Compactness = \frac{\sqrt{(\frac{4}{\pi}Area)}}{Dmax}$
Orientation	Angle between 0° and 180° of the biggest axis of the grain, measured in the trigonometric direction (0° at the right side, 180° at the left side, 90° on top)

Tab. 3: Possibility to perform a quantitative evaluation using 3D photogrammetric methods

N°	Alteration	Description	Quantitative Parameters
1	**Cavities**	Presence of cavities of variable shape and size, called alveoli, often interconnected and with non-uniform distribution	Height Area Volume Min diameter Max diameter Aspect ratio Roundness
2	**Crust**	Modification of the surface layer of stone materials	Height Area Volume Co-flatness Perimeter
3	**Deformation**	Variation of the shape, that affects the entire thickness of the material	Height Area Volume Co-flatness
4	**Differential Degradation**	Loss of material from the surface that highlights the heterogeneity of weaving and structure.	Height Area Volume
5	**Disintegration**	Decohesion with loss of the material in the form of dust or very small fragments	Height Area Volume
6	**Erosion**	Removal of material from the surface that in most cases is compact.	Height Area Volume Co-flatness Min diameter Max diameter
7	**Fracturing or Cracking**	Loss of continuity in the material that implies reciprocal displacement of sections. (cer.) In the case of incomplete fracturing without fragmentation of the object	Height Area Volume Min diameter Max diameter Aspect ratio Roundness Orientation
8	**Lack**	Loss of three-dimensional elements (arm of a statue, an amphora handle, piece of relief decoration, etc.)	Height Area Volume Min diameter Max diameter Form factor Aspect ratio Roundness
9	**Pitting**	Formation of blind holes, numerous and close together. The holes have a hemispherical shape with a maximum diameter of few millimetres	Height Area Volume Min diameter Max diameter Aspect ratio Roundness

Each criterion is connected to a range of numerical values (1-3), from the best to the worst, according to which it is possible to separate the detected grains into three intervals. However, it is important to underline that the four criteria have distinct weights, according to the kind of defect. The idea is to consider each defect singularly, and to attribute every time a different weight to the same criterion (L. M. Galantucci, Tricarico, & Spina, 2000). Therefore, the total severity index for the generic alteration is defined as:

$$I_s = W_f{*}C_f + W_d{*}C_d + W_u{*}C_u + W_v{*}C_v \quad (1)$$ [7]

The method illustrated above was applied to some specimens, dense point clouds corresponding to small portions of the main façade of the building with spreading lacks and cavities or with cracks.

As an example, in Table 4 it is illustrated a proposal for three alterations (cavities, cracks and lacks), with weights associated to the selected criteria, varying for each considered alteration.

The numerical values correspond to the parameters calculated by the software for each motif.

Tab. 4: Table with classifications associated with selected criteria, to which different weights are attributed

N°	Alteration	Criterion	**Classification**	Weight
1	**Cavities**	Form (f)	*Circular* (C) = 1 *Pseudo-Circular* (PC) = 2 *Oblong* (O) = 3	W*f* = 50 %
		Depth (d)	*Surface* (S) = 1 *Sub-Surface* (SS) = 2 *Deep* (D) = 3	W*d* = 30 %
		Uniformity (u)	*Regular* (R) = 1 *Medium* (M) = 2 *Irregular* (I) = 3	W*u* = 50 %
		Volume (v)	*Minimum* (MIN) = 1 *Medium* (MED) = 2 *Maximum* (MAX) = 3	W*v* = 60 %
7	**Fracturing or Cracking**	Form (f)	*Circular* (C) = 1 *Pseudo-Circular* (PC) = 2 *Oblong* (O) = 3	W*f* = 70 %
		Depth (d)	*Surface* (S) = 1 *Sub-Surface* (SS) = 2 *Deep* (D) = 3	W*d* = 100 %
		Uniformity (u)	*Regular* (R) = 1 *Medium* (M) = 2 *Irregular* (I) = 3	W*u* = 50 %
		Volume (v)	*Minimum* (MIN) = 1 *Medium* (MED) = 2 *Maximum* (MAX) = 3	W*v* = 50 %
8	**Lack**	Form (f)	*Circular* (C) = 1 *Pseudo-Circular* (PC) = 2 *Oblong* (O) = 3	W*f* = 50 %
		Depth (d)	*Surface* (S) = 1 *Sub-Surface* (SS) = 2 *Deep* (D) = 3	W*d* = 20 %
		Uniformity (u)	*Regular* (R) = 1 *Medium* (M) = 2 *Irregular* (I) = 3	W*u* = 10 %
		Volume (v)	*Minimum* (MIN) = 1 *Medium* (MED) = 2 *Maximum* (MAX) = 3	W*v* = 100 %

[7] W: weight of the criterion C: numerical value corresponding to the criterion

Tab. 5: Classification of motifs according to four selected criteria, with definition of thresholds

