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SENIGALLIA HISTORIC TOWN WALLS: MATERIALS AND STABILITY ANALYSES

Paolo BUSDRAGHI, Francesco VENERI & Valentina IAMPIERI

University of Urbino Carlo Bo - Department of Earth, Life and Environment Sciences (DiSTeVA)
Corresponding author: francesco.veneri@uniurb.it

EXTENDED ABSTRACT

Il presente studio analizza le caratteristiche e lo stato di conservazione delle Mura storiche perimetrali di Senigallia (AN, Italia). Nate nel Rinascimento come poderosa opera di ingegneria militare eretta a protezione della Città, quindi ampliate a seguito dell'espansione della stessa in epoca settecentesca, con l'avvento di nuove tecniche e strategie belliche e per i mutati scenari geopolitici dell'Ottocento hanno progressivamente perso la loro funzione originaria. Tale inevitabile declino, unitamente ad una poco oculata pianificazione urbanistica, hanno causato nel tempo la perdita dell'unitarietà dell'Opera, che è stata inglobata e dispersa nel tessuto urbano cittadino, rendendone oggi difficile una adeguata fruizione, fino ad arrivare alla situazione attuale, in cui rischia di venirne compromessa anche l'integrità strutturale.

L'Amministrazione comunale di Senigallia ha pertanto promosso uno studio integrato multidisciplinare per giungere alla completa conoscenza dello stato di fatto di questa struttura, indispensabile per individuare le migliori tecniche di restauro e di risanamento conservativo così da poter elaborare il peculiare Manuale di Manutenzione dei Corpi di Fabbrica che la costituiscono.

Al fine di caratterizzare dal punto di vista chimico e fisico-meccanico i materiali lapidei di cui le Mura sono costituite, sono state individuate 16 parti campione di 1m x 1m, rappresentative delle diverse situazioni di degrado riscontrate, nonché delle caratteristiche costruttive delle fasi diacrone. Per ciascuna stazione, oltre alle riprese fotografiche e alle analisi macroscopiche, con relativa descrizione archeometrica e dello stato di degrado, è stata rivolta particolare attenzione allo studio delle malte, considerandone le differenti tipologie di utilizzo nelle murature, distinguendo cioè quelle strutturali da quelle dei giunti. Ciò in quanto le malte rappresentano gli elementi di maggior debolezza strutturale dell'intera opera architettonica, e sono state quindi oggetto di specifiche analisi mineralogico-petrografiche e fisico-tecniche, in situ ed in laboratorio.

Gli studi e le ricerche svolte hanno permesso di ricostruire lo stato di fatto materico e geotecnico dell'apparecchio murario, la cui conoscenza è indispensabile per individuare e progettare le possibili soluzioni di intervento sull'Opera in relazione al particolare pregio storico-architettonico del monumento. La caratterizzazione storica e quella materico-strutturale dei manufatti ha accertato condizioni di conservazione a luoghi insufficienti, anche in conseguenza delle evoluzioni incontrollate del corpo di fabbrica originario. Le analisi mineralogiche e fisico-meccaniche hanno infatti evidenziato la qualità scadente dei materiali in opera. In particolare le malte mostrano una ridotta resistenza meccanica, sia per la crescita di sali dovuta agli sprays marini ma soprattutto a causa della dissoluzione del legante carbonatico delle malte, con conseguente riprecipitazione di sali di neoformazione. Inoltre, e non ultimo, gli effetti dell'inquinamento atmosferico da traffico veicolare, con emissione di particolato carbonioso ma anche di ossidi di zolfo, hanno portato alla formazione di croste nere e alla trasformazione del carbonato di calcio del legante in gesso, solubile, che hanno determinato la decoesione intergranulare, con conseguente formazione di vuoti e incremento della permeabilità, e quindi al distacco dei paramenti dalla massa muraria. Va inoltre considerato che questi effetti agiscono su un'architettura "povera", eseguita con materiali di riutilizzo/reimpiego e con leganti a base di calce idrata, definibile "bastarda" in quanto ottenuta con materie prime e temperature di cottura non del tutto idonei, quindi senza le necessarie doti fisico-tecniche. Ciò può portare nel tempo alla disgregazione dei materiali lapidei e, quindi, al disfacimento dell'opera. Ciononostante le resistenze della massa muraria, pur considerando gli interventi urbanistici incontrollati, in particolare quelli di sopraelevazione, fino ad oggi realizzati, sono comunque al di sopra, in condizioni statiche, dei carichi applicati, anche se potrebbero non essere sufficienti in caso di eventuali accelerazioni sismiche che dovessero interessare il sito.

Riguardo invece i terreni fondali, tramite i numerosi dati disponibili in letteratura sono state ricostruite la stratigrafia e le proprietà fisico-meccaniche del substrato geologico sopra cui si sviluppa il centro storico. In base ai dati ottenuti e ricostruendo le quote fondali in vari settori della Città, è stato possibile stimare in due aree campione, rappresentative delle differenti situazioni riscontrate, i carichi unitari che l'opera difensiva trasferisce al terreno, valutandone l'interazione con questo anche in considerazione dell'elevato rischio sismico cui l'area urbana di Senigallia è esposta. Considerando questo aspetto alla luce della normativa vigente risulterebbe che i carichi ammissibili dei terreni fondali sarebbero lievemente inferiori ai carichi applicati. L'apparente incongruenza tra ciò e il fatto che la struttura non manifesti alcuna evidenza di cedimento è giustificabile considerando che i lunghi tempi di fabbrica, di cui le passate tecniche edificatorie necessitavano, davano modo ai terreni fondali di assestarsi gradualmente man mano che i carichi venivano applicati, migliorando così i propri valori di resistenza. Ciò tuttavia non può emergere dai dati disponibili in letteratura in quanto nessuno dei campioni esaminati deriva direttamente dai terreni posti sotto la fondazione dell'apparecchio murario ma soltanto da aree circostanti, non sottoposte a sovraccarico.

ABSTRACT

This work analyses the characteristics and state of preservation of the historical perimeter walls of the town of Senigallia (Ancona Province, Italy) and faces the problems tied to its degradation. This situation, in conjunction with incautious urban planning, has caused the loss of a sense of unity of the work, now absorbed and scattered in the current urban fabric; this renders its proper fruition difficult, arriving up to today's situation in which the risk of being structurally compromised has arisen.

This study presents innovative elements in the field of restoration work. The wall is analysed as if it were a geological body, especially the mortar characteristics which are its primary structural weakness; the analyses range from mineralogical – petrographic to physical-technical and were carried out both in situ and at the laboratory, with an evaluation of the foundation soil. The goal is the reconstruction of the current state of the Senigallia historic walls and, in particular, to bring out its technical, structural and physical characteristics of great architectural-historical value, in addition to its interaction with the geological substrate. This was carried out in order to identify the best restoration and preservation techniques so as to elaborate a peculiar Operations and Maintenance Manual for its constituent elements, bearing in mind the seismic properties of the area.

Keywords: Senigallia (Italy), historic walls, building technique, stone materials characterization, stability

INTRODUCTION

This study is launched in July 2011 as a part of the 'Senigallia Town Wall Network Preservation and Development Plan', promoted and coordinated by the Administration of the same. For this purpose, an interdisciplinary team of local-based professional experts and of neighbouring universities researchers has been set up in order to gather the necessary scientific expertise for the study at hand. All geotechnical, chemical and physical aspects have been entrusted to the University of Urbino, given its long-standing experience in these disciplines.

The urban walls of the town of Senigallia, conceived as a work of military engineering for the town's protection, lost their original use after the advent of new military strategies and techniques, resulting in the decomposition of its wall components and its more and more irremediable decline towards an 'urban ruin'.

Thus, the aim of this study has been to identify and define the constituent stonework elements (mortar, bricks and stone) through a contextual analysis based on their degradation and production timeline. In particular, this study has focused on the binding agent, the mortar, which is easily subject to decomposition and disintegration processes, and so represents the weakest and most critical element of the entire wall structure.

Keeping in mind that these areas are characterized by a high seismic risk, the interaction of the wall structure with the geological substrate has also been evaluated.

For this reason, a multidisciplinary integrated study conducted by work group was deemed necessary, its members being: Senigallia Council Architects, Archaeologists belonging to the University of Bologna History, Culture & Civilization Department and Geologists of the University of Urbino Department of Earth, Life & Environmental Sciences. This methodological approach, a fundamental element in formulating an overall assessment, takes into account a number of crucial factors while each member provides one another with complementary indications.

HISTORICAL BACKGROUND

During its very important past, the town of Senigallia has played major roles in political and historical affairs on a national level. Each historical phase corresponds to important moments in urban transformation, especially the surrounding walls between the XV and XVIII Century A.D. A particular reference is made to the construction work commissioned by Guidobaldo II della Rovere at the end of the XVI Century, in line with the classic City-Fortress of the Renaissance Era, and the eighteenth century work, designed as a city expansion by will of Pope Benedict XIV.

In fact, Senigallia, which was already known in ancient times as the capital city of the Gallic tribe of Senones (Sena Gallica), is brought back to the fore at the end of the XV Century under the management of the Malatesta family, after having undergone a period of heavy decadence and dereliction in medieval times. The Malatesta commissioned the first rectangular-shaped fortification and the nucleus of the citadel (Raggi, 2013). In 1508, Senigallia comes under the dukedom of Urbino, thanks to the Della Rovere. The citadel is completed in this period and expansion work on the surrounding walls is set in motion, taking on a pentagonal shape (Fig. 1) surrounded by a moat - a very common layout for Italian Renaissance towns.

Thanks to a long period of political stability, the eighteenth century bears witness to demographic and economic growth, its peak being the Maddalena Fair: an event created around the XIII Century, later becoming a custom tax free fair. Spurred on by its strategic position and tax concessions introduced in Malatestian times, it emerges as one of the top European fairs, exchanging goods from the four corners of the Mediterranean. Such a development heralded the need of a new city expansion (Fig. 2), hence also its surrounding walls, given the inadequacy of the current settlements and facilities (Raggi, 2013). In this phase, the walls running across the right bank of the Misa River were demolished in order to give rise to the first portici (Portici Ercolani), the last part of the current historical centre is built, the south-west section of the river's watercourse is rectified and some bastions are modified.

