Interdisciplinary conservation issues of an “unstable” architecture: researches about the bell tower of St. Augustine the Greater in Naples

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1. The seventeenth-century building and the transformations over the centuries

In the big architectural complex of St. Augustine the Greater (or alla Zecca) in Naples - main seat of the Order of the Hermits of St. Augustine in the South of Italy - the bell tower is a high quality landmark as for building processes as for figural and decorative solutions. Object of long-term researches [Russo 1997; Bezoari G., Casiello S., Russo V., 2001; Russo 2002; Russo, de’ Gennaro, Cappelletti, Ceniccola, 2012], that part of the Augustinian convent assumes an urban value for dimensions and location in the historic center of Naples. The knowledge of the building has been previously methodologically articulated according to the following steps:

a. direct and photogrammetric survey of the northern front [Bezoari, Casiello, Russo, 2001];

b. exploration of bibliographic, archival and iconographic sources [Russo, 1997; Russo, 2002]. Afterwards, the collapse of a Piperno block in 2011 from the baroque bell tower has stimulated interdisciplinary researches focused on the problems of stability and materials’ preservation of its architecture [Russo, de’ Gennaro, Cappelletti, Ceniccola, 2012].

The bell tower was built between 1618 and 1624 with a total height from the ground of about 54 meters (Fig.1). The new building incorporated pre-existing structures, still partially visible in the Piperno basement. The attribution of the project is still complex because of the absence of documents about it: the involvement of Giovan Giacomo Conforto as architect and of the sculptor Nicolò Carletti seems probable. The 17th century bell tower was articulated in the succession of four levels, marked, besides the first corresponding to the access to the convent, by the use of the Doric, Ionic and, at the top, Corinthian order both in angle pilasters both in the treatment of the windows and friezes (Fig.2). As in the coeval bell tower of the convent of Carmine the Greater in Naples, the Augustinian tower probably had a termination characterized by an attic and a lantern at the top.

Because of the damages caused by earthquakes and by the natural deterioration of materials, the bell tower has undergone over the centuries several strengthening works. The installation of tie rods and metal cramps for the support of external coverings can be related to the construction process. In 1731, as it emerges from the incision by F.B. Werner, the bell tower had already reduced its height: the demolition of the attic and the upside cone,
together with the creation of a watchtower (garitta) for going to the coverage, may chronologically refer to the period just after 1688, year of the earthquake which caused large damages to Neapolitan architectures. In that year, in fact, the first restoration works carried out on the bell tower are documented, as it is clear from the Book of Proposals of the convent, conserved at the State Archive of Naples. In 1732 and in relation, once again, to an earthquake, more strengthening works on the tower as «severely damaged» are known, too. On that occasion, «many iron chains» were put on the bell tower; these latter can still be recognized, at the four order, with their terminations which are of slightly different sizes in respect to a previous system of chains, probably assignable to the tower construction yard.

Phenomena of collapsing of stone blocks are not new to the bell tower, as already occurred in 1889. This collapse led to a complex restoration between 1914 and 1919, directed by Superintendent Adolfo Avena and documented in detail by archival sources: the intervention, identifying the causes of damages in the separation and progressive expulsion of the coating parts and in the erosion of mortars, conducted to the introduction of metal rods for the strengthening of the bell tower and of many iron clamps, coated by copper. Aiming to safeguard the external appearance of the building, the interventions were partly masked by stone pieces among blocks of the decorations and walls. In addition, following a diffusing praxis, concrete was widely used in order to improve the adherence of coverings to the tuff nucleus. After a century since this extensive restoration - minutely documented in archival sources - the bell tower shows signs of widespread damage, deriving from factors intrinsic to the building system itself (masonry nucleus-facing fixing) and from the aging of the same parts put in work in order to ensure the monument’s preservation.

2. The stratigraphical analysis of vertical parts

The building presents a Neapolitan Yellow Tuff internal core - set on horizontal lines with lime joints 2 cm thick and different parallelepiped ashlars - and an external covering in bricks with white marble and limestone for decoration. Piperno stone is used as cornerstone, for the cornices and for the facing of the first level.

Reading the masonry means to recognize the “yards” that have defined the construction and, consequently, to comprehend the building history by integrating the scarce documentary sources. Nevertheless, the data are not only aiming to a better knowledge but they are directed to guide a preservation plan, too, compatible with the materials and the building techniques. On the external finishing of St. Augustine bell tower it is possible to identify some “yards”, recognizable from the typology of the bricks, the construction method, the joints’ dimension as well as from materials used for the finishing itself. It is possible to suppose that the bricks were almost produced in Ischia furnaces, as they do not seem very regular, with not perfectly straight edges, curved, with an irregular thickness, variable colour between dark red and different tonalities of grey [Guerriero, 1999, p.305]. Moreover, the examination of a brick section makes possible to distinguish an external part which is 1 cm thick and
grey that includes a dark red core where the different tonalities depend on different firing times.

