# 6 DEFENSIVE ARCHITECTURE OF THE MEDITERRANEAN
## XV to XVIII Centuries

Ángel Benigno GONZÁLEZ AVILÉS (Ed.)

# DEFENSIVE ARCHITECTURE OF THE MEDITERRANEAN

XV TO XVIII CENTURIES

Vol. VI

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## XV TO XVIII CENTURIES

## Vol. VI

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Ángel Benigno González Avilés
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# The Santa Croce wall structure of Cagliari's ancient fortifications (Sardinia, Italy): construction technologies and stone decay

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**Abstract**
The research discusses a part of the modern fortification of Cagliari built since the XVI centuries: the bastion of *Santa Croce*. The Cagliari fortifications show the designs of "modern" technologies that around the middle of the XV century in Europe replaced the medieval walls, with several changes to the structures (*i.e.*: lowering of buildings, replacement of quadrangular medieval towers with lesser height cylindrical, increase of the thickness of the walls through the creation of embankments, etc.).
For the boundary walls of *Santa Croce*, built between 1568 and 1578 and completed with additional outworks in the XVIII century, were used local carbonate rocks of Cagliari's geological Miocene formation. The main represented lithologies used in the wall structure are the *Pietra Cantone*, *Tramezzario* and *Pietra Forte* limestones. These rocks are also used in the *La Concezione* and *San Guglielmo* structure walls. Subordinately, in the bastion of *Santa Croce* (as well as in the curtain of *San Guglielmo*) there are the occasionally presence of volcanic ashlars belong to Asuni area (central-south Sardinia). These volcanic ashlars are used as materials for the recent consolidation and restructuring of the fortifications of Cagliari, implemented in the century before.
Primarily, the study analyzes the relationships between the ancient construction technologies and the use of stone in these building walls. Secondarily, it analyzes the decay of geomaterials to define the chemical and physical processes in progress in the monument, and to identify how to intervene in the restore works, in order to consolidate the material where there is obvious static-structural criticality.

**Keywords**: Medieval and modern fortification; Geomaterials; Mechanical strength; Decay, bastion of *Santa Croce*

## 1. Introduction

The work shows the relationship between the building technologies used in the sixteenth centuries and the use of stone in the construction of Cagliari modern city walls.
These fortifications highlight a design that employ "modern" technologies that in the middle of the fifteenth century in Europe modified the fortifications built during the Middle Ages; in this period medieval walls designed from the twelfth century were made of rectilinear walls, interspersed with numerous towers often defended by more fortifications that surrounded them. This evolution entailed several changes to the structures like: lowering of the buildings, use of cylindrical surfaces with the replacement of quadrangular towers, which had the dual function of better resist to the hits and reduce the disastrous effects of the collapses.
Then, increase the thickness of the existing boundary walls through the creation of embankments.

In the sixteenth century was also defined the design of the pentagonal bastion, an embankment supported by masonry partitions usually connected by vaulted structures.

To study the use of stone in the construction of Cagliari fortifications, a mapping of the various rocks was made in the Santa Croce's area (within the *Castello* district). The aims of the work are the petrographic characterisation of the employed geomaterials, and define their physical-mechanical properties (i.e., real and bulk density, porosity, compression and tensile strength, etc.), to highlights the chemical-physical decay of stones and their correct use in wall structure in relation with the ancient construction technic.

## 2. The fortifications of Cagliari in the modern age: construction technique of the bastioned front

Since the beginning of the sixteenth century the strongholds of Cagliari and Alghero in Sardinia are interested by a series of works entrusted to the military engineers.
The technicians in the service of Spanish Kingdom will modify the medieval lines with a sequence of pentagonal bastions described in archival documents and drawings; these graphical representation, show the high level design that characterizes the work of Rocco Capellino and Jacopo and Giorgio Paleari within the sixteenth-century war scene (Pirinu 2013).
Complete mastery of modern techniques of urban survey and military treatises, high quality in the graphic representation, are some of the aspects that characterize the intervention of the engineers in the second half of the sixteenth century.
Several examples of the application of the technique can be seen in the Spanish Mediterranean strongholds like Cagliari, Alghero, Pamplona, Peñíscola, Alicante, just some of the sites that preserve the testimony of the work of military engineers and in particular of Jacopo and Giorgio Paleari Fratino that faithfully employ the treaty realized by Girolamo Maggi and Captain Castriotto (Fig. 1).