CLASSIFICATION OF MOTIFS							
Form (f)		**Depth (d)**		**Uniformity (u)**		**Volume (v)**	
Circular (1)	AR[8] < 1,5 and R[9] >0,4 and C[10]>0,5	***Surface*** (1)	H_m[11] < 2 mm	***Regular*** (1)	$\frac{Hmax}{Hmed} < 5$	***Minimum*** (1)	V < 200 mm^3
Pseudo-Circular (2)	AR < 1,5 or R > 0,4 or C > 0,5	***Sub-Surface*** (2)	2 mm < H_m < 4 mm	***Medium*** (2)	$5 < \frac{Hmax}{Hmed} < 20$	***Medium*** (2)	200 mm^3 < V < 1000 mm^3
Oblong (3)	AR > 1,5 and R < 0,4 and C < 0,5	***Deep*** (3)	H_m>4 mm	***Irregular*** (3)	$\frac{Hmax}{Hmed} > 20$	***Maximum*** (3)	V > 1000 mm^3

In order to classify the detected motifs, each criterion was divided into three intervals, through the attribution of particular conditions, expressed by numerical threshold values and equations (Table 5). For example, according to the form-criterion, if all the three conditions are verified (AR < 1,5 and R > 0,4 and C > 0,5), a grain is circular, and its numerical value is one. If at least one of the conditions is verified (AR < 1,5 or R > 0,4 or C > 0,5), it is pseudo-circular, and its numerical value is two. Otherwise the motif is oblong, and its numerical value is three. The three parameters of Aspect Ratio, Roundness, and Compactness are suitable because their equations refer to the main geometric characteristics, such as maximum and minimum diameter, area. Therefore, they allow to understand the kind alteration, which they are part of. In fact, if the motif is circular or pseudo-circular, it could belong to a lack or a cavity, instead, if the grain is oblong most likely it belongs to a crack.

The results of the motifs analysis were exported in excel tables and elaborated through a specific spreadsheet (Table 6). For each motif all the values were calculated, based on the criteria and the thresholds, and finally it was extrapolated a Severity Index (1), as the linear combination of the four criteria. The Severity Index can vary in a range from 1 to 8 and it, related to the chosen weights (Wf, Wd, Wu, Wv). It is important to highlight that an adequate classification of the grain can be done only considering the four criteria simultaneously. For example, if a grain is oblong, it does not represent a crack necessarily. In fact, if it is surface or sub-surface, it may stand for a lack or an erosion.

Before elaborating the results, some motifs were excluded, because they are too smaller to be significant: for example, motifs with maximum height inferior to 1 mm, or with an area inferior to 4 mm^2, or a volume inferior to 200 mm^3, or a maximum diameter inferior to 1 mm, and a minimum diameter equal to 0 mm.

In the form-criterion, the choice of the thresholds was strictly related to the mathematical meaning of the parameters (Table 2). In the other criteria, the choice was made, considering the distribution of the values obtained through the motifs' analysis.

5. Conclusions

Considering the lack of regulations containing quantitative specifications about damages on built heritages, the principal scope of the research was to elaborate a proposal of integration of the existing standards, including a quantitative classification of the detected damages. The adopted survey technique is photogrammetry, because of the non-invasiveness, simplicity and affordability. Furthermore, it allows obtaining high-resolution 3D models, in the form of dense point clouds. In fact, the ones used for the experimentation have a ground resolution around 0.27-0.3 mm/pixel, which is the dimension of the minimum detectable object.

[8] *Aspect Ratio* = $\frac{Dmax}{Dmin}$

[9] *Roundness* = $\frac{4Area}{\pi(Dmax)^2}$

[10] *Compactness* = $\frac{\sqrt{(\frac{4}{\pi}Area)}}{Dmax}$

[11] *Medium Height* = $\frac{Volume}{Area}$

The analysis was conducted with the help of 3D microscopy analysis software (as TalyMap 3D), which gives quantitative data about the characteristics of the studied surface. It is possible to segment the surface into motifs, and in correspondence of each of them, the software calculates geometrical parameters (like depth, area, volume, maximum/minimum/medium diameter of a grain, co-planarity, aspect ratio, roundness, compactness, orientation). The parameters can be associated to the 27 alterations, which refer to the Italian Standard (UNI 11182:2006), in order to define quantitatively some of them (as shown in Table 3). This kind of estimation can be extended to the majority of the alterations, especially those articulating in three dimensions. The geometrical characteristics of the grains lead to define some meaningful criteria to the grouping and classification. The criteria (in the specific case: form, depth, uniformity, volume) require additional partitions, according to the identification of some thresholds, related to the mathematical meaning of the principles, and to the observation of the distribution of the parameters, among all the detected motifs.

It was possible to use these results, to define a unique Severity Index, calculated for each motif, as the linear combination of the selected criteria. In this case, the study involves only three kinds of alteration: cavities, cracks and lacks, and it was applied to dense point clouds of limited portions of the main façade, mostly affected by cavities, lacks, or cracks. Each of the three pathologies has a different Severity Index, gathered from the application of different weights for every criterion and every alteration. The Severity Index has a range of variation from 1 to 8, depending on the weights attributed case by case.