From the masonry’s samples that have been identified it is possible to recognize at least two “yards” for each level (with reference to the brick masonry) and four ‘yards’ at the last level, traces of a probable change in the supply of materials and of working techniques. The “crucial point” of the construction of the bell tower is the highest part of the third order (Fig. 3), where a change of the texture is visible: the bricks, just placed according to the “Gothic manner” and alternatively placed in the long side and in the short one, are replaced by a masonry characterized by bricks all disposed on the long side. The used bricks have lengths between 26 cm and 30 cm, thicknesses between 3-4 cm, with regular or curved sections; in the last order (North side), moreover, it is recognizable a “yard” where the bricks are characterized by a particularly rough and irregular surface, sign of a supply of material with unrefined quality. In relation to the third dimension, on the basis of the sizes deduced from some fallen bricks, it is possible to deduce that it is 10 cm long. The vertical joints, absent in some parts, reach a maximum thickness of 2 cm, with an average of 1 cm; they are aligned with the bricks and smooth at the last order while they appear rough at the other levels. The horizontal joints, however, show a clear difference between the first orders and the last one: if in the first case the thickness is between 1.5 cm and 2.5 cm, at the last order it changes between 0.3 cm to 2 cm with joints mainly 1 cm thick, producing, together with the presence of ashlars with curved sections, a wavy brickwork. In relation to the mortars placed among the bricks, they are characterized by the presence of volcanic aggregates of various sizes and “cadinelli”, that are clots of not slaked lime. To a close and careful observation, it can be noted that the brick facings are covered with a protective layer still visible underneath the layer of surface deposit whose consistency varies according to the exposure. This protective layer assumes variable shades from deep red to pink as it is visible only at the last level (West side) (Fig.5).

The differences in size of the bricks and of the horizontal and vertical joints generate multiple textures with specific morphological characteristics. It is important to take into account the surface quality of the bricks and its role in the composition of the “patina” that changes the perception of the building during time. In addition, the decay phenomena change in relation to the quality and the characteristic of each “yard”; an aspect, this last, to take into consideration in the building preservation strategies.

3. The bell tower geomaterials

The resolution of many problems related to the preservation of historical buildings cannot disregard mineralogical-petrographical contributions. In fact, the conservation of architectural heritage requires a thorough knowledge of geomaterials (either natural or “transformed”) that constitute it, with an accurate diagnosis of degradation processes. For the study of the bell tower of St. Augustine church, a survey on lithological materials was performed, aimed at their recognition and quantification on each façade; furthermore the state of conservation and forms of degradation were evaluated (Fig.4).
Cornerstones, edges of the belt courses, the timpani and part of the pilasters at the openings were all realized in Piperno. This is a product of the Campanian Ignimbrite eruption, dating back to 39,000 years ago [Fedele et al., 2008], and it can be classified petrographically as a trachyte/phonolite. The few and limited outcrops of this important material are all located at the foot of the hill of Camaldoli, in the western sector of the city of Naples. It is characterized by its peculiar texture (eutaxitic), with black flattened scoriae (fiammae or flame) of variable length and thickness, immersed in a light cineritic gray matrix. This feature gives the stone a unique design especially when used in the contro or verso directions. The main mineralogical constituent is sanidine (89-96%), mainly of secondary origin [Calcaterra et al., 2005]. Carrara marble constitutes the statue of St. Augustine (first order, North elevation), the stripes marking the third and fourth order, some rectangular slabs alternating Piperno at the top of the second order, all the angular capitals of the fourth order and some details that adorn the main side openings. Carrara marble used here displays a saccharoid (medium-fine grained) compact structure. Brick masonry is present outside, between openings and cornerstones in Piperno that border each order of the bell tower. Thin section observations of a sample placed in the third order (East side of the opening on the right) show the presence of abundant fine-grained aggregate, poorly sorted, dense and without any orienting. Clasts are primarily made up by pumice, small scoriae and rare carbonate fragments. Morphology of clasts displays low sphericity and angular to subangular contours. Minerals fragments are: plagioclase, clinopyroxene, biotite and alkali feldspar, along with obsidian. The brick is affected by the local geological situation, as evidenced by the presence of volcanic aggregates: this leads to the assumption that furnaces probably used Campanian clays of uncertain origin mixed with volcanic aggregates. Thin sections observations on limestone (calcari con requienie) shows lithoclasts of different formations and limestone facies typical of Mesozoic carbonate platform succession. The matrix is scarce and is composed of wackestone-packstone fine fragments of rudists, fragments of echinoderms. The presence of Orbitoides sp., globotruncane and calcisfere in the matrix suggests a Campanian-Maastrichtian age. The lithoclasts represent facies of different ages but all Cretaceous (from the basal Cretaceous/Neocomian to the Campanian-Maastrichtian). Breccias similar to this, in composition and texture of the clasts, are present in the “Breccia Irpinia” and crystalline limestones such as “Pietra di Padula”. The Neapolitan Yellow Tuff (NYT), constituting the masonry nucleus, is a large pyroclastic deposit dating 15,000 years from the present [Deino et al., 2004] and it is a consequence of the lithification zeolitization processes of the original volcanic glass. Its use as a building stone has always characterized the Neapolitan area since the early human settlements, playing a primary role in the architecture and historic buildings and yet deeply impacting on the development of its territory [de Gennaro et al., 2013]. Among other geomaterials, white pigmented plaster is present in negligible percentages compared to the exposed surfaces. It is found mainly as filling of the timpani (triangular and curved) located above the main openings in the four facades. The quantitative analysis of geomaterials used in relation to all
four examined elevations, reveals that Piperno is the predominant geomaterial. Marble, bricks and limestone are also present. To a lesser percentage, almost negligible, there is the white plaster. The Neapolitan Yellow Tuff constitute the core of the wall structure. Noteworthy, exclusively in the western facade, is the presence of Somma-Vesuvio lavas, replacing Piperno at the string course at the top of the fourth order.