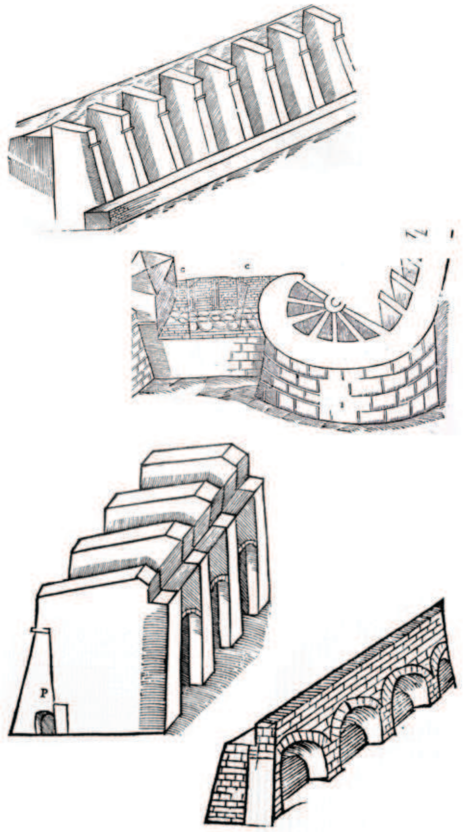

Fig. 1- Construction technique indicated in the treaty *Della fortificatione della città* written by G. Maggi and J.F. Castriotto

A further refinement of the technique is carried out in the eighteenth century through the work of the technicians in the Savoy service.
These works (in sixteenth century) are composed by earthworks supported by structures made of local stone and additional works. In the eighteenth century the repertoire of design solutions has been enhanced with options such as the Horn work -like the piedmontese bastion of San Filippo- primarily made with local *Pietra cantone* limestone.
The first results of the study (Columbu & Pirinu 2016) are related to the western sector of *Castello* district that preserves an important

example of construction techniques developed from the Middle to the Modern Age.
Several materials used for the construction and restoration work undertaken since the early twentieth century, involving different rocks in the recent restorations. In some cases, these latter (with the replacing of original stone) have led to recovery compositions with the loss of the original texture.

Fig. 2- Aerial view of Santa Croce's area

### 3. The Santa Croce's area

From the beginning of the sixteenth century the area of *Santa Croce* (Figs. 2, 3, 4, 5, 6) is interested by a transformation that will lead to the construction of a pentagonal bastion (sector 6 of Fig. 3) integrated in the 18th century by a counter-guard (sector 4, Figs. 3, 5) and low flank (sector 5, Figs. 3, 6).

Modifications, collapses and reconstructions in the period between 1568-1578 and recent restorations offer the possibility to observe different lithologies used to realize the works. In particular the west flank (Fig. 7) of the bastion preserves the original stone that - as the archival documents indicate – during the Spanish Kingdom of Felipe II had to be cut in three main dimensions (Casu 2002).

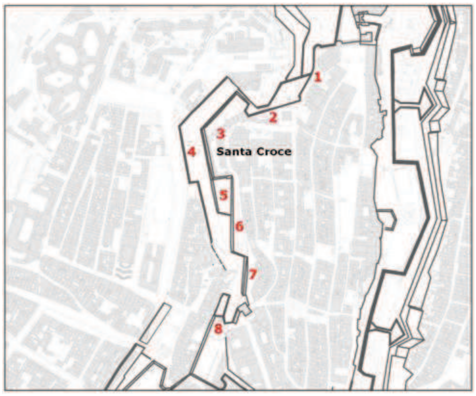


Fig. 3- West front of Castello's fortifications divides in different sector. 1: Bastion of *La Concezione*, 2: Curtain of *San Guglielmo*, 3: Bastion of *Santa Croce*, 4: Counterguard of *Santa Croce*, 5: Low flank of *Santa Croce*, 6: Curtain of *Santa Chiara*, 7: Curtain of *De Cardona*, 8: Bastion of *Balice*