It is necessary to underline the influence of the variation of weights, on the final classification of the level of risk of a pathology, through the Severity Index. The attribution of weights presented here is an example, deriving from considerations about the nature of each defect. However, it could be interesting to use investigation methods, like the Delphi method, which includes the participation of experts, who identify values that can be universally recognized and accepted.

This proposal of integration of the standard was conducted only on three alterations, as an example. Further developments could be about the analysis of the other defects. Moreover, it could be interesting to identify some intervals, to divide the range of variation of the Severity Index, according to different level of risk, associated to the damage.

Tab.6: Spreadsheet with the calculation of the Severity Index of each motif, in case of cavities or lacks (in the first line under the names of the criteria, there are the associated weights)

	DEFINITION OF THE THRESHOLDS				NUMERICAL VALUE ASSOCIATED TO THE THRESHOLDS				CAVITIES				
N° of motif	Form (*f*)	Depth (*d*)	Uniformity (*u*)	Volume (*v*)	Form (*f*)	Depth (*d*)	Uniformity (*u*)	Volume (*v*)	Form (*f*)	Depth (*d*)	Uniformity (*u*)	Volume (*v*)	Severity Index
									0,5	**0,3**	**0,5**	**0,6**	
1	PC	SS	M	MAX	2	2	2	3	1,0	0,6	1,0	1,8	4,4
2	PC	S	M	MAX	2	1	2	3	1,0	0,3	1,0	1,8	4,1
4	PC	S	M	MED	2	1	2	2	1,0	0,3	1,0	1,2	3,5
5	PC	S	M	MAX	2	1	2	3	1,0	0,3	1,0	1,8	4,1
6	PC	S	M	MAX	2	1	2	3	1,0	0,3	1,0	1,8	4,1
9	PC	S	M	MIN	2	1	2	1	1,0	0,3	1,0	0,6	2,9
10	PC	S	R	MIN	2	1	1	1	1,0	0,3	0,5	0,6	2,4
11	PC	S	M	MED	2	1	2	2	1,0	0,3	1,0	1,2	3,5
12	PC	D	R	MAX	2	3	1	3	1,0	0,9	0,5	1,8	4,2
15	PC	S	I	MIN	2	1	3	1	1,0	0,3	1,5	0,6	3,4
16	PC	S	I	MIN	2	1	3	1	1,0	0,3	1,5	0,6	3,4
17	C	S	M	MAX	1	1	2	3	0,5	0,3	1,0	1,8	3,6
23	PC	D	R	MAX	2	3	1	3	1,0	0,9	0,5	1,8	4,2
24	PC	S	I	MIN	2	1	3	1	1,0	0,3	1,5	0,6	3,4
25	PC	S	M	MED	2	1	2	2	1,0	0,3	1,0	1,2	3,5

	DEFINITION OF THE THRESHOLDS				NUMERICAL VALUE ASSOCIATED TO THE THRESHOLDS				LACKS				
N° of motif	Form (*f*)	Depth (*d*)	Uniformity (*u*)	Volume (*v*)	Form (*f*)	Depth (*d*)	Uniformity (*u*)	Volume (*v*)	Form (*f*)	Depth (*d*)	Uniformity (*u*)	Volume (*v*)	Severity Index
									0,5	**0,2**	**0,1**	**1**	
1	PC	SS	M	MAX	2	2	2	3	1,0	0,4	0,2	3,0	4,6
2	PC	S	M	MAX	2	1	2	3	1,0	0,2	0,2	3,0	4,4
4	PC	S	M	MED	2	1	2	2	1,0	0,2	0,2	2,0	3,4
5	PC	S	M	MAX	2	1	2	3	1,0	0,2	0,2	3,0	4,4
6	PC	S	M	MAX	2	1	2	3	1,0	0,2	0,2	3,0	4,4
9	PC	S	M	MIN	2	1	2	1	1,0	0,2	0,2	1,0	2,4
10	PC	S	R	MIN	2	1	1	1	1,0	0,2	0,1	1,0	2,3
11	PC	S	M	MED	2	1	2	2	1,0	0,2	0,2	2,0	3,4
12	PC	D	R	MAX	2	3	1	3	1,0	0,6	0,1	3,0	4,7
15	PC	S	I	MIN	2	1	3	1	1,0	0,2	0,3	1,0	2,5
16	PC	S	I	MIN	2	1	3	1	1,0	0,2	0,3	1,0	2,5
17	C	S	M	MAX	1	1	2	3	0,5	0,2	0,2	3,0	3,9
23	PC	D	R	MAX	2	3	1	3	1,0	0,6	0,1	3,0	4,7
24	PC	S	I	MIN	2	1	3	1	1,0	0,2	0,3	1,0	2,5
25	PC	S	M	MED	2	1	2	2	1,0	0,2	0,2	2,0	3,4

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