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Research

The Conception of Ramparts in the Sixteenth Century: Architecture, “Mathematics”, and Urban Design

Abstract. The discovery of gunpowder and its military applications caused a revolution in the common systems of defence, which had not changed substantially from the Roman period. New methods of laying out urban defences in the second half of the sixteenth century was the product of a continuous response to the evolution of fire arms and their increasing power. The goal of this article is to explain these assertions, analysing in detail the factors that characterized the “science of fortification” in the sixteenth century.

Introduction

Did a relationship really exist between mathematical sciences and the birth and the evolution of the new techniques of defence in the first years of the sixteenth century? And if it existed, what influence did science have on the formulation of the military architecture principles? Was this relationship bilateral, i.e., did the evolution of military architecture also exert a driving influence on experimentation in physics and mathematics?

The answer is not immediate and not certainly simple. So we need to linger over these questions in order to explain if this relationship really existed and what role it played in the wider historical context.

Surely the discovery of gunpowder and its military applications caused a deep change – actually, a revolution – in the common systems of defence, which had not changed substantially from the Roman period. It is also true that the new method of laying out urban defences in the second half of the sixteenth century was the product of a continuous response to the evolution of fire arms and their increasing power.

Moreover, the impulse for the birth of ballistic physics was probably caused in part by military exigencies and, consequently, the improvement of ballistics also determined the mature formalization of the new defensive front.

It is also certain that the new techniques of fortification played an active role in the conception of the Renaissance “ideal town”, in which the Euclidean precision of street lines and defensive walls was principally motivated by military requirements.

Gunpowder and the introduction of firearms in war tactics

Some historians attribute the discovery of gunpowder composition to the English friar Roger Bacon (1214-92) at the end of the thirteenth century. Conscious that his discovery could have caused destruction and death, Bacon disguised the ingredients in an anagram: *Sed tamen salis petrae LURU VOPO VIR CAN UTRIET sulphuris, et sic facies tonitrum et coruscationem si scias artificum* (saltpetre ... LURU VOPO VIR CAN UTRIET and sulphur; in this way you will generate thunders and lightning, if you really know the trick) [Luisi 1996, 107]. In the earliest years of the twentieth century, W.L. Hime recognized in

the anagram the composition of gunpowder: “R.VII.PART.NOV.CORUL.V.ET. sulphuris”, which means “Sed tamen salis petrae recepe VII partes, V novellae coruli, V et sulphuris... .” (...seven parts of saltpetre, five parts of coal and five parts of sulphur...) [Hime 1904].

Apart from other possible interpretations of the anagram, we can deduce that in this first period the approach is still quite alchemic. Subsequently the research was directed towards the improvement of the composition of gunpowder, in order to increase its explosive power, up to the second half of the nineteenth century, when gunpowder was substituted by new stronger explosives, such as nitro-glycerine and dynamite.¹

Composed of saltpetre (potassium nitrate), coal, and sulphur, gunpowder had already been used in the past for pyrotechnic displays. Only beginning in the fourteenth century was its use applied in Europe for offensive purposes. At the end of the sixteenth century the composition was definitively set forth: six parts saltpetre, one part coal, one part sulphur.² These three components were ground into powder, mixed together and then sifted to obtain a more or less fine powder.

If the last two elements were easily available, this was not the case for saltpetre. It was naturally found in form of efflorescence in wet places – such as cellars or caverns – where the action of nitrifying bacteria was possible. Only later were special deposits for nitrification were built for the production and the stocking of rough saltpetre, produced by soil rich in organic waste (the excrement of sheep), diluted with water and then decanted by using boilers.

In contemporary with the improvement of pyrotechnics, the production of firearms started. Even if the first use of firearms is attested in the second half of the fourteenth century,³ artillery did not assume an important role during battles until to the end of the fifteenth century, when fire arms were still primitive, heavy, and hardly manoeuvrable. Forged in iron, they required a long time to reload and were not very powerful. They were without wheels for being transported and the elevation of the barrel was made earth or crossbars of wood. Projectiles were still in some cases stone and not iron.

A new impetus for the improvement of artillery – and consequently of military architecture – came from the encounter between the French and the Italian armies in 1498, when Charles VIII of France came into Italy to claim his hereditary right to the throne of Naples. His army had superior equipment: cannons were forged in bronze and projectiles in iron. Cannons were more easily transportable by horses, more powerful and required less time for reloading.