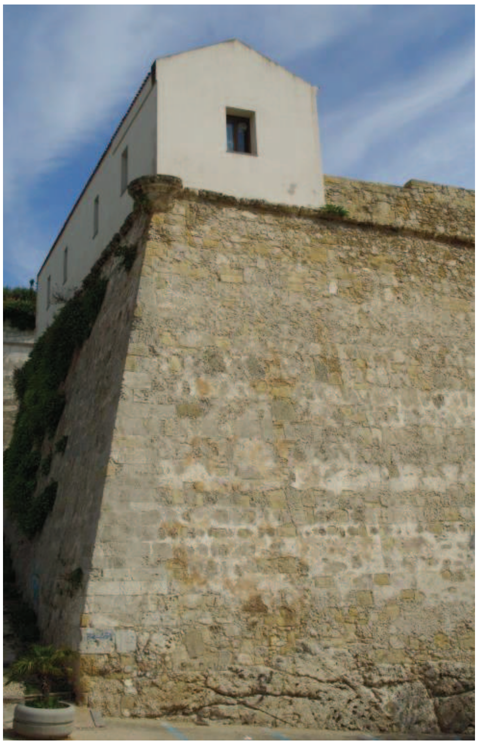

Fig. 4- North west sector of the bastion of *Santa Croce*

Fig. 5- Counterguard of *Santa Croce*

Fig. 6- Low flank of *Santa Croce*


Fig. 7- Rectified photography the shows a part of the west flank of the bastion of Santa Croce. We can observe the original materials adopted in the sixteenth century and characterized by a unique dimension

## 4. Stone materials

### 4.1 Methods

The mineralogical and petrographic analysis of volcanic rocks was performed on thin sections under the polarizing microscope (Zeiss photomicroscope Pol II).

For physical tests, cubic specimens (size = 1.5 • 1.5 • 1.5 mm) were dried at 105 ± 5°C and the dry solid mass ($m_D$) was determined. The solid phases volume ($V_S$) of powdered rock specimens (on 5-8 g and with particle size less than 0.063 mm) and the real volume (with $V_R = V_S + V_C$, where $V_C$ is the volume of pores closed to helium) of the rock specimens were determined by helium Ultrapycnometer 1000 (Quantachrome Instruments). The wet solid mass ($m_W$) of the samples was determined after water absorption by immersion for ten days.

Through a hydrostatic analytical balance, the bulk volume $V_B$ ($V_B = V_S + V_O + V_C$ where $V_O = (V_B\text{-}V_R)$ is the volume of open pores to helium) is calculated as: $V_B = [(m_W\text{-}m_{HY})/\rho_W T_X]100$, where $m_{HY}$ is the hydrostatic mass of the wet specimen and $\delta_W T_X$ is the water density at a temperature $T_X$. Total porosity ($P_T$), water and helium open porosity ($\Phi_O H_2O$; $\Phi_O He$), closed porosity to water and helium ($\Phi_C H_2O$; $\Phi_C He$), bulk density ($\rho_B$), real ($\rho_R$) and solid density ($\rho_S$) are computed as:

$\Phi_T = [(V_B\text{-}V_S)/V_B]100$

$\Phi_O H_2O = \{[(m_W\text{-}m_D)/ \rho_W T_X]/V_B\}100$

$\Phi_O He = [(V_B\text{-}V_R)/V_B]100$

$\Phi_C H_2O = \Phi_T - \Phi_O H_2O$

$\Phi_C He = \Phi_T - \Phi_O He$;

$\rho_S = m_D/V_S$; $\rho_R = m_D/V_R$; $\rho_B = m_D/V_B$

The weight imbibition coefficient ($CI_W$) and the saturation index (SI) were computed as:

$CI_W = [(m_W\text{-}m_D)/m_D]100$

$SI = (\Phi_O H_2O/\Phi_O He) = \{[(m_W\text{-}m_D)/ \delta_W T_X]/V_O\}100$

The punching strength index was determined with a Point Load Tester (mod. D550 Controls Instrument) according to the International

Society for Rock Mechanics (1972; 1985) on the same cubic rock specimens used for other physical properties.
The resistance to puncturing ($I_S$) was calculated as $2P/D_e$, where P is the breaking load and $D_e$ is the "equivalent diameter of the carrot" (ISRM, 1985), with $D_e = 4A/\pi$ and A = WD, where W and 2L are the width perpendicular to the direction of the load and the length of the specimen, respectively. The index value is referred to a standard cylindrical specimen with diameter D = 50 mm for which $I_S$ has been corrected with a shape coefficient ($F_S$) and calculated as: $I_{S(50)} = I_S F = I_S(D_e/50)^{0.45}$.
The compression and tensile strengths were calculated by punching index values respectively as: $R_C = I_{S(50)} \cdot F_C$; $R_T = I_{S(50)} / 0.8$, where:
$F_C$ (conversion factor) is between 15 and 50 as function of size, characteristics and anisotropy of samples.
To construct the Santa Croce fortification (Figs. 2-7) different facies of Miocenic limestone (outcropping in the same site) were used.
These sedimentary rocks are frequently used in the civil and historical architecture of Cagliari city. As well as other lithologies, they belong to the sedimentary-volcanic stratigraphic sequence widely outcropping in western Sardinia (from north to south) within the "Fossa Sarda" graben (Vardabasso 1962), a complex geological-tectonic context of Sardinia (Adkovaat et al. 2014; Cherchi and Tremolieres 1984).
According to Cherchi (1971) and Pecorini & Pomesano Cherchi (1969), the geological formation of Cagliari area mainly consists (from bottom in the stratigraphic sequence) of the following lithologies:
- clays ("Argille del Fangario"), sandstones ("Arenarie di Pirri"),
- marly limestones ("Pietra cantone"),
- biocalcarenites ("Tramezzario"),
- biohermal limestones ("Pietra forte").