4. Alteration and degradation of geomaterials

The analysis of degradation processes affecting the surfaces of geomaterials employed for the realization of architectural artifacts has carried out following tested methodologies, both to evaluate the intensity of the phenomenon, and for recognizing forms of degradation and their relative impact (NOR.MA.L. 1/88, upgrade April 2006). The degradation has been detected and reported on appropriate thematic mapping (Fig. 6) using three different levels of intensity (de Gennaro et al., 2000). The analysis of the areas affected by degradation was performed in situ, and was quantified through MAP INFO 10.0 GIS software.

In general, Piperno main type of degradation is represented by differential phenomenon, with an incidence ranging from 54% (West front) to about 90% (East front), in contrast with literature data [Calcaterra et al, 2005; Morra et al. 2010] that indicate alveolization as the most common degradation phenomena for Piperno. Presence of vegetation was also observed (maximum incidence of 12%, West front), replacements (8%, West front), lacking (7% in the South facade), fractures (up to 6%, West front), biological patinas (incidence max 3%), black crusts (max 3% incidence) and subordinate alveolization, efflorescences and cement additions, due to the early 20th century restoration. As Carrara marble is regarded, the most widespread degradation is represented by the occurrence of black crusts, with percentages ranging from 45% (South facade) and 83% (West facade). XRD analysis shows the presence of gypsum and bassanite, linked to sulfation processes of carbonates and the consequent incorporation of particulate from air pollution. Lesser percentages of integrations (24%, South facade) and fractures, vegetation, omissions and substitutions are present.

Bricks are affected by high degrees of degradation, due to black crusts (incidence of 50% in the East, South and West façade) and lackings (50%), observed in all fronts, as well as exfoliations. In some cases, presence of red patinas was observed (III order, West side), probably related to previous restoration interventions or to original protections (Fig. 5).

Limestone, used to a lesser extent and therefore with a lower exposed surface, also presents abundant black crusts, with a percentage between 48% (South facade) and 90% (East facade). Cement additions (27% in the South facade), lacking (10% -20%) and replacements are also present.

Plaster is affected mostly by detachments, thus allowing to observe the underlying Neapolitan Yellow Tuff walls (slightly altered). Obviously, considerations on degradation of individual geomaterial may vary. Their condition often differs in the different facades and should be correlated to exposure and previous restoration interventions. Generally speaking, as regards East, North
Naples, St. Augustine the Greater bell tower: 1. North elevation metric survey; 2. South elevation othophotoplan and materials' identification; 3. Third order building "yard". It is noticeable the rosy layer protection on the bricks and on the horizontal joints. The mortar shows the presence of volcanic inert and white "calkinelli"; 4. East front, fourth order: Piperno (a), Carrara marble (b) and bricks (c); 5. Red patina on bricks (40X PPL); 6. Northern front: Synthetical mapping of the weathering forms; 7. a) FE model of the bell tower; b) computed stresses under gravity loads; c) damage distribution under horizontal loads.
and West facades, intensities and levels of degradation are definitely higher, when compared with the South facade, this latter displaying a better state of conservation.