The affirmed use of firearms caused an inevitable revolution in the common tactics of war and, consequently, of the ancient techniques of defence: a new age was coming.

New exigencies and first architectonic experimentations

After the introduction of gunpowder at the end of the fourteenth century, medieval fortifications showed themselves to be inadequate for resisting the force of fire arms, when enemies during siege began trying to open a breach in the walls rather than climbing them.

In the second half of the fifteenth century, architects tried to plan new forms of fortifications, in order to improve their resistance to the impact of projectiles. In this period of transition the experimentation of new constructive typologies was principally applied to

fortresses and citadels (figs. 1-4). Even if the character of these was still deeply medieval, it is possible to recognize in them some innovative typological elements.

Fig. 1. Types of towers and “dead ground”

Fig. 2. View of Volterra Fortress (Francione, 1472)

Fig. 3. Harquebus slit, Volterra, fifteenth century

Fig. 4. Plan of Volterra Fortress (G. Panazzi, 1755). Courtesy of the Biblioteca Guarnacci, Volterra

First of all, the recovery of flanking and grazing defensive fire as a generating principle is the main point of this new way of planning.⁴ The search for a regular planimetric conformation of the walls is the immediate consequence of this principle, in order to minimize the “dead ground”, that is, the area outside the walls not reachable by defensive shots. The corners of walls were reinforced by cylindrical towers, projecting outward from the boundary walls. The cylindrical form was preferred because its behaving as an arch was more resistant to shots. The circular form also optimised the flanking defence and minimized the “dead ground”, especially in comparison with square towers.

The height of walls and towers was limited; a high tower, in fact, represented a dangerous target for enemy fire. A great number of slits for small bombards and the *harquebus* (a predecessor of the musket) were opened along the perimeter of the fortress.⁵ Towers were larger in diameter than medieval ones, to allow for placing firearms and accommodating their recoil. The boundary walls had a great scarped revetments, a concept called *mura fuggitive* (literally, fugitive walls), that is, the property of sloping walls to deflect cannonballs.

All around the perimeter, the moat was deeper and larger, in order to keep enemy posts as far as possible from walls. All the same, the crowning of towers were still typically medieval, with brackets, merlons and trapdoors, which show that climbing walls persisted in siege tactics.⁶

The new attention paid to geometrical simplicity in plan represented the modern character of military architecture. From cylindrical towers to arrowhead bastions, the step was short.

Some historians attribute the paternity of the bastion to Francesco di Giorgio Martini, after his famous drawing from the *Codice Magliabechiano* (fig. 5).

In this period of experimentation, Francesco di Giorgio was surely the most innovative architect. He was really the first to reintroduce flanking as the most important principle in fortress project.

Fig. 5. Francesco di Giorgio Martini. La rocca di San Leo

Fig. 6. Giuliano da Sangallo, detail of the *fianco ritirato con orecchione* in one of the bastions of the Fortezza Nuova in Pisa

But if Francesco di Giorgio understood that the arrowhead form of towers was more effective, we must attribute to Giuliano and Antonio da Sangallo the mature definition of the bastion's formal parameters and the modern way of fortifications (fig. 6). In particular, they invented a special form of bastion, which became an indispensable element in planning fortifications in the centuries that followed: the bastion with orillions, *fianco ritirato con orecchione*, i.e., the flank of bastion where the embrasure was hidden by a curved projection that defended it from enemy's cannonade.

Euclidian geometry in the treatises of military architecture

At the end of the fifteenth century, architects began conceiving new methods for the design of urban defences. If until that time the figure of the architect had retained the characterization given to him by Vitruvius – that is, of a man of universal learning – in consequence of the technological revolution induced by firearms, a slow process of specialization started. The figure of military architect was born as a specialist in military problems.

The desire to set forth their own experiences induced many of these architects to write specialized treatises on fortifications, war tactics and ballistic theories.⁷ The cultural discussion took place in an international context, all over Europe.