For the Santa Croce fortification *Pietra forte* and *Tramezzario* facies were mainly used and subordinately also *Pietra cantone*.

*Pietra forte*

It is a compact and hard limestone with high physical-mechanical strength, but more difficult to work with respect to the *Tramezzario* or *Pietra cantone* limestones. The *Pietra forte*, together other local limestones, was employed for the ashlars in the Cagliari fortifications, between which Santa Croce walls (Figs. 6, 7).
Moreover, also other monuments from different time were constructed using this limestone, *e.g.*: the Municipality building, the Cathedral of Cagliari, the Bonaria Basilica, the ancient towers (*i.e.* Elefante, San Pancrazio).
It is a cliff limestone, as bioherma or biostroma facies (Pecorini & Pomesano Cherchi, 1969), generally of whitish colour with yellowish spots. It is rich in remains of molluscs and especially algae (lithotamins), and big foraminifers (Amphistegin, Miogypsina, Elphidium, Rotalia, etc.) and briozoic colonies.
Based on the association of planktonic micro-fauna, the *Pietra forte* was referred to the Tortonian and, according to affinity with other similar formations present in the Gulf of Oristano, Messinian and perhaps partly also Pliocene (Cherchi 1974).
Excluded for parts characterized by the presence of large porosities and natural vacuoles (often with size from 0.5 to 4 cm) due to petrogenetic and / or karst processes, this rock has a high apparent density (typically ranging from 2.58 to 2.70 g / $cm^3$). This is due to its low porosity (usually < 4% vol.) and, on the other hand, to the high presence of calcite (which has a density of 2.71 g / $cm^3$).
Depending on these petro-physical characteristics, the mechanical resistance is high compared to the other two lithologies, with indirect compression strength ($R_C$) generally comprised between 16 and 58 MPa. The high data variability (with high standard deviation values) is due to the variable presence of variable pores and fractures at micro-, meso- and macro-scales. The indirect tensile strength ($R_T$) generally varies between 3 and 9 MPa. The physical-mechanical results accord to the data of Barroccu et al. (1981).

Due to good physical-mechanical resistance, the *Pietra forte* limestone does not show advanced forms of alteration.


Fig. 8- Compact limestone ashlar of Santa Croce's wall facade, with evident exfoliation and pitting processes and detachment of flake with thickness about of 5 mm

*Tramezzario*

It is a clayey limestone ($CaCO_3$ about 85-88%, Barroccu et al. 1981) with whitish colour and minute clasts and organogenic fragments. Based on the present macro-fauna (*i.e.* fragments of lamellibranchs and gastropods) and the microfauna it was referred to the Tortonian by Pecorini & Pomesano Cherchi (1969). It is generally an average compact limestone with good physical-mechanical characteristics and at the same time a good workability. For this reason it has been widely used in the ancient buildings until the beginning of the last century.
In the case of fortification of Santa Croce was used for the ashlars of walls. In some cases, due to high micro-fracturing processes (Barroccu et al. 1981), this rock has low consistency and poorly physical-mechanical behaviour.
It shows a high value range of bulk density (1.58-1.95 g/cm$^3$), due to the variable incidence of secondary porosity generated by micro-fracturing. The primary porosity is generally under 8% vol., but it can also rease more high values.
The compression and tensile strengths (on average: 9-13 MPa and 1-2.5 MPa, respectively) are much lower with respect to those of *Pietra forte*. For these reasons the *Tramezzario* some times shows evident macroscopic alteration forms: e.g., exfoliation and flaking on the surface portion of substrate (Fig. 8).

