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Construction evolution of medieval tuscan monasteries: The case of badia San Savino in Cascina (Pisa)

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The Abbey «Badia di San Savino» is a medieval monument complex dominating the Pisan plain near the Arno river. This monastery's buildings surround the southern and western slopes of a presumably man-made embankment, atop which stands a Romanic church, flanked by its imposing bell tower. The northern side has been eroded by landslides, while the eastern is sustained by a retaining wall with stone barbicans. The aim of the study presented herein is to interpret the data on the geometric configuration and construction materials of this religious centre. Such data has been compiled via architectonic survey and on-site inspection of the current state of the buildings, supplemented by a wide-ranging inquiry into historical archive documents, including iconographic and bibliographic sources.

The most important stage of this preliminary study has been the historical analysis: the history of the S. Savino complex is marked by many alterations and modifications to the original structures, presumably carried out to adapt them to the demands of different ages and different functions (Ceccarelli Lemut and Garzella, 1996 —Pazzagli, 1985— Redi, 1984): the original monastery has successively undergone transformation to a strategic fortress of the Pisan Republic, to an estate of the Order of the Knights Saint Stephan, and finally to residential dwellings. From this historical evolution it is possible to recognize various construction techniques used in each period. Moreover, from the static perspective, the structure faces the eastern front of the embankment, a front formed by the monastery's terminal furthermost side and a high retaining wall, against which lean a secondary entry tower, a recently added concrete buttress and three centuries-old stone barbicans.

By means of computerised F.E.M. analysis of the masonry structures, it has been possible to confirm some assumptions about the different time settings of several of the restructuring operations in this part of the Abbey, as well as their static roles. Such an analysis has moreover made it possible to improve our understanding of the structural behaviour of masonry erected with age-old construction techniques and to propose appropriate restoration operations for consolidation of the structures, currently in a state of severe deterioration.

HISTORICAL REMARKS: DIACHRONIC ANALYSIS

The oldest iconographic sources date back to the 17th century.[1] Thus, for the period elapsed from the monastery's origins up to that time, written historical sources and the hypotheses emerging from historical studies on the building were used for reconstruction of its chronology:[2]

— in the early 11th century the embankment was not surrounded on all four sides, and only two of the current building blocks existed, the one on the west and the other on the south, which

were separated by an incline. The southern block was topped by a tower with a dovecote, which was accessible via two archways on the roadway plane;

— important developments came about during the subsequent two centuries: two transverse buildings were added to the southern block, and on the other side, the southwest corner was still taken up by the incline, but now closed at its base by a small wall joining the southern and western building blocks;

— in the 14th C the two other corner buildings were erected, and the entire monastery complex was elevated by the addition of a storey. This raising and closing off of the hillock was likely the consequence of the events of the time, during which the Abbey found itself caught in the middle of the war between Pisa and Florence. It can therefore be assumed that the complex was first completed and then crowned with a crenellated wall to be able to carry out its new functional requirements as fortress and then only subsequently covered. Still today, the various constructional additions are visible on the facades, particularly on the western front, where the occluding stone wall is present at about the midpoint of the original building (analogous to the northern closing on the same front), and interrupted only at about two metres from the roadway plane, where the two masonry walls have been «embedded» into the original facade. Only traces of the furthermost southern building and its tower now remain;

— in the 15th century the cloister and the two transverse building blocks disappeared, in whose place only a garden or grove now remains: traces of the western building are evident on the church's southern flank, where cement vestiges trace the profile of a gable roof on its walls.

The first written document (Castiglia, 1998) from which it is possible to draw significant information on the morphological and functional state of the monastery, already transformed into an estate of the Military Order of the Knights of Saint Stephan, is an expense record:[3] one of the first entries, dated August 19, 1575,[4] attests to the need to demolish and reconstruct the walls «on the eastern part».[5] No reference is made to any barbicans or bastions, which historical studies instead indicate as having already been added (Testi Cristiani, 1987).