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All of the factors identified may represent both initial cause and the pathogenic condition of the degradation processes. Each of them, often in competition with others, potentially triggers degenerative processes attributable to three main categories [de’ Gennaro et al., 2008]:

1. chemical processes: environment acts on materials so as to alter their composition, generating new compounds that have new and different characteristics. Variation in resistance and volume, disintegration, crystallization of soluble salts, chemical modification of the organic compounds (phytochemicals modifications, oxidation) may arise.

2. physical-mechanical process: environmental factors act on materials, inducing mechanical stress (internal stress, abrasion, etc.) or tension caused by the change of state of the liquid contained in the materials (evaporation, condensation, etc.). These phenomena can cause the following effects: fracture, deformation, increases porosity, surface disruptions.

3. biological processes: presence of biodeteriogens alters the structure of geomaterials, with direct or indirect biological actions of various types. These processes can trigger chemical processes with the following effects: disruptions, dislocations and removal of materials, structural instability in the case of high level vegetation.

Each of these processes assumes specific trends in relation to different factors and to the physical-chemical properties of the geomaterials. Very often these processes are present together (Fig.4). In conclusion, all four facades present an advanced state of deterioration. The main reason of degradation can be associated to the peculiar exposure of the monumental complex, close to the sea and to the long-standing rainwater.

5. Assessment of structural behaviour under seismic actions
A finite element model of the bell tower was generated in ABAQUS to assess the structural behaviour under vertical and horizontal loads. A nonlinear static (pushover) analysis was performed. The three dimensional solid model of the tower was implemented in a computer aided design system and then was imported into the finite element code to generate the geometry of FE model (Fig. 7a). The solid parts of the model were meshed with the C3D4 4-node linear tetrahedron element, with three degrees of freedom at each node, namely the translations along the nodal x, y, and z directions. The damaged plasticity model was selected for constitutive law. The model is based on isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity to represent the inelastic behaviour of brittle material. The yield function of Lubliner is considered as failure surface, with the modifications proposed
by Lee and Fenves to account for different evolution of strength under tension and compression [ABAQUS, 2010]. The values of parameters considered in the analysis are reported below:

With regard to the load modelling in pushover analyses, two steps were considered. In the first step gravity loads were applied to the FE model and in the second one a uniform distribution of accelerations along the horizontal direction was considered. As far as the boundary conditions are concerned, full restraints were assumed at the basement of the structure and along connections with the main building. The results of the analysis in terms of stress distribution under gravity loads as well as damage prediction for horizontal actions are shown in Figs.7b, 7c. The analysis shows that the value of the maximum compressive stress at the base, next the openings, is about 1.2MPa. The results of pushover analysis showed that the collapse of the structure occurs for cracking failure between the first and second row of openings, with rigid rocking of the upper part of the bell tower. The lateral capacity is attained for a value of the peak ground acceleration of about 0.15g, which is comparable with the value of PGA given by seismic codes for this area.

6. Conclusions
The conditions of deep decay of the bell tower of St. Augustine the Mayor, with the collapses of the external blocks occurred in April 2011, have pressed for the re-opening of interdisciplinary researches whose results are aimed to defining a forthcoming program of conservation and risk mitigation. As the result of an accurate samplings, the laboratory analyses carried in synergy among university departments have clarified the nature of the materials used in the construction phase and in surface treatments, including historical protection layers so as to provide also a new contribution about the design concept that the baroque architecture was to take in the urban context.

The direct survey of the building, thematically led with attention to the “yards” and the construction techniques used over the centuries, has highlighted the differentiated distribution of the degradation processes and the widespread risk status for the architecture, with local situations of separation of stone parts and cracking in structures. The interaction between the masonries and the restorations’ additions – especially the metallic ones – allows to recognize many instability problems at the local level that precede the triggering of a wider range of phenomena. At the same time, the knowledge of the present conditions of the building is followed by a preventive approach related to the risks that may arise to the bell tower from dynamic stresses, including the vibrations coming by the presence of the adjacent metro line in a short time. Intertwining the history of the yard, the results of the surveys, the investigation about geomaterials and structural modeling, the research team aims to provide an original system of knowledge of the factors of vulnerability of the building, until now rarely investigated although the recent stone detachments. The critical issues that arise from the interdisciplinary researches can define the necessary basics for overcoming the dangerous logic of emergency, rather in favor of a conscious system of interventions tending to improve the conditions of the “weak” bell tower.
Notes
* Although the present short paper is the outcome of a collective work among the authors, par. 1 and 6 are due to V. Russo, par. 2 to G. Ceniccola, par. 3 and 4 to P. Cappelletti and M. D’Amore and par. 5 to R. Landolfo and F. Portioli.


References