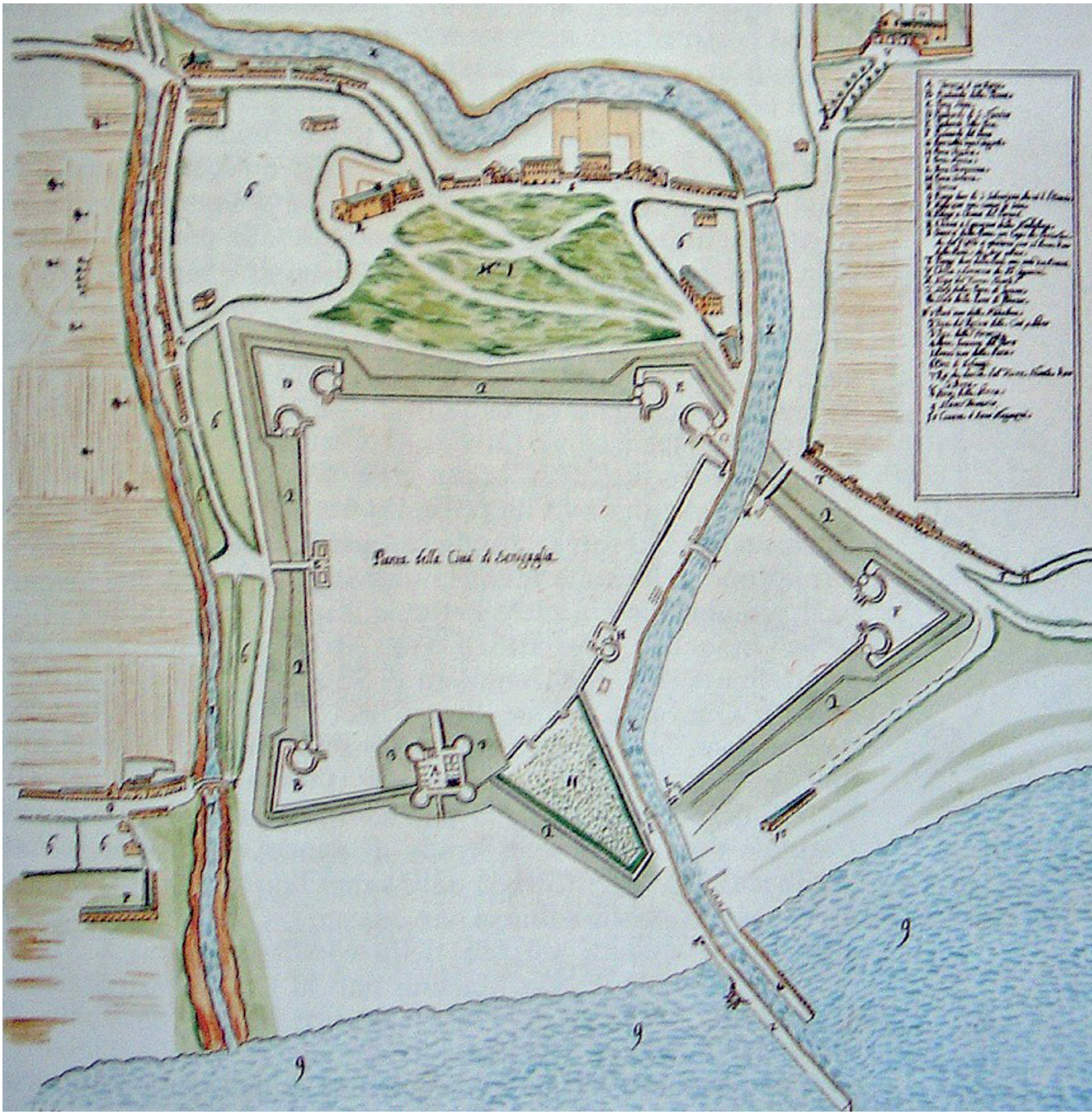


Fig. 1 - Senigallia city map where the pentagonal shape of the fifteenth century fortification is clearly visible (A.S.PU Apostolic Legate, newsletter reply, b.5, 1732)

The Maddalena Fair crisis is therefore followed by a degradation caused by the concurrence of a number of factors, such as the ever-growing major trade shift from the Mediterranean to the Atlantic, the spread of plague and the non-stop progressive landfilling of the riverbed. The city will overcome this period of crisis towards the end of the nineteenth century, thanks to its new tourism-seaside resort vocation, paving the way to new urban planning, with many instances of demolition along the surrounding walls.

The beginning of the XX Century witnesses the definitive loss of the 'walled city' identity, also due to the devastating effects of the 1930 earthquake which caused the city huge historical-

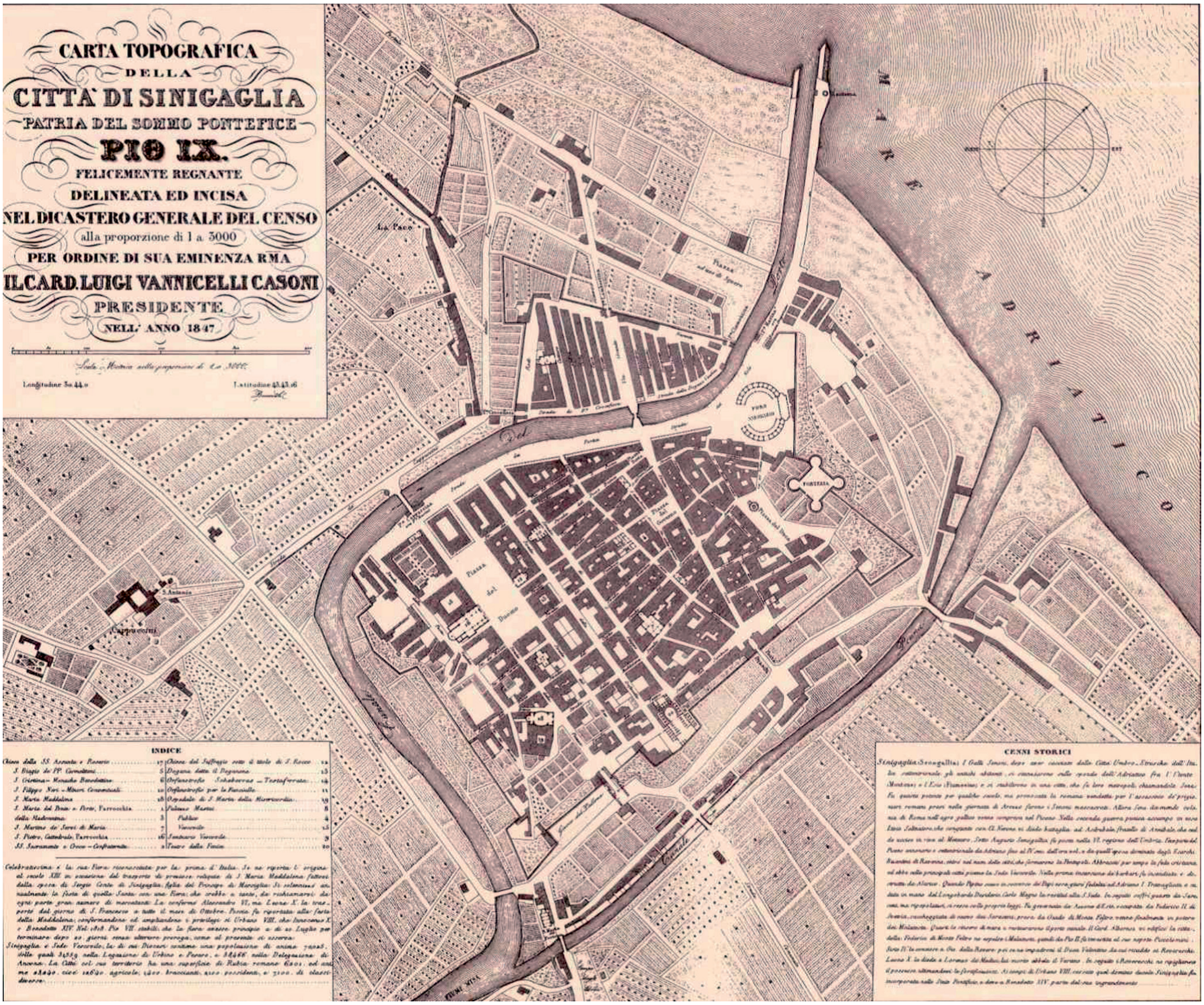


Fig. 2 - Eighteenth century expansion of the city, along with the expansion of the urban walls (Census Main Office, Senigallia City Topographic Map, Vatican City, 1847)

cultural heritage devastation. Notwithstanding the tourist-seaside resort progress, the state of the walls continued to worsen through a lack of maintenance and resulting phenomena of degradation, up to today's current situation.

ARCHITECTURE, GEOLOGY AND CITY SEISMICITY

The almost flat morphology of the Senigallia historical centre, with the exception of the sloping banks of the Misa River, does not present significant height differences or higher slabs on which to situate defensive structures. Therefore, the walls have been built in elevation with respect to ground level and consist of a series of bastions connected by curtain walls, that support and protect a defensive rampart at least 4-5 metres high and about ten metres wide. The latter has the function of increasing the overall thickness and strength of defensive structure and also acts as a sentinel walkway.

The presence of a curtain wall to protect the inner side of the rampart it is not always perceivable and scientists have different opinions regarding its existence.

The cortina wall is made up of an external clay-brick masonry wall in double course pattern, and an internal semi-pattern made up of rock and/or brick. Amongst these elements we can find a filler, a 'rubble stone fill' with a chaotic structure, made up of bricks, both fragmented and whole, mortar and chalky rubble. The external scarped masonry has a 10º outwards inclination (Fig. 3).