In a 17th-century architectural plan the complex encircles the terreplein of the embankment on the southern and western sides and the south-eastern corner, while the olive-grove surrounding the church on two sides up to the wall bordering the garden is sustained by a crenellated retaining wall that together with the building completes the four-sided structure topping the hillock (Severini , 1994–Sitte, 1992). The plan shows only one pentagonal cross-sectioned bastion[7], overlain by a similarly shaped room, perhaps an old look-out station of the fortified structure, which however has not survived to the present[8] There is no trace of the other bastions, whence doubts could be raised as to the dating of the document, which, if considered reliable, would be before 1682, the year in which the «the estate register» reports its construction: « . . . the grove boundaries have been restored, as they were in ruins in many places, and barbicans made»[9]

The cadastral survey performed by the engineer Pier Francesco Paoli in October, 1743 provides further information:[10] the northern view corroborates the integrity of the crenellated enclosure, but does not include the corner bastion, which was instead erected together with a second one behind the church apse (Barsanti D., 1992).[11]

A building plan compiled by the surveyor Giovanni Domenico Riccetti in 1776 instead indicates both the barbicans and the walls.

State of the art: surveying the structures' current state

A visual survey of the degree of cracking was carried out, during which any damage was recorded together with the most important features having potential effects on the structures' static equilibrium (Gucci et al. 1997). In particular, on the eastern façade we discovered rotation of the frontage wall in proximity to the S-E corner, insufficient mortar on the entire base portion of the masonry in the same corner, wide-spread cracking in the initial segment of the retaining wall near the tower, large, full-thickness fissures beneath the reinforcing chains, two nearly symmetrical diagonal cracks in the wall segment between the two barbicans, and vertical lesions in this same segment near the

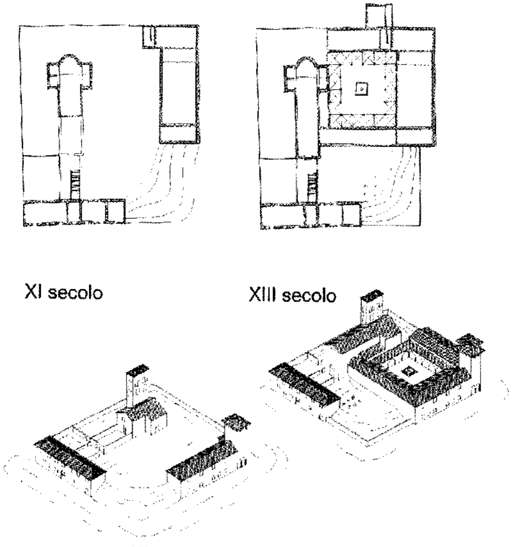

Fig.1
Historical views of the Badia S. Savino (XI–XIIX century)

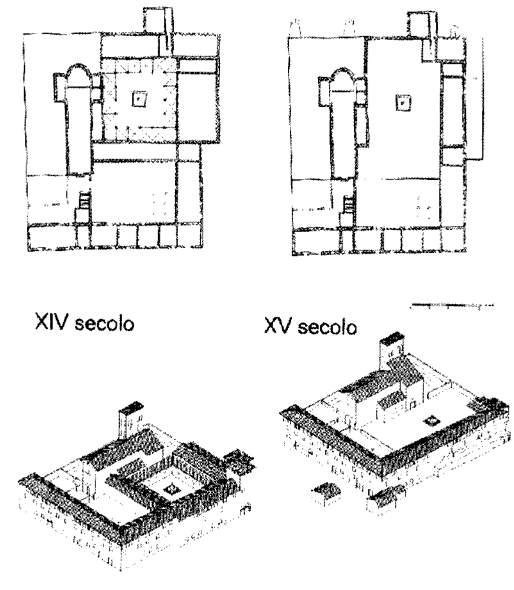

Fig.2
Historical views of the Badia S. Savino (XIV–XV century)

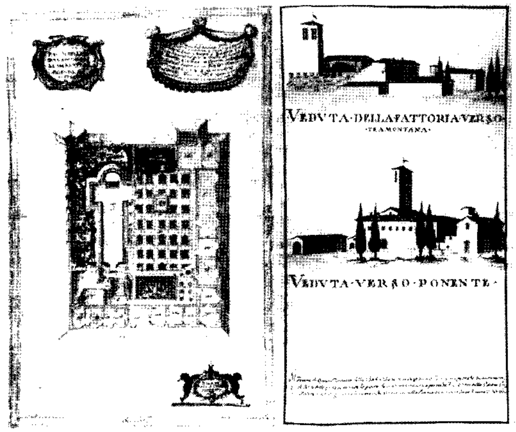

Fig.3
Drawing from P.F. Paoli manuscript (see footnote 9)

northern buttress, all of which are continually subjected to the mechanical action of the overgrowing vegetation.