Fig. 9- View of part of Santa Croce's wall facade, with obvious replacements of the ashlars and cornice stone with other new of Orosei limestone and vulcanites (on the left and middle of photo, respectively) and the *garitta* decorative element completely decayed (on the top left)

*Pietra Cantone*

According to Folk (1959) and Dunham (1962) classifications this rock can be defined as biomicritic limestone and as wackestone, respectively. However, on the basis of microscopic observations and given the environment of deposition conditions, it is preferable to define them as marly limestones poorly cemented, with mainly muddy microcrystalline matrix and variable presence of bioclastic components. It has a $CaCO_3$ content generally assessed on the order of 75-80%, but can vary between 64 and 89% (Barroccu et al. 1981) depending on the different areas of Cagliari and on the depth of sedimentation. It characterised by low cementing degree, high porosity (on average 28-36% vol.) and for these reasons by an easy workability. It shows a bulk density ranging from 1.76 to 1.96 g/cm$^3$ (according to Columbu et al. 2017), as function on the composition and fabric of stone.

The compressive strength values are low (4.5-9.5 MPa), with values under the frequent ranges of unaltered samples taken from quarry. However, the values do not reach those of strongly altered samples taken at the surface of the outcrops (0.4÷0.8 MPa, Barroccu et al. 1981).

Fig. 10- View of decayed *garitta* of Santa Croce's wall and several replacements of the original ashlars with other new of vulcanites (in the corner of walls). This decorative and functional architectural element shows important dehoesion, exfoliation and alveolation processes with a risk of collapse

The *Pietra Cantone* generally shows a variable clay component (ranging from 10 to 30%) within the geological formation. For its easy workability and the wide availability in the territory around Cagliari, this limestone has been widely used to the historical buildings (Fig. 2) of all periods from Nuragic, to Phoenician-Punic, Roman and medieval (references in Columbu & Pirinu 2016). When not protected *versus* the weathering processes on monuments, especially in the presence of humidity or circulating aqueous solutions, this limestone frequently shows decay problems (Columbu et al. 2017). In the Santa Croce wall it was used mainly for the two "garitta" (*i.e.* sentry-box) and for the horizontal decorative frame with half-round section located in the upper side of wall, now virtually absent due to the evident decay (Figs. 9, 10).

## 5. Conclusions

The Santa Croce fortification was constructed using the main Miocenic lithologies locally outcropping in the Cagliari area: *Pietra forte, Tramezzario, Pietra cantone*. The first two, more resistant under physical point of view, were used to realisation of the ashlars of the walls, while the third, definitely less consistent, was used for the decorative parts (*i.e*., horizontal cornice, *garitta*) where more workability was needed. If the use of *Pietra cantone*, which had excellent workability, on the one hand facilitated the artisan in the processing of stone, on the other hand also facilitated the consequent processes of alteration, as can be seen from the great state of decay in which these decorative elements pour. So this choice was not technically perfect. The alteration processes of this stone are due to their intrinsic compositional and physical features, characterised by high porosity (generally >25% vol.) and the presence of hygroscopic phases (*e.g.* clay minerals, various kind of soluble salts). These latter lead to continuous hydration / dehydration cycles with physical decohesion inside the stone, a decrease of mechanical strength and consequent exfoliation/flaking processes on the surface, making this limestone easily degradable.

Differently from this latter, the *Pietra forte* and *Tramezzario* limestones (especially the first) show a different physical-mechanical behaviour with respect to the decay processes. In fact, due to their lower porosity (generally < 8% vol. on the bulk rock, excluding the macro-pores) and consequently higher bulk density, and different composition characterised by the absence of hygroscopic phases, they not have evident physical decay. However, some ashlars of the Santa Croce's wall realised with *Tramezzario* limestone show flaking process with occasionally detachment of the outer portion of material (Fig. 8).

In any case, the three studied limestones are regularly are affected by chemical alteration processes for the dissolution (or sulphation) of the carbonate matrix by acid rain (frequent in the urban environment), leading to obvious pitting processes and gypsum precipitation on surface, respectively.

Although several restoration works have been carried out in recent decades on the ancient walls, it is probably the case to think at least to intervene in the restoration of two *garitta* made in *Pietra cantone*, which pour into an advanced state of chemical-physical degradation. In fact, being positioned as a cantilever as a shelf (subjected to a constant tension effort, Figs. 9, 10), they could collapse, resulting in danger for those below the walls.

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