The importance of Euclidian geometry clearly emerged from these works, whether written by architects or by soldiers. It is not by chance, for example, that in the frontispiece of his treatise of 1537, *La Nova Scientia*, Niccolò Tartaglia wrote, *Nemo Huc Geometriae expers ingrediatur* (in effect, let him who will understand these theories have a thorough knowledge of (Euclidian) Geometry). His work, which was the first attempt at a mathematical treatment of the movement of projectiles, was really innovative and became a point of reference for all the other writers. In particular, his study tried to geometrize the trajectory of projectiles on the basis of the force of launch and of the inclination of cannon barrels (fig. 7).

With Jacomo Lanteri (1557), moreover, military architecture was clearly considered not as a design practice, but very much a part of the mathematical sciences: he declared that the finality of his treatise is “to talk about the way of planning fortresses using Euclidian principles”.⁸

At the end of the sixteenth century, while he was professor of Mathematics at Padua University, Galileo Galilei wrote two treatises. In his *Trattato di architettura militare* (1593) the approach to the problem is strongly geometrical and mathematical. Thus, before starting to write about architecture, he reserved the first pages for the explanation of graphical methods for solving geometrical problems, necessary for planning ramparts: how to trace perpendicular lines, for example, how to divide a corner in equal parts, or to draw regular polygons.

With Galileo, the relationship between military architecture and mathematics was universally recognized. That's the reason why we choose to refer to his rules in describing, even if briefly, the formal principles of “modern” way of planning fortifications (fig. 8).

Tartaglia N.,
La Nova Scientia, 1537

SUPPOSITIONE III

Lo effetto piu lontano dal suo principio, che far possa un corpo egualmente graue di moto uiolente sopra a qualunque piano, ouer sopra a qualunque retta linea, è quello che termina precisamente in esso piano, ouer in essa linea (essendo eiecto ouer tirato da una medema possanza mouente.)

PROPOSITIONE V

Tutti li transiti, ouer moti uiolenti de corpi egualmente graui, si grandi come picoli egualmente eleuati sopra a l'orizzonte, ouer egualmente obliqui, ouer siano il pian de l'orizzonte sono fra lor simili, & consequentemente proportionali, & similmente le distantie loro.

PROPOSITIONE VII

Se il transitio ouer moto uiolente dun corpo egualmente graue sarà elleuato sopra a l'orizzonte, la parte curua di quello sarà maggiore della quarta parte della circonferentia del cerchio donde deriuà, & quanto piu sarà eleuato tanto piu sarà maggiore di la quarta parte de detta circonferentia, & tamen mai potrà esser la metade di essa circonferentia.

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Fig. 7.

"[...] E perché le difese de' baluardi vengono scambievolmente dall'uno all'altro, né può un baluardo difendere sé medesimo, però nel disegnarli non si disegneranno soli, ma due insieme, cavando le loro forme da i tiri, da i quali devono essere difesi.

Però prima si tirerà una linea retta, la quale sarà per la cortina tra l'uno e l'altro fianco, la cui lunghezza si determinerà o maggiore o minore, secondo la grandezza del recinto [...]

E nel presente esempio sarà la cortina la linea AA, sopra la quale si metteranno ad angoli retti i fianchi, come si vede per le linee segnate AB; delle quali se ne prenderanno braccia 30 per le larghezze delle piazze di sotto, segnandole AC. [...] Dalla linea AC ci tireremo in dentro braccia sette; e tirata un'altra linea ad essa parallela, verrà formata la grossezza del muro dinanzi alla piazza. Di poi, ritirandoci in dentro sei braccia, tireremo un'altra linea segnata ED, la quale comprenderà la sortita: ed averemo tra queste linee una larghezza di braccia 13, delle quali, quando noi saremo all'altezza di 7 in 8 braccia dal piano del fosso, la scarpa ne avrà consumato braccia $1\frac{1}{2}$, tal che resteranno braccia $11\frac{1}{2}$, sendo scemato dalla parte di fuori lo spazio sino alla linea FG. Pigliando dunque il mezzo tra DE ed FG, vi tireremo la linea HI, sopra la quale, cominciando dalla cortina A, misureremo due braccia per la prima cannoniera: doppio, pigliando con il compasso la misura di braccia 5 e quarti 3, segneremo un cerchio, che avrà di diametro braccia $11\frac{1}{2}$; doppo il quale si lasceranno due altre braccia per la larghezza della seconda cannoniera: doppio la quale disegneremo un altro cerchio con il medesimo diametro