The structure of the retaining walls of the Abbey's ground basement retaining walls has been simulated by means of an FEM code with 50 × 50 cm shell elements. From the mechanical point of view, the principal hypotheses were the following:

— Stress-strain law: in consideration of the aims of the analysis (to numerically verify the position of the existing cracks) and the uncertainties regarding the materials and loads, the material was considered to be elastic. Young's modulus was determined via the

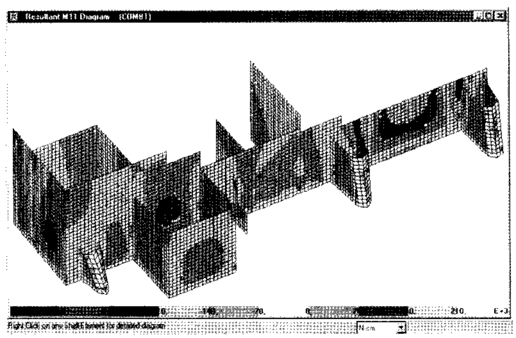

Fig.4
Finite element mesh of basament wall (M11 diagram)

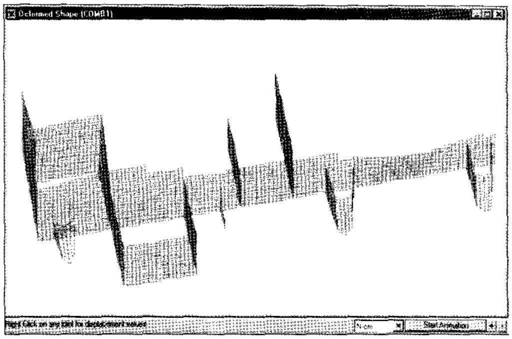

Fig.5
F.E.M. model with deformed geometry of basament wall

Hillsdorf pile-model. The masonry has been simulated as a series of regular layers of blocks and mortar of a given thickness (s_b, s_m) and elastic moduli (E_b, E_m) (ν_b, ν_m). Thus, the apparent Young's modulus is $E = Eb(1 + r) / (n + r)$, with $r = s_b / s_m$ and $n = E_b / E_m$. Several groups of masonry bonds have been distinguished, yielding six different types of walls.

— Restraints and supports: the masonry walls have been considered to be perfectly adherent to the ground, taking into account the progressive rising of the external ground level with respect to the original 11th-century Abbey nucleus, due to periodic flooding of the nearby Arno river, as demonstrated by the partially covered masonry arches on the southern façade of the basement.
— Horizontal ground load: two different geotechnical conditions have been examined for the ground behind the retaining walls: the absence of water (permanent load - drained case) and the presence of water (accidental load - undrained case).

By evaluating the stress diagrams, we have been able to arrive at a satisfactory correspondence between the critical cracked zone and the maximum tensile stress values (Mastrodicasa, 1943).

— the diagram of the bending moment acting in the horizontal direction (M_{11}) shows for the most part homogeneous values along the wall, except adjacent to the two northern barbicans: in this zone the effect of negative bending, as in a continuous beam near an intermediate support, produces strong tangential stresses and slops, while in the middle of the wall, the maximum positive normal stresses cause vertical cracking, as was corroborated by the survey of the Abbey's retaining walls;
— the diagram of the bending moment acting in the vertical direction (M_{22}) and the corresponding strained elastic configuration reveal a considerable loss of verticality in the central upper portion of the wall between the barbicans, as in a vertical cantilever beam loaded by the pressure of the earth. The cracks caused by this mechanism are not visible on the wall's free surface, but the combination of the two effects (M_{11} and M_{22}) produce characteristic symmetrical, upwardly concave, parabolic cracks, as in the present situation.

Given the peculiar results obtained in the northern portion of the support wall, the analysis regarding this section was extended: the panel between the barbicans acts as a plate fixed at its base and free at the summit, though partially bound on its lateral borders and subjected to a thrust orthogonal to its own plane. To better study this configuration's behaviour, the output stresses were rearranged using vertical wall sections on which to project the values yielded by the analysis.