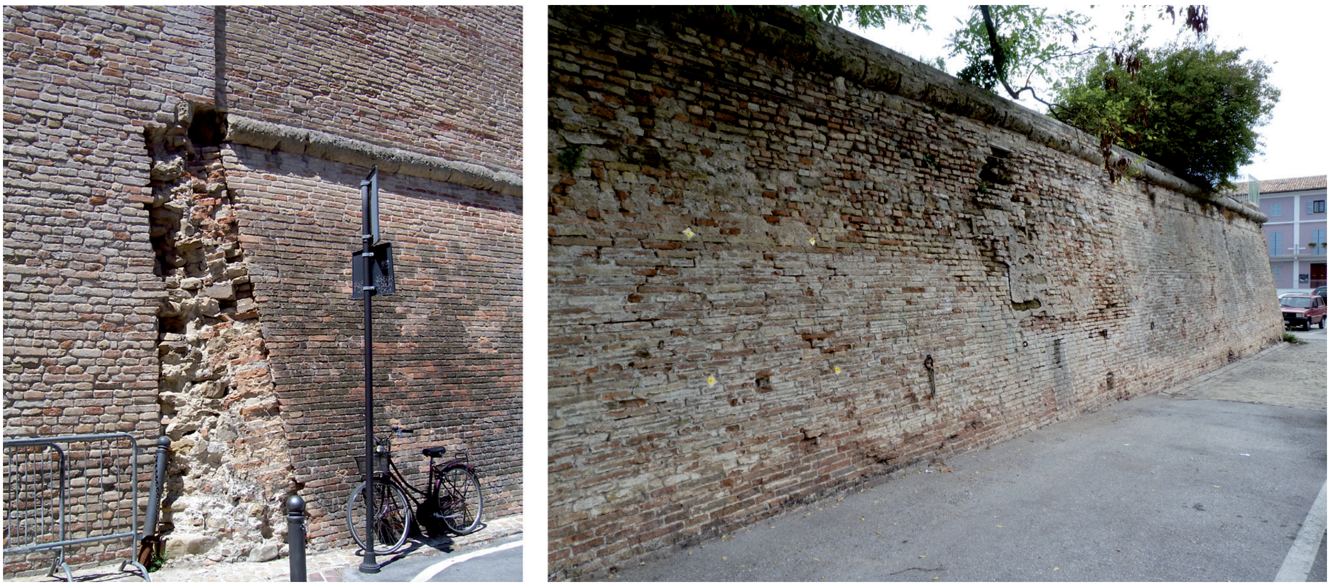


Fig. 3 - Left: section of the sixteenth century scarped walls near Porta Lambertina; it is possible to make out the characteristic 'rubble stone fill' structure, characterized by an orderly outer brick wall face with sporadic stonework elements, and an internal portion of filler (the internal façade is not visible here), chaotic, in which recycled materials of various nature may coexist, like whole or fragmented bricks and rocks; these are all immersed in mortar. Right: eighteenth century heavily eroded outer brick wall, Gothic brick wall pattern

Fig. 4 - Della Rovere walls: spine walls in the excavation site of the Baluardo del Porto (left) and of the new Teatro La Fenice within the San Martino Bastion (right) (RAGGI, 2013)

The cortina walls have an average width of about 170 cm at floor level; due to tapering, it is reduced to about 60 cm at the top, which is embellished by perimetral calcarenitic circular edgings. Well-connected orthogonal spine walls stem from the cortina wall to create a structural link between masonry and rampart (Fig. 4).

The bibliographical and archive research has helped to identify the different diachronic construction work phases of this architectural structure, which has partially superposed itself over the original artefacts and the foundation substrate. This has made it possible to identify homogeneous wall portions and, thus, to divide the city walls by main historical periods, namely: the Rocca Roveresca at the end of the fifteenth century, the Walls of the sixteenth century and the eighteenth century walls (cf. Fig. 8).

A first reconnaissance along the city wall perimeter was conducted in order to evaluate the current state of the locations. This has drawn the attention on numerous situations of degradation. Furthermore, this study has been conceived as a reference for future restoration and preservation, which cannot be isolated from an in-depth knowledge of the 'matter' pertaining to the architectural complex; the latter is intended as an unicum between artefact and foundations in their reciprocal interaction. The pertaining territorial context has also been taken into account.

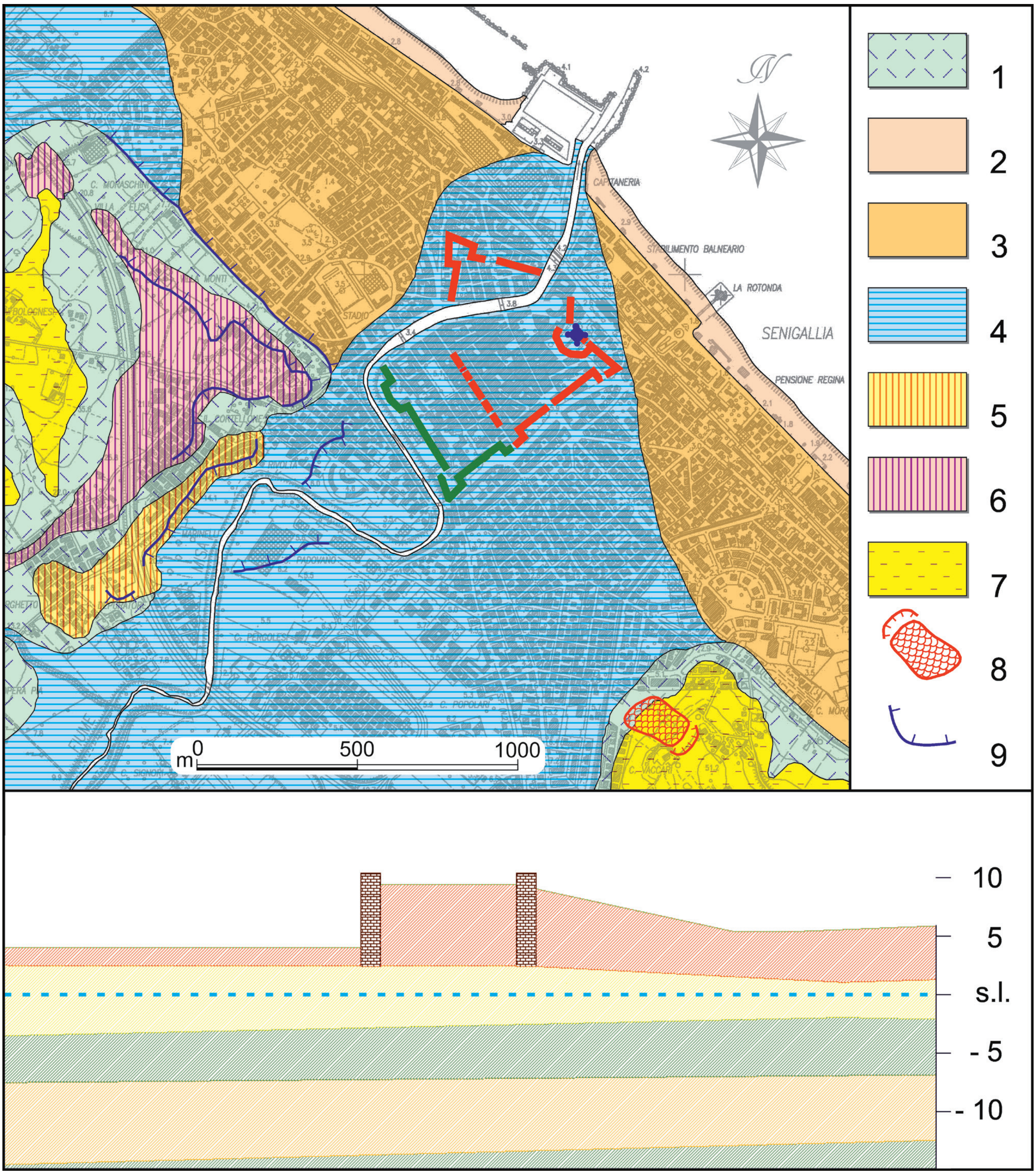


Fig. 5 - Above, geological map of the Senigallia area (modified from Bozzano et alii, 2007; AA.VV., 2010). Below: 80 m long stratigraphic profile with the eighteenth century city walls in the centre. The stretch is between the Benedictine Monastery and the Misa River, developed on the data reported by Bozzano et alii (2007). The wall foundations are set in the soft lime-clay soil (yellow), under a layer of backfill (red) which, situated just under the walls, is up to 7m thick; greater depths alternate between layers of gravel (green) and sand-lime soil (orange), attributable to the alluvial deposits, up to the Argille Azzurre Formation, situated at more than 20m below ground. The continuous light blue line represents the piezo line, which has an unknown evolution and real backfill permeation value

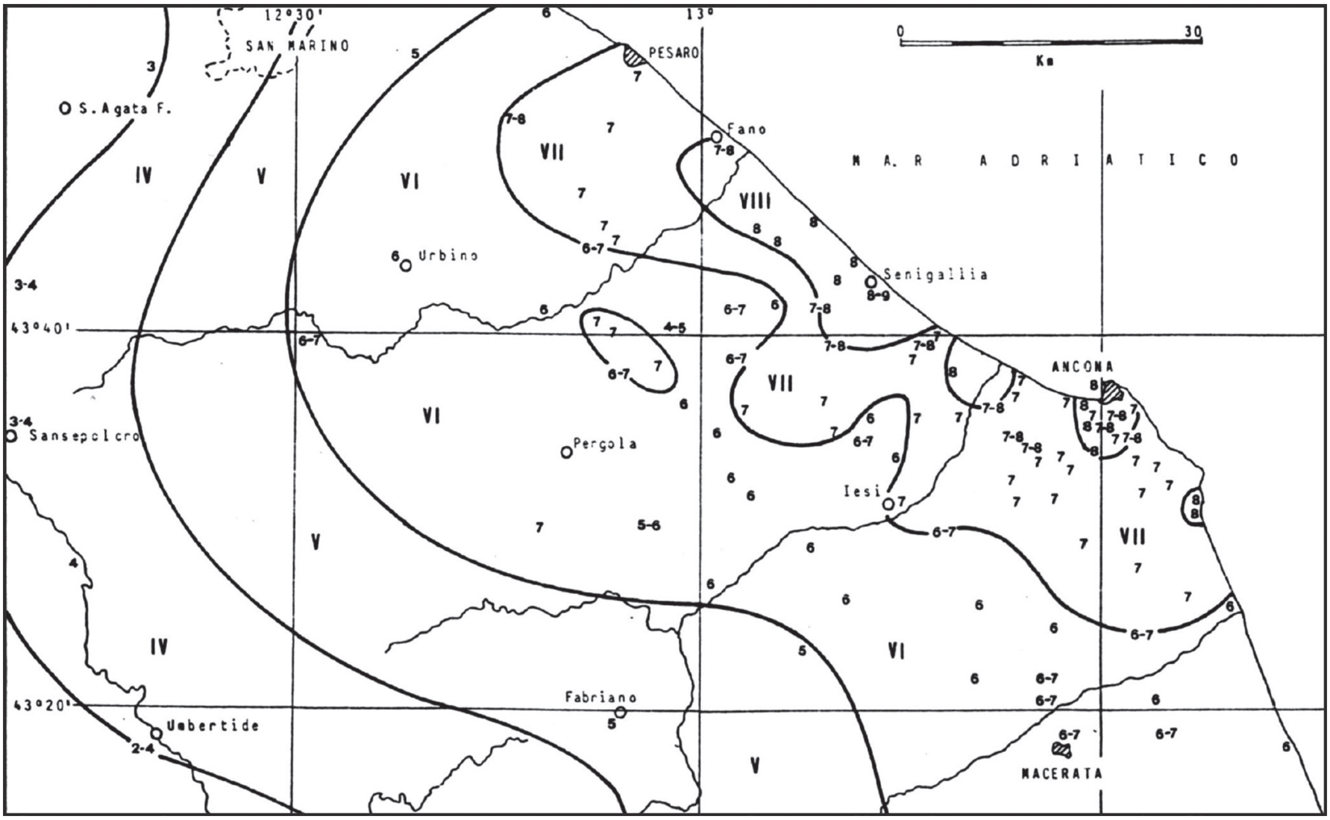


Fig. 6 - *Isoseismic map of the 1930 earthquake. The most damaged area is clearly stretched NW by SE (da* Molin *&* Mucci*, 1992)*

Following the dispositions set forth by the NORMAL Commission (NORmativa MAnufatti Lapidei) founded in 1977 by Ministry of Cultural Heritage decree, later turned into UNI-EN, the units have been the object of an on-site macroscopic survey. Thanks to a qualitative analysis of the fundamental stone work materials (mortar, clay-brick and stone) it was possible to evaluate the state of preservation.

It was then proceeded to take samples for further laboratory analyses. The attention was focused on the mortar, given that the latter represents the least resistant material of a masonry wall (Vannucci & Busdraghi, 1991; Busdraghi *et alii*, 1992, 1994, 1997; Busdraghi & Veneri, 1994, 2003), displaying physical-mechanical properties which are generally mediocre. Both the structural mortar of the filler ‘rubble stone fill’ (Fig. 3) and the masonry joints have been taken into account in order to define the structural characteristics of the brickwork and ascertain the different phases that have been brought to light by the historical-architectural study.

The materials investigation cannot be lacking in an in-depth knowledge of the geological characteristics of the foundation soil. The reciprocal interaction between foundation substrate and artefacts does in fact influence the condition of stability of the latter.

The subsoil of the historical centre of the city (Fig. 5) mainly consists of continental, Quaternary deposits of fluvial origin, situated beneath a man-made fill (often variable in thickness, in average 3m, but with values up to 6m in sections that, starting from the Foro Annonario, lead towards the Misa River bend and Porta Lambertina). These alluvial deposits are mainly silty with thin and discontinuous sandy and gravelly intercalations; one or two levels of gravel with sandy matrix there are also present at their base.

Starting from about 22 m from ground level, this alluvial succession rests to Plio-Pleistocene pelitic deposits of marine origin (Argille Azzurre Fm.) that locally represent the geological bedrock.

This type of layout confines the deeper ground waters within the basal gravel levels, that therefore contain a pressurised aquifer. Vice versa, the topsoil possesses unconfined groundwater which is recorded, keeping the moderate a.s.l. difference in mind, i.e. the base level of the surface water circulation, as only a few metres under ground level (4-5 m in the historical centre). These characteristics, along with the high-risk seismic area, expose the city and, in particular, the historical centre which was inevitably built without any of the current anti-seismic norms on seismic risk. In fact, the city was already hit and nearly wiped out (Dolce & Speranza, 2007) by a violent earthquake with epicentral intensity I_{max} = 8.5 MCS and estimated magnitude M_w = 5.9 (Fig. 6) (Molin & Mucci, 1992; Rovida *et alii*, 2011), which expressed

Fig. 7 - 1930 earthquake damage assessment map of the Senigallia Historical Centre (Dolce & Speranza, 2007)

its disruptive force within a 15-20 km radius and that represents a classic example of northern Marche coastal belt seismicity (Basili *et alii*, 2008; DISS Working Group, 2010).

The event manifested according to a reverse fault mechanism, Senigallia seismogenic source ITIS030, with a hypocentre recorded between 3 and 8 km below ground. The effects of the event were as significant as to call for a massive demolition and reconstruction intervention, causing a radical mutation in the urban and structural planning. Thanks to a series of photos, Dolce & Speranza (2007) were able to create the map of the Senigallia Historical Centre Damages (Fig. 7) which involved numerous portions of the wall adjacent to the urban buildings. Their direct involvement had produced hefty damage, both for the eighteenth century and sixteenth century walls, as well as the Foro Annonario-Rocca Roveresca.

CHARACTERIZATION OF THE STONE MATERIALS

As described above, the Senigallia historic town walls are made up of bricks and, to a lesser amount, of blocks of stone (mainly calcarenite), with a mortar binder. In order to characterize these constituents, 16 1m x 1m 'sample squares' have been chosen (Fig. 8); they represent different degradation scenarios, as well as the construction characteristics of the diachronic phases. For each station, in addition to the photographs, macroscopic analysis have been made, with archeometric description and state of degradation evaluation, highlighting different employment typologies, from structural to joint utilization, for the mortar.

Then, from each 'sample sites' small parts/portions of mortar have been collected (Fig. 9) to be destined for ESEM microscopic observation and X-ray diffractometry, so as to, consequently, characterize the mortar to be utilized in operations of preservation and restoration. This will ensure an affinity with the original materials, both for durability and, more importantly, will not damage the pre-existing structure. In addition, ad hoc investigations have been carried out for the physical-mechanic characterization of the mortars with the following parameters: gravity weight (*Gs*), dry unit weight (γ_d), porosity (*n*), inbibition coefficient in weight and volume (*I.C.w* and *I.C.v*) and saturation index (*S.I.*). Finally, given the aims of this study, to evaluate the entire wall structure resistance under compressive and/or shear stress and, at the same time, to verify the overall stability conditions along with the foundation soils, even the mechanical properties of wall less resistant materials, i.e. the mortars, have been determined.

All of these elements in this integrated study, which vary from Earth Science to Material Technology, have led to evaluate the most suitable actions of preservation and restoration for the encountered situations.

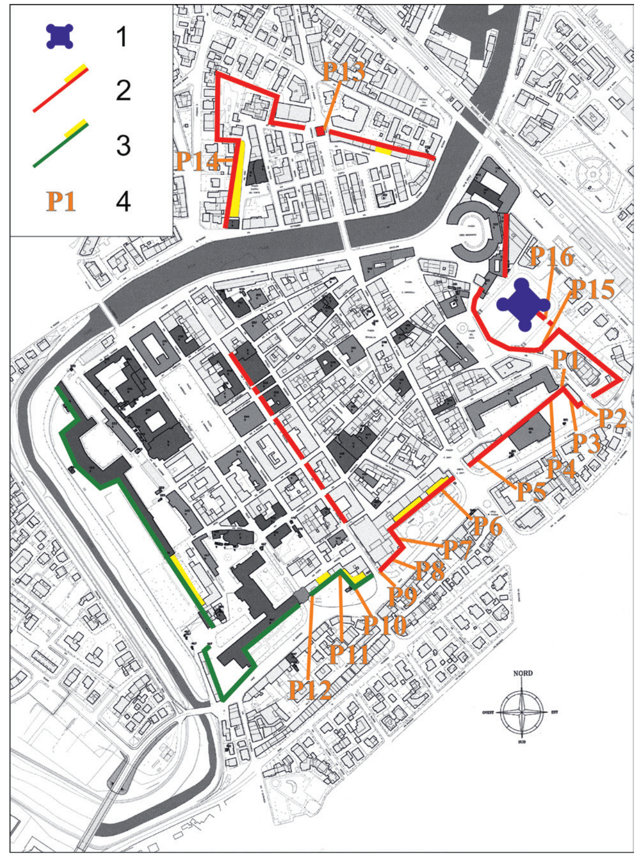


Fig. 8 - Senigallia city map with, in color, the perimeter of the three main construction phases of the urban walls: 1) the Rocca Roveresca (end of XV Century); 2) the Renaissance walls (XVI Century); 3) the eighteenth century walls and 4) location of the 16 survey sites
The yellow coloured bands indicate the sections in which rampart is preserved

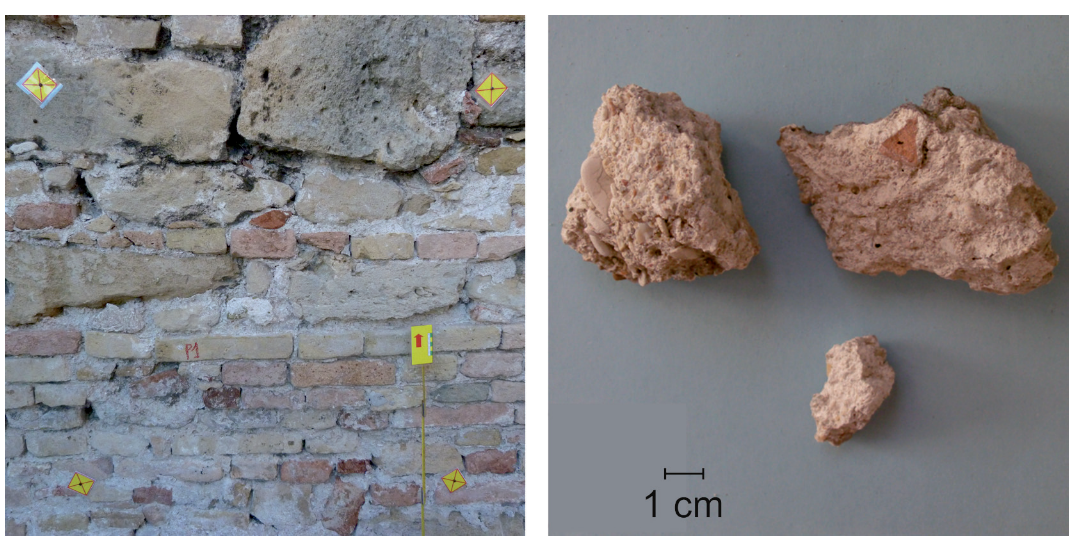


Fig. 9 - Left: part of sample P1 (1m x 1m) in which four reference points in cross formation mark the extremities; Right: mortar sample taken from this site

Fig. 10 - Left: detail of some windows built in the lower wall beside the Penna bastion during construction of the upper building. The wall section is susceptible to degradation phenomena (a light grey 'patina' formation most likely tied to exhaust gas emissions from vehicles in the adjacent parking lot) Right: sixteenth century walls contiguous to the Penna bastion. The chemical degradation is coupled by a physical-mechanical action exerted by weeds (wild capers) along the mortar joints

The first onsite reconnaissance has helped to identify highly degraded and abandoned situations, together with chemical alteration processes due to traffic pollution and salty air. In fact, Senigallia is a seaside town and, therefore, is affected by sea sprays, forming salt efflorescence. The decay by marine spray is well known in literature (Laurie & Milne, 1927; Arnold & Zehnder, 1989; Zezza, 1996; Nunes *et alii*, 2013).

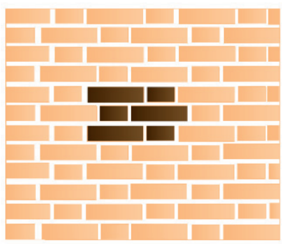
The chemical alteration phenomena have also led to the formation of black crusts, which, probably, are the most studied type of degradation on carbonate-based stones. The calcareous stone elements, mortar and plaster, are in fact attacked by water acidified by carbon dioxide, which transforms the carbonates, insoluble, into bicarbonates, soluble[1], and water, acidified by sulphur trioxide from atmospheric pollution, which transforms the carbonates into calcium sulphate dihydrate (gypsum), with much faster dissolution rates for porous materials, such as mortar. The most common products referred as constituents of such black crusts are, indeed, calcium carbonate, gypsum and soot. Easily distinguishable from the underlying parts by their different morphological and chromatic characteristics, these black crusts are variable in thickness: hardened, fragile, and easily detachable. At the surface, in fact, crust becomes thicker, while, below, the gypsum crystals growth cause the detachment of the overlying crust (haloclasty), leaving a bare, powder-like material which can be easily attacked by further physical-chemical processes (Lazzarini & Laurenzi Tabasso, 1986). Also efflorescence, with the formation of a generally whitish, crystal-looking substance, powdery and filamentous on the surface of the brickwork[2] contribute to the general decay of the wall structure.

In parallel to the chemical alterations are the physical-mechanical and biological processes, which have an even greater effect; besides having a direct effect, they create preferential way for water infiltration, one of the substances which has a greater degradation capability on the structure, both chemical - as indicated above - and physical.

The observed physical-mechanical processes are represented by the following phenomena: pitting, with the formation of deep cavities of variable shape and size, often interconnected; superficial cracks, hairline cracks on the plastering surface; discolouration, chromatic alteration of the surface connected to phenomena such as oxidation and prolonged exposure to atmospheric agents; superficial deposit of atmospheric dust and other foreign materials of different thickness, scarcely coherent and adhesive to the plastering surface; superficial erosion,

[1] *The process, even though generally slow, leaves the surface of the material corroded and weak with respect to other corrosive agents and phenomena; the formation of the actual black crust is attributed to the re-crystallization of the previously dissolved calcium carbonate*

[2] *In case of saline efflorescence, typical of coastal areas, crystallization can sometimes come about from inside the material, often causing the more superficial parts to detach themselves from the wall. In this case, the phenomenon is thus called 'crypto efflorescence' or 'sub efflorescence'*



Bricks and mortar joints parameters mean values	Sixteenth century wall	Eighteenth century wall
Bricks length (cm)	*30.6*	*31.4*
Bricks height (cm)	*5.5*	*4.7*
Bricks width (cm)	*14.2*	*15.2*
Horizontal mortar joints tickness (cm)	*1.6*	*1.1*
Vertical mortar joints tickness (cm)	*1.2*	*0.9*
"Yellov bricks" predominant colour (Munsell Color Chart)	*10YR7/4 - Very pale brown*	
"Red bricks" predominant colour (Munsell Color Chart)	*10R5/6 ÷ 2.5YR5/6 - Red*	

Tab. 1 - Table summarizing the mean values of the main dimensional and chromatic parameters for sixteenth and eighteenth century wall bricks and mortar joints. Left: Brick Gothic or Polish Brick Pattern, a common factor in both sixteenth and eighteenth century walls

exfoliation, cracking, moisture penetration, pulverisation, swelling, chipping, flaking and wall cracks caused by past seismic phenomena present in this area.

As far as the aggression of biological agents is concerned, a biological patina has formed: a clearly organic surface film, soft and homogeneous, adhering to the surface, of variable colour, mostly green, made up mainly of micro-organisms, such as lichens, to which dust and soil can adhere. The biological degradation is also connected to the top infesting vegetation and other organisms, such as musk and mushrooms. Furthermore, poor management of the structure from an urban planning perspective must not be overlooked: buildings too close to the walls, instances of neglect or poor maintenance (Fig. 10).

The archaeometric characterization highlights the differences between the sixteenth and eighteenth century walls. In Table 1 are reported the main dimensional parameters of bricks and mortar joints of these two historical periods. In particular, an overall colour difference, already clear at first glance, can be observed. This was objectively confirmed by using the Munsell Color Chart (Munsell, 1994). In fact, during the XVIII Century the percentage of yellow-coloured bricks versus red is significantly increased, the latter more frequent in the sixteenth century walls. This is, without doubt, to be attributed to the improvement of the brick firing, allowing higher and more homogeneous temperatures to be reached (Busdraghi *et alii*, 1992). Furthermore, the eighteenth century bricks seem to be longer and thinner with thinner mortar joints. However, the pattern of the brickwork remains unchanged.

The hand specimen examination shows that the analysed mortars are lime mortars, with some irregular whitish lumps of various sizes. The cutting surfaces of the specimens reveal the poor consistency of the mortars. The texture of the aggregate fraction is fine to medium grained, from moderately to poorly sorted, with a considerably coarse tail of well-rounded medium to coarse carbonate pebbles up to 2 cm in size.

Optical microscopy petrographic observations reveal that the silicate components of aggregates consist of monocrystalline angular quartz, polycrystalline sub-rounded quartz and unaltered feldspars (mainly plagioclase). Besides mentioned pebbles, carbonates are represented by sparry calcite grains, also of medium size, and smaller bioclasts and bioclastic fragments. Intergranular binder, that ranging from 15% to 25%, appears rather well cloudy, with lumps of lime of various sizes, sometimes abundant, and/or voids deriving from the dissolution of these. It consists of a micro- to crypto-crystalline carbonate matrix embedded in a non-crystalline phase.

Then, only the binder fraction, mechanically split from aggregates under a direct light microscope, have been analysed. The ESEM analyses (Fig. 11) have helped to identify halite, chalk and barium minerals, albeit in small quantities in comparison of what one would expect and, above all, delimited to the most superficial portion. The X-ray diffractometer analysis (Tab 2) of highlights a high contents of calcite, an abundant amount of quartz and a minor quantity (a few percentage points) of other silicates, such as plagioclase and other feldspars. The calcimetry tests (Fig. 12) have confirmed the XRD analysis results, displaying a high content of $CaCO_3$ in all samples, to values ranging between a minimum of 46.91% for the crusts, up to a maximum peak of 67.22% for sample P10 of the Eighteenth century.

The mortar elements under examination refer to highly impure hydrated lime and carbonate aggregates and, in a complementary fashion, silico-carbonates; they have been produced by non-uniform firing of local calcareous-marly rock

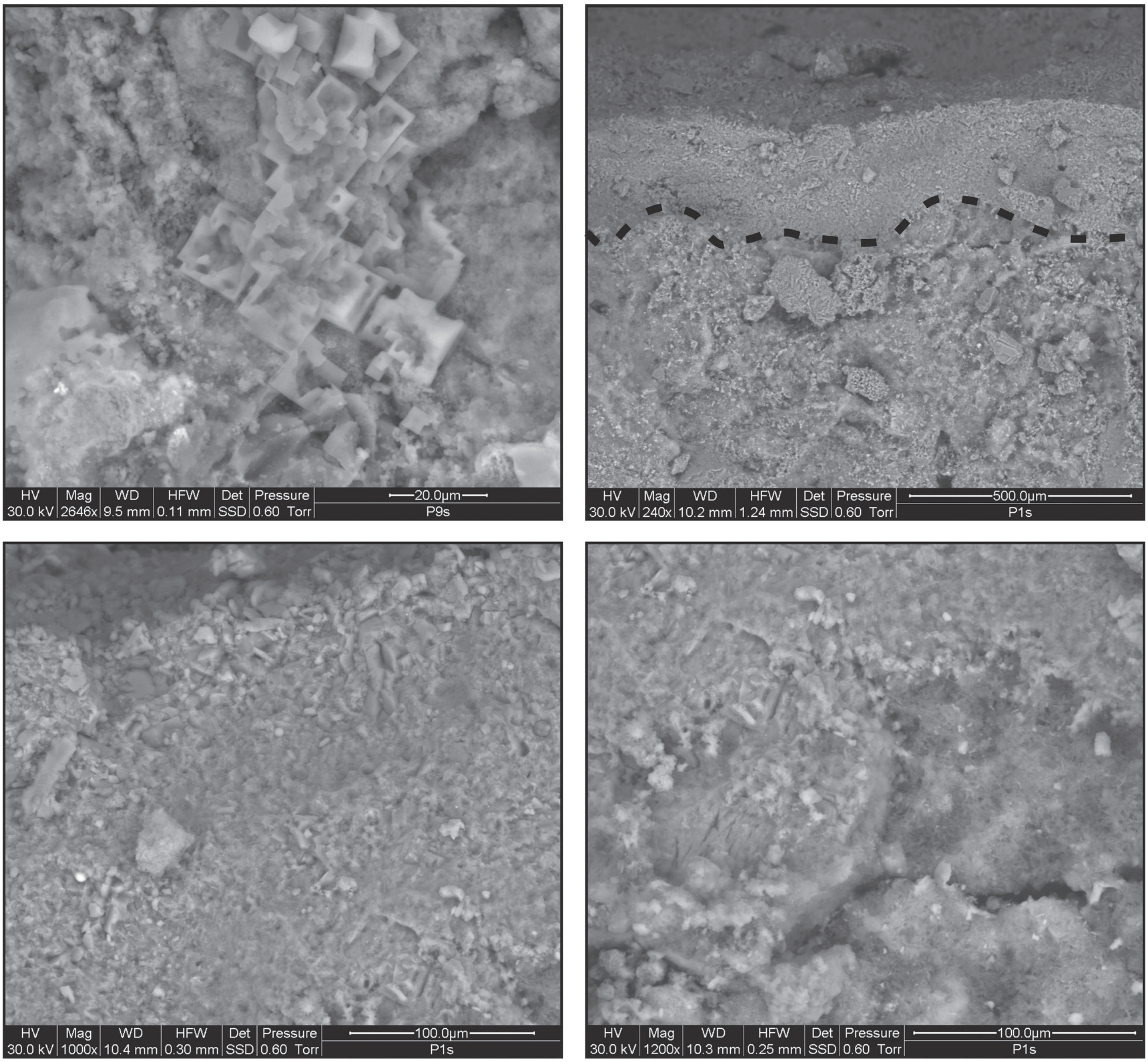


Fig. 11 - ESEM images: 1 - sample P9, where NaCl crystals with their characteristic cubic crystalline shape are highlighted; 2 - a top to bottom pass from crust to unaltered portion in sample P1 (numerous quartz crystals can be observed); 3 - magnification of the crust of sample P1; 4 - the unaltered portion of sample P1

Mortar bulk composition					
Sample	**Epoch**	**Quartz %**	**Calcite %**	**Feldspar %**	**Gypsum %**
P9 s	*'700*	*36*	*59*	*5*	*-*
P10 g	*'700*	*14*	*75*	*2*	*9*
P12 g	*'700*	*50*	*45*	*5*	*-*
P13 s	*'500*	*42*	*58*	*-*	*-*
P14 s	*'500*	*44*	*54*	*2*	*-*
P15 g	*'500*	*42*	*53*	*4*	*-*
P16 s	*'500*	*43*	*55*	*2*	*-*

Tab. 2 - X-ray diffractometer analysis results. s = structural mortar, g = mortar joints

fragments at around 600-650°C (Busdraghi *et alii*, 1994). They are defined as 'bastard' for their poor purification from their non-carbonated fraction and/or containing a certain amount of non-hydrated calcium oxide (quick lime lumps), giving rise to mediocre physical-mechanical characteristics (the total of samples taken/observed break apart easily with mere pressure of the fingers) with earthy appearance. The inert, with a 2:1 ratio presence to the binding material, is part carbonate, part silicate, with a relatively dispersed grain size distribution, medium-

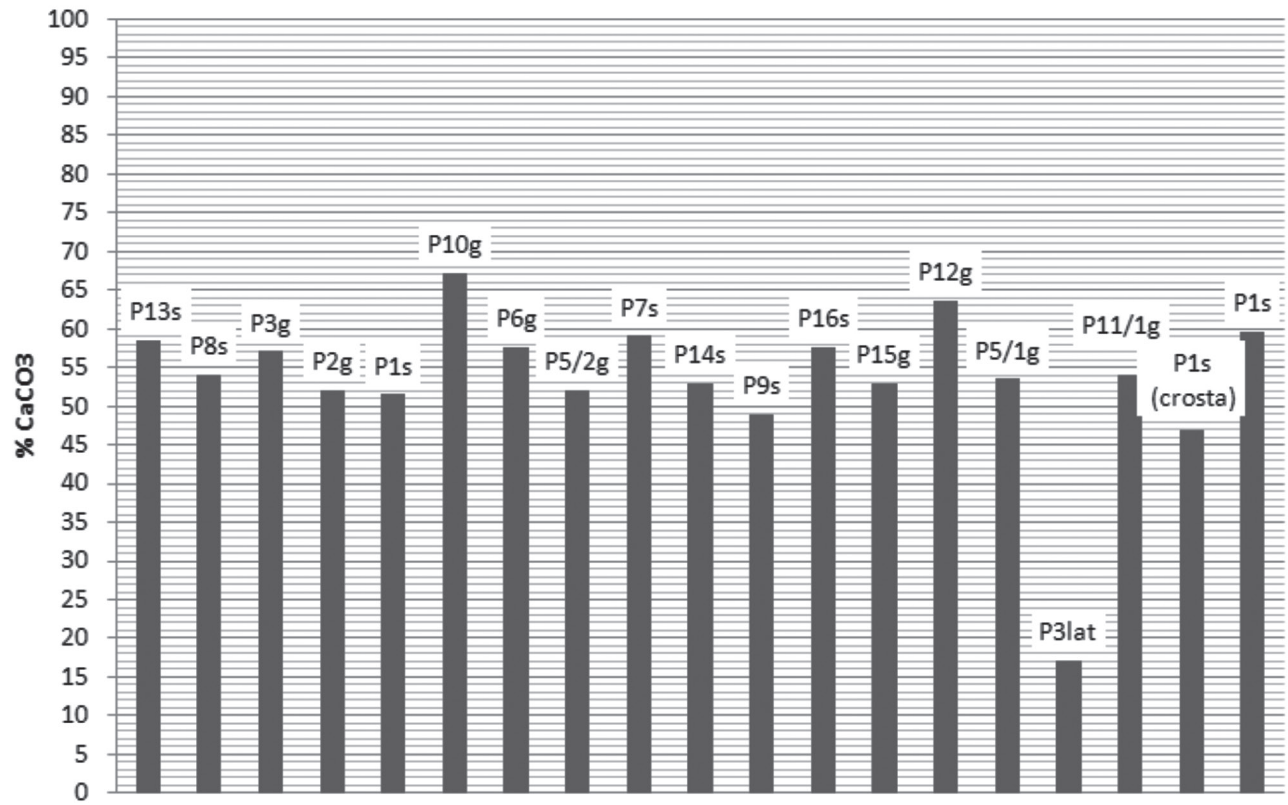


Fig. 12 - Calcium carbonate content test results. s = structural mortar, g = mortar joints, lat = brick sample

fine silt or sand grains possessing a significantly coarser 'tail', variable in quantity from sample to sample.

A sand volumetric method analysis was chosen to define the mortar dry unit weight γd, given the highly irregular shapes of the small samples collected, elevated porosity and permeability of the material tested, making it very difficult to utilize other analytical methods. A sand pycnometer was custom built to solve this problem; the results are shown in Figure 13, yielding a mean value of γ_d =15.9 kN/m^3. This value is rather low in comparison to the characteristics of a similar mortar, the latter oscillating between 16,7-17.6 kN/m^3, but it is nevertheless close to the mortar used in the same era in the Urbino walls. (Busdraghi *et alii*, 1994). The low values of γd (see also the elevated porosity values and the consequent absorption levels) are to be contextualized along with the presence of newly-formed minerals (transformation/dissolution - cf. Tab. 2)

After determining the gravity weight of (*Gs*), it was possible to calculate the void ratio (*e*) and porosity (*n*), the latter being fundamental, given that it is one of the principal parameters connected to brickwork material degradation (Manganelli Del Fà, 2002). The following formulas were adopted:

$$e = (Gs/\gamma d)-1 \qquad n = [e/(1+e)]\ 100$$

The analyses carried out have yielded *Gs* values between 23.0 and 25.6 kN/m^3 and, consequently, also very high values of porosity for the sixteenth century masonry, above 50% in some cases (Fig. 14).

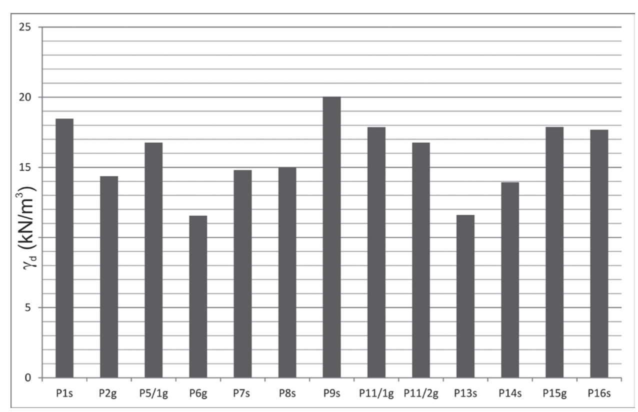


Fig. 13 - Dry unit weight γd value determination through the sand volumeter method

The determination of the dry unit weight of the bricks, thanks to the greater dimensions and a rather regular shape of the samples acquired, has been carried out directly by the use of a callipers and a 1/100th gram scale. The results yielded a mean value of γ_d = 14.4 kN/m^3 which is rather low when compared

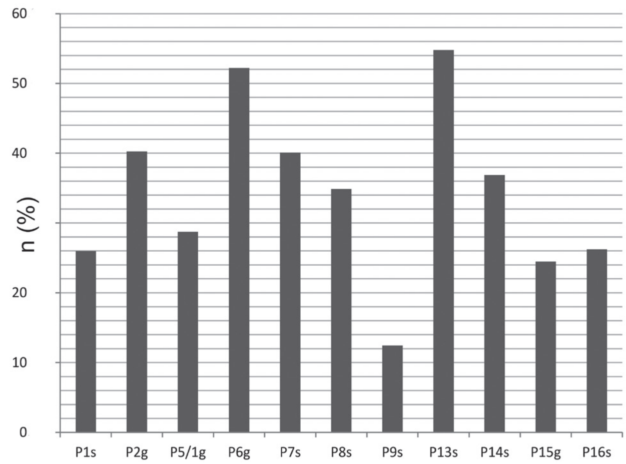


Fig. 14 - *Porosity (n) expressed as a percentage, s = structural mortar, g = mortar joints, lat = brick sample*

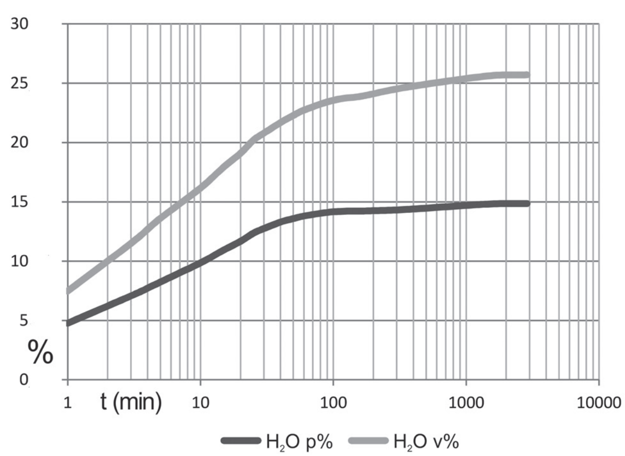


Fig. 15 - *Average values from the capillary absorption test results on 12 samples. It should be noted how an increment in water weight and volume occurs in less than two hours*

to values quoted in the literature for renaissance brickwork analogous to the City of Urbino, which denote, instead, values of around 16.0 kN/m^3 (Busdraghi *et alii*, 1994). This is undoubtedly caused by the state of neglect of the artefacts and consequent degradation that followed.

The results gathered from the capillary absorption tests (UNI EN 15801:2010) carried out on 11 mortar samples and 1 brick sample, used as a comparison, are very interesting and highlight the high water capillary absorption capacity of all samples over a short time (Fig. 15). Indeed, the first inflection point of absorption curve is reached in about 20-30 minutes, whereas the asymptote value of absorption is reached after more than two days. The presence of a highly porous constituent material in an environment with, at times, very intense precipitations (e.g. the 2014 flood), the proximity to the sea both in terms of relatively high moisture levels and an aquifer close to the ground level, raises the issue of an increase of the masonry weight through water absorption, jeopardising the stability of the walls, especially in case of a seismic event.

To understand the current structural condition of the historic walls structure, the mechanical properties of the mortars have been evaluated. Considering that in-situ tests are very destructive (and, so, not applicable for historical buildings) and given the small size and the irregular shape of collected samples, which would have made other type of tests almost impossible to carry out, the only possible test is the Point Load Test (ASTM, 2003). Through point load strength index *Is(50)* it is possible to estimate the uniaxial compressive strength *Su*[3], which is a key parameter stated in many standards. The values obtained (Tab. 3) are rather low for both the sixteenth and eighteenth century mortar.

STRUCTURE AND FOUNDATION INTERACTION

In light of the elements presented in this study, it is clear how planning for conservation is essential, especially on a geotechnical and structural level.

In order to evaluate the conditions of stability of the wall structure (Biscontin *et alii*, 1983), apart from the mortar characterization and constituent materials in general, the interaction with the foundations has also been taken into account.

As far as foundation depths are concerned, recent studies (Silani, 2014), carried out with geophysical methods in the Catalani Gardens area (cf. Fig. 8), allow the identification of the foundation base at more than 4 m below ground level. However, this does not represent the original depth, given that along this stretch of city walls a moat was created to strengthen the defence structures of the urban nucleus; after outliving its defensive purpose, the said depression was buried in 1885 since it contained insanitary stagnant water (Raggi, 2013), increasing the backfill thickness considerably. In other areas, in fact, like the section of seventeenth century walls running along the Misa River and coinciding with the Monastery of St. Cristina of the Benedictine nuns, the foundations are estimated to reach a depth of 2.7 m.

Based on such data, it is possible to estimate the base unit load, keeping in mind that the defensive structure is made up not only of curtain walls but also spine walls, even though they have been preserved only in some sections, but also by the rampart. It may seem difficult, at first glance, to evaluate the contribution of each element; nonetheless, research has shown that both the walls and backfill have similar values of unit volume weight. It was also fairy simple, considering the overall dimensions of the structure, to estimate its base unit

3 *The uniaxial compressive strength values has been obtained with the formula Su=k(50)·Is(50), with a conversion factor k(50) ranging from 11.4 and 13.4, as recently proposed, for mortars, by Tuncel et alii (2016)*

Sample	Epoch	L_{mean} (mm)	D (mm)	P (N)	D_e (mm)	Is (MPa)	F	$Is_{(50)}$ (MPa)	Su (MPa)
P1 s	*'500*	*55.225*	*43*	*1900*	*54.99*	*0.63*	*1.044*	*0.66*	*9.24*
P2 g	*'500*	*13.7*	*8*	*50*	*11.81*	*0.36*	*0.522*	*0.19*	*2.66*
P5 g	*'500*	*15.79*	*15*	*200*	*17.36*	*0.66*	*0.621*	*0.41*	*5.74*
P6 g	*'500*	*17.2*	*8*	*1100*	*13.24*	*6.28*	*0.550*	*3.45*	*48.30*
P7a s	*'500*	*20.46*	*18*	*400*	*21.66*	*0.85*	*0.686*	*0.59*	*8.26*
P7b s	*'500*	*20.81*	*10.5*	*100*	*15.08*	*0.44*	*0.583*	*0.26*	*3.64*
P8 s	*'500*	*20.86*	*23*	*1400*	*24.50*	*2.33*	*0.725*	*1.69*	*23.66*
P9a s	*'700*	*27.07*	*10*	*900*	*19.59*	*2.34*	*0.656*	*1.54*	*21.56*
P9b s	*'700*	*14.23*	*20*	*150*	*16.31*	*0.56*	*0.604*	*0.34*	*4.76*
P11a g	*'700*	*22.76*	*13*	*50*	*17.87*	*0.16*	*0.629*	*0.10*	*1.4*
P11b g	*'700*	*41.28*	*32*	*1900*	*32.83*	*1.76*	*0.828*	*1.46*	*20.44*
P13 s	*'500*	*22.87*	*16*	*300*	*25.07*	*0.48*	*0.733*	*0.35*	*4.90*
P14 s	*'500*	*49.73*	*37*	*1450*	*53.17*	*0.51*	*1.028*	*0.53*	*7.42*
P15 g	*'500*	*35.6*	*22*	*700*	*30.17*	*0.77*	*0.797*	*0.61*	*8.54*
P16 s	*'500*	*47.34*	*17.5*	*550*	*29.27*	*0.64*	*0.786*	*0.50*	*7.00*

Tab. 3 - Point Load Test Results. s = structural mortar, g = mortar joints

load. Inversely, if only the curtain walls were to be taken into account, characterized amongst other things by a tapering angle that renders it particularly thin at the top, the pressure exerted on the foundations would be underestimated.

Finally, it has been calculated that the existing walkway rampart exerts an additional downward force on the curtain wall equal to 10.95 t/ml.

As far as the foundation soils are concerned, even though specialized studies have not been carried out within this research in order to determine its nature and characteristic parameters, it was possible to reconstruct the stratigraphy and substrate properties of the historical centre thanks to the bibliographical and archive research, and the results of the in situ tests carried out for Seismic Microzonation studies of the city (Bozzano *et alii*, 2007).

The results show that the walls of Senigallia are perched on mainly silty alluvial deposits (from clay silt to sandy silt soil type-CL 'low plasticity clay' from normally to weakly over-consolidated), with sandy and gravelly intercalations, and one or two levels of gravel with sandy matrix (SM or SW with 50 to 90% Dr, sand and gravel from medium to very dense) containing a pressurised aquifer. The man-made fill covering the alluvial deposits has an average thickness of 3 m, up to a maximum of 6m, containing an unconfined aquifer, where in some places the piezometric surface is close to the ground level. Lastly, the Argille Azzurre Fm. bedrock is made up mainly of consistent clays (marly, over-consolidated clay of low and high plasticity - CL, CH).

As previously mentioned the main geotechnical parameters of such soils, specified in Table 4, are taken from numerous studies, surveys and tests carried out, over the years, on the historic city centre area of Senigallia. It is possible to observe how these parameters are, generally, poor; in an overall evaluation, this is, undoubtedly, to be considered as a concomitant factor to the gradual deterioration process of the city walls.

The complete parameter evaluation of the wall structure, along with the foundation terrain, has helped to formulate the following considerations.

The foundation soil is made up of pelitic deposits that are underlain by sandy-gravely terrain. Given the construction

Lithology	γ kN/m^3	c_u kPa	c' kPa	φ' °
Man-made fill	*16,3*	*35*	*22*	*26*
Clayey silt	*19,8*	*40*	*20*	*19*
Sandy silt	*19,7*		*1,57*	*22*
Gravel	*16,5*			*37*
Marly clay (bedrock)	*20,0*	*50*	*30*	*26*

Tab. 4 - Average geotechnical characteristics of the subsoil terrain based on the Senigallia historical centre geognostic investigations

	A Catalani Garden	B Monastery of the Benedictine nuns
Foundation depths m b.g.l.	*4.5*	*2.7*
q_{lim} (kN/m^2)	*388.80*	*348.81*
q_{lim}/γ_R (kN/m^2)	*129.60*	*116.27*
q (kN/m^2)	*151.97*	*151.97*

Tab. 5 - Bearing capacity and structure unit load in the two considered sectors of city walls

modality adopted, which required no doubt a very long construction time, and also the fact that the structure has been standing on the building grounds for a number of centuries, the relative loads were gradually applied to the substrate; in doing so, enough time was given to the pelitic levels to reach a certain degree of over-consolidation, thus improving the geotechnical characteristics. These data must also be taken into account when calculating the load bearing capacity.

Furthermore, it is undoubtedly out of place to assess the progressive structural yieldings since they had already manifested during and after construction; hence, today they have already settled and been absorbed by the structure. Small increments related to new loads that could be applied, in conjunction with a possible preventive improvement of the load capacity if deemed necessary, will be more than compatible and, in any case, to be recalculated in relation to the foundation improvement typology chosen at the final project verification.

The structure transfers the load to the terrain with direct, strip footing foundations like 'grade beam'. Two sectors of the architectural structure have been taken into account, being representative of the different foundation conditions and applied loads, in relation also to the poorest litho-technical characteristics of the substrate; the presence of the aquifer was not taken into account, given the pelitic nature of the foundation soil. As described above, not only the load deriving from the curtain wall must be taken into account but, obviously, also that of the rampart which makes up, as a whole, the city walls.

According to NTC criteria, the bearing capacity values, with allowable stress design method, are the following (Tab. 5):

Similarly, for analogous situations encountered by authors observing a heritage site of great historical-architectural importance, the values obtained would indicate - even without considering contingent seismic ground acceleration - conditions approaching stability limits, or even a potential instability of the masonry mass.

Furthermore, a consistent part of the urban wall perimeter, the external wall face and the orthogonal spine walls have been used as a building base for the construction of public and private buildings (Fig. 16). Thus, the load of such raised buildings must be added on to the load bearing capacity of the masonry walls, even though the rampart load value would be contextually ignored.

As regards to the masonry compression resistance level, the existing norms state that such an evaluation is to be conducted by considering the geometry of the stone elements and the overall resistance contribution of the same (brick, stone and mortar). Nonetheless, as a precautionary approach based also on experience acquired on similar heritage sites with comparable material-structural characteristics, a preferential choice was made in the final calculation to use only the compression resistance value of the mortar, the latter warranting masonry mass cohesion; maximum compression values were excluded for their inability to represent the current weakness conditions of the walls. Mean and minimum values of the structural mortar were also taken into account, 6.46 MPa and 3.64 MPa, respectively.

In order to obtain the compression resistance value from the masonry f_k, the NTC (2008) indications were thus applied by adopting the formula

$$f_k = f_m - k \cdot s$$

f_m = mean compressive load failure, tested on at least n = 6 samples, k = probability coefficient tied to the number of samples used, s = standard deviation of sample compression resistance.

This resulted in f_k = 3.44 MPa, i.e. far greater than the overall load of the masonry mass.

As previously stated, this value does not take into account possible diachronous body additions and/or urban planning variations, in addition to the poor drainage supervision of rain water (load increment by absorption) and/or groundwater (load increment by capillary imbibition).

For the purpose of computational convenience, the masonry sliding resistance value was assimilated to the shear resistance value along the weak points of the masonry mass; in particular, the mortar joints of the wall face cover, but also between the aggregates of the chaotic rubble stone fill, and the clear relation between the two. The cortina wall shear resistance will now be discussed.

The allowable bearing capacity calculated on the structural mortar samples under examination (the mortar resistance being the lowest resistance of the masonry wall) oscillate between 3.64 and 9.24 MPa. Keeping in mind the minimum and average values (6.46 MPa), without prejudice to the consequent variability and elevated extension and anisotropy of the wall structure and the indications of the NTC 2008, the shear resistance values attributed to the masonry wall fall into the 0.10-0.20 MPa range, as suggested by Ippolito *et alii* (1993); the minimum value, to be used as a safeguard, registered 0.17 MPa. In both cases, these values are not very high, yet typical of analogous masonry walls subject to similar environmental conditions (Busdraghi *et alii*, 1994), especially in the characteristic high-risk seismicity of the area.

At this point we have attempted to verify, with the aid of a special spread sheet if, based on the previously discussed data, the Senigallia wall structure meets the required prerequisites of the existing norms (NTC 2008). This was carried out with a

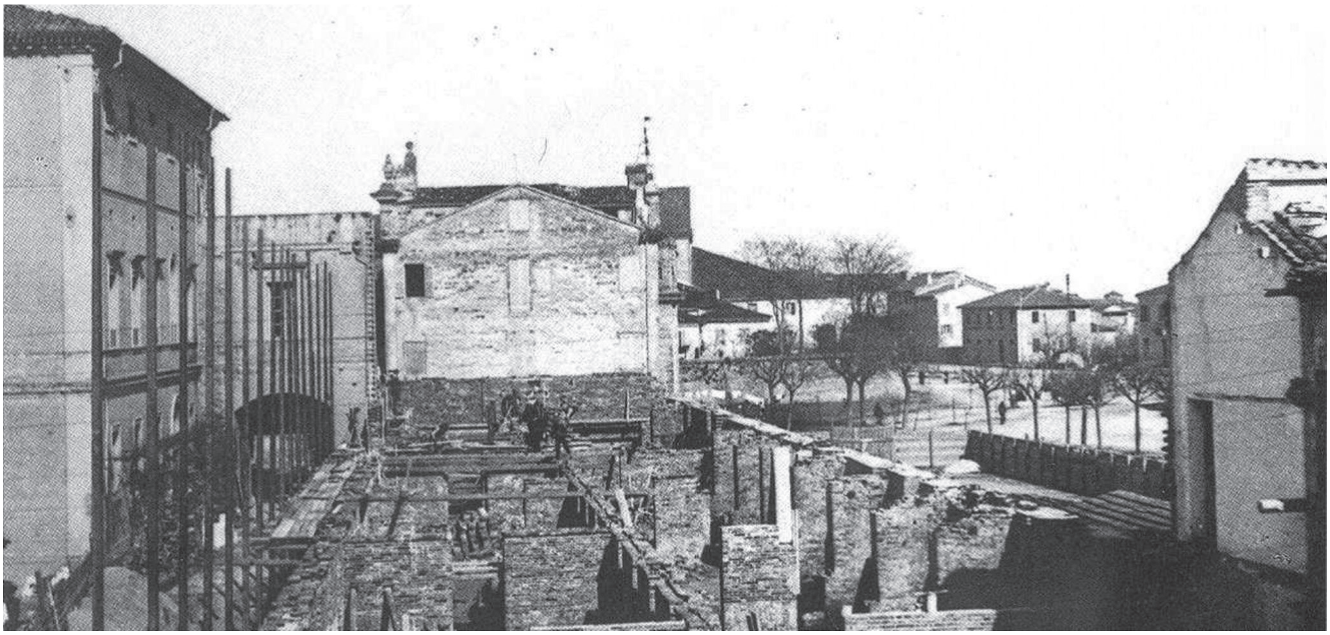


Fig. 16 - Opera Pia Service Wing construction supported by the eighteenth century walls. The spine walls act as dividing element to the ground floor premises (1926 project, built in 1929)

semi-probabilistic approach to the limit state designs and partial safety coefficient implementation, as well as adopting the seismic coefficients which are characteristic to the site.

When considering only the external curtain wall, the values of the stability analysis are constantly well below the factor of safety, both in seismic and static conditions. This is fairly comprehensible, given the particularly slender nature of the wall and, in the foundations, a total lack in the foundations of any type of ledge capable of counteracting a tipping movement. This situation will not be able to guarantee structure stability, not only in high risk conditions.

Nonetheless, the fact that the walls have stood fast for over 500 years, even after having withstood the 1930 seismic event (used in this area as a reference earthquake to study seismic microzonation) would seem to contradict the results of the same.

In this regard, it should be remembered that it is a 'majestic' wall, made up of curtain wall which contain/sustain a very heterogeneous rampart about ten metres acting as mass (hence, resistance) for the defensive structure. In this study case, the adjunct orthogonal spine walls, firmly interlocked, have the purpose of structurally binding the masonry wall mass and the rampart together. On the whole, the said structure makes up what can be considered as a reticular system, compensating for the expected load tilting and creeping.

During the excavation and restoration works carried out on the said walls it was ascertained that the spine walls reach the top cornice of the wall, even though further interventions have partially, or entirely, removed said walls (e.g. the area of the new Teatro La Fenice), which might determine loss in cohesion of the masonry wall mass.

Additionally, the Senigallia defensive structure shouldn't be considered as a simple load bearing wall. Rather, its box-like structure should be ascertained, given the combination of the wall face cover with the internal spine walls and the rampart, conveying a sense of unity to the entire structure.

CONCLUSIONS

This research has helped to reconstruct the current material content and geotechnical state of the wall structure, aimed at a subsequent project design of the possible solutions for the brickwork as far as the historical-architectural value of the monument is concerned. The examination of the architectural work, i.e. both the historical and material-structural characterization of the artefact, has confirmed poor preservation conditions and sites as, moreover, a consequence of the uncontrolled evolution of the original body of the building.

In particular, the ESEM observations, concomitantly to other analyses, have highlighted: the poor quality of the materials under examination, especially the reduced mechanical resistance which is also due to presence of salts tied to sea sprays and the dissolution of the carbonate bond in the mortar; the newly-formed salt reprecipitations; a carbonaceous particulate and, more in general, car traffic pollution (black crusts, gypsum, etc.). The latter is divided into: intergranular decohesion, wall face separation from the masonry wall mass, subsequent void formation and permeability increase, brickwork material disgregation and structure decay.

Nonetheless, the permitted loads for the masonry wall mass in static conditions are, however, greater than the applied loads, even taking into account the indiscriminate urban projects carried out up to today. Even so, this kind of 'poor' architecture that characterize the masonry wall mass might not be able, throughout time, to maintain a sufficient resistance to withstand possible ground accelerations that might interest the structure, due to progressive degradation of materials of which is constituted, especially binders, for their poor quality.

Finally, the allowable bearing capacity of the foundation soil has proven to be slightly below the applied loads. On the other hand, the building techniques of the past, that required long construction times, gave the foundation terrain a chance to gradually settle with the increasing load, improving so its resistance values. This behaviour, however, cannot emerge from the collected geotechnical parameters because none of the tested samples come from soils directly under wall foundation but only from surrounding, not overloaded areas.

The present study is to be seen as a preparatory study for material and structural renovation work. In fact, the need to out the correct material restoration is rather obvious, both for historical/ornamental reasons and as a way to effectively contrast the degradation ensuing from anthropic activities, but also potential seismic events. This can be followed up by the conventional modalities that foresee the use of compatible stone materials to fill large medium to large gaps, carried out with indenting and injecting ad hoc bonding mixtures; the small gaps are filled with the perfusion of a highly penetrating hardening product. Special attention should be given to the improvement of the foundation characteristics of the sectors discussed.

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