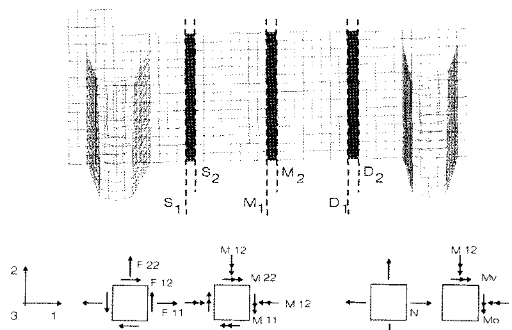

Fig.6
Vertical sections M, S and D between barbicans

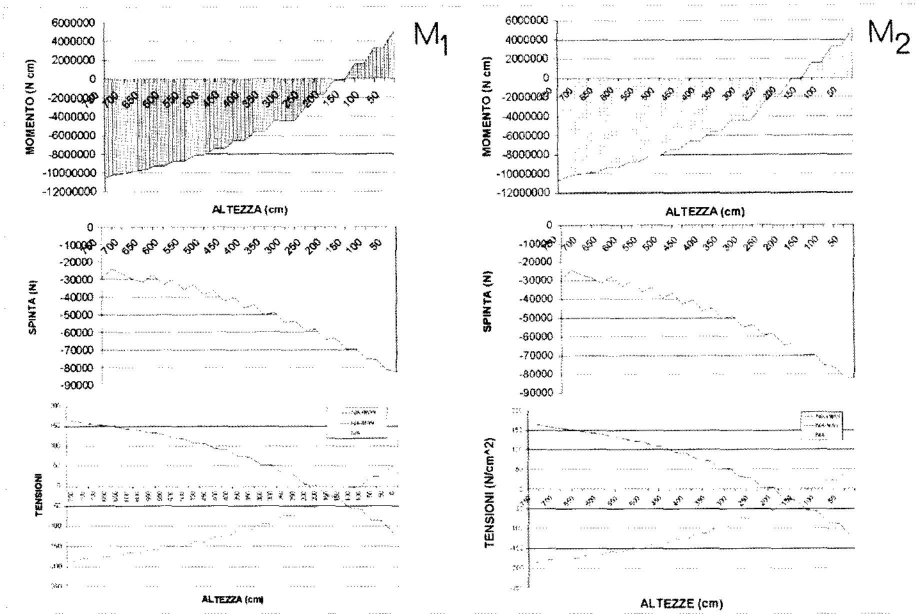

Fig.7
Bending moment, horizontal force and normal stress on section M1

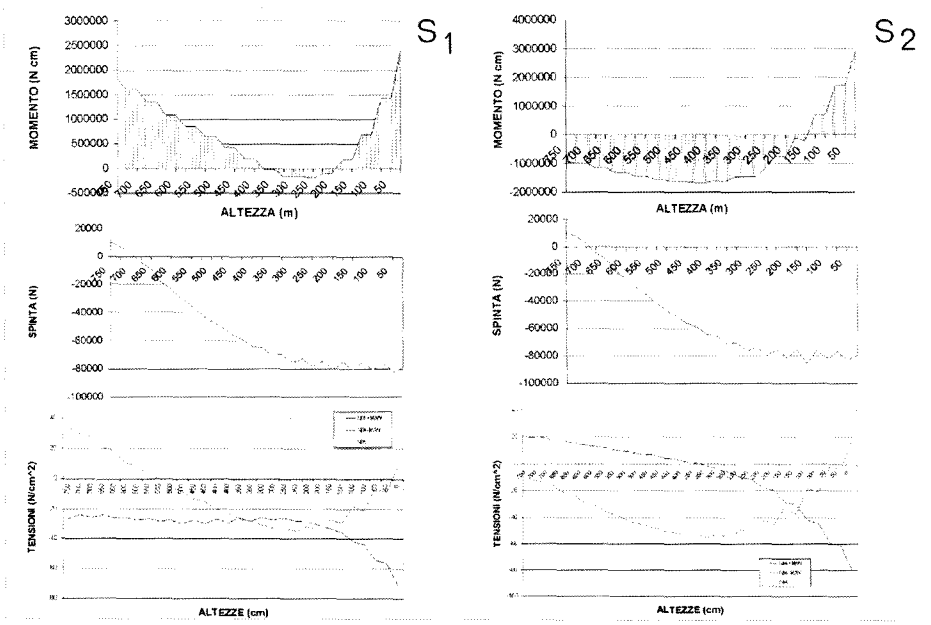

Fig.8
Bending moment, horizontal force and normal stress on section S1

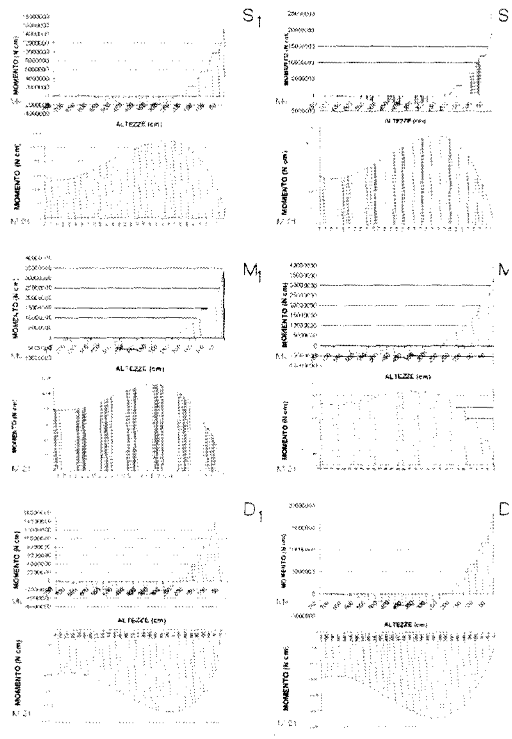

Fig.9
Bending moment and torque on sections M, S and D

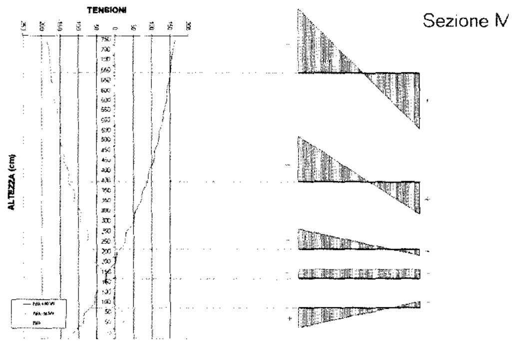

Fig.10
Vertical normal stress along section M

— Examining the panel along vertical sections reveals that the torsional moment, M_{12} and the bending moment, M_{22} are related to the shear force, T_2 and, in the same fashion, the horizontal panel sections reveal a relation between M_{11} and M_{12} and the shear force T_2, both defined by the well-known equilibrium equation:

$$\partial M_{11} / \partial x_1 + \partial M_{12} / \partial x_2 = T_1;$$

$$\partial M_{12} / \partial x_1 + \partial M_{22} / \partial x_2 = T_2.$$

— To such actions we must add the contributions of the axial strain. Due to the wall's own weight, the axial strain acts along the horizontal sections and stabilizes the wall against bending effects, which are in turn impeded by the stiffening against torsion offered by the barbicans. Ultimately, along horizontal sections the panel exhibits maximum bending in its upper portion where the stiffening effect of the barbicans is lower, while in the lower part, the greater thickness of the wall jointed with the axial stress leads to less bending, with consequently smaller tensions, resulting in a advantageous «arch effect» between the bases of the two barbicans.

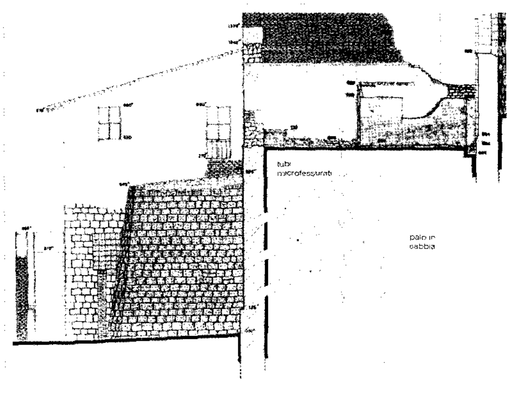

Fig. 11
Geotechnical reinforcement behind the basament wall

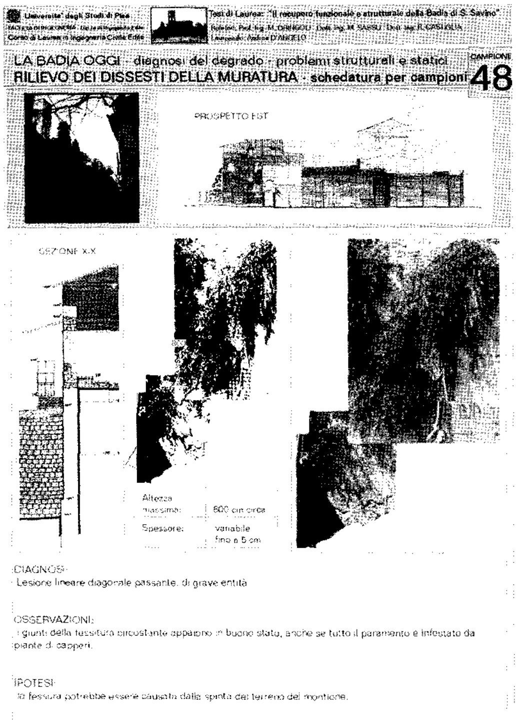

Fig.12
Typical schedule of structural survey

Conclusions

The combined historical and equilibrium analyses of the Abbey has furnished some interesting indications:

— it has helped to define the static behaviour of the building structures, revealing the arch effect operating in the wall's northern portion, where due to the presence of the bastions opposing orthogonal displacements, a thrust develops in the vicinity of the base and furnishes a bearing capacity entirely analogous to that of an arch.

— it has confirmed some of the assumptions regarding the different times at which various structural modifications were made and their effects on the static configuration. For instance, the structural role of the chains and the r.c. buttress are nearly irrelevant to the structure's overall behaviour, as they only act locally to re-establish equilibrium conditions, which the masonry would, according to the theoretical model (made up of elastic, homogeneous, intact material), reach on its own,.

— it has allowed proposing appropriate consolidation operations in order to enable the structure to satisfactorily perform its support function: the burden of the thrust from the undrained water in the bastion turns out to be a major factor in its instability. Thus, a first necessary operation (above and beyond repair of the wall in the degraded areas), will have to be the reopening of the old drain holes and the creation of new ones to assure good water outflow. Such operations may even be sufficient in the wall's southern portion, where sinking has substantially reduced the thrust of the ground. However, this is not the case in northern segment between the two barbicans, where the results of modelling, in addition to the alarming nature of the cracking already present, point to the need for further precautionary measures.

Fig.13
Views of the Badia S.Savino, Cascina (PI)

In conclusion, the first operation to be carried out is to restore the original load-bearing sections of the wall, without however modifying its historical bonds. The second stage then calls for increasing the embankment's ability to drain off rainwater, thereby substantially reducing the thrust acting on the retaining wall.

NOTES

1. *Plan of Badia S. Savino della Sacra e Ill.ma Religione di S. Stefano*, (Public Historic Archive of Pisa) ASPI, Ordine di S. Stefano, Piante e Disegni, 18, fig. 3.13.
2. A graphical hypothesis of the Abbey's historical evolution that we have followed in the present work is presented in «Piano di Recupero della Badia di S. Savino» («Plan for Recovery of the Abbey of S. Savino»), drawn up by the Cascina Township in 1996. The precise heading of the work is *Comune di Cascina, Hypothesys of historic evolution of Badia di S. Savino. Survey and schemes by: Bracaloni Cristiana, Turini Davide, Turini Sandra (degree dissertation, Aprile 1996)*, in Studio Architetti Associati M. Ciampa P. Lazzeroni, *Piano di . . .* , op. cit.
3. «Book of Badia di S. Savino manuscripted by prior Domenico di Brando da Greve, fattore, started on 31 March 1572». ASPi, Ordine di S. Stefano.
4. ASPi, Ordine di S. Stefano, S 2828.
5. Actually, the statements are interrupted because of tears and missing or illegible parts in the documents. For the presence of the bastion see F. Redi, *Edilizia medievale e organizzazione del territorio*, Pisa 1984, p.123.
6. «Plan of Badia di S. Savino della Sacra e Ill.ma Religione di S. Stefano», ASPi, Ordine di S. Stefano, Plans and Drawings, 18: is a 71.60 × 45.90 cm china-ink and watercolour paper manuscript, in a graphic scale of 5 Florentine arm lengths (2.91813) = 13.40 cm.
7. The pentagonal section is illustrated as mostly regular, contrary to that present today, which though still pentagonal, has been built up in the direction orthogonal to the walls.
8. ASPi, Ordine di S. Stefano, M 714, c. 95 v.
9. «Plans of the farm properties of Badia di S. Savino della Sacra e Ill.ma Religione di S. Stefano», P. F. Paoli 1743, ASPi, the document «Ordine di S. Stefano, Piante e Disegni, 46»: is a hide and rigid parchment manuscript (84.15 cm × 61.00 cm) containing China ink and watercolour sketches, which include 17 plates of various sizes: 7 plans of the «Seidici» estate, the lands at Piaggia d'Arno and the holdings of the San Savino estate, as well as panoramas of these last.
10. There are however 8 battlements illustrated therein, one less than those indicated in the 17th-century plan.
11. ASPi, Ordine di S. Stefano, piante, n. 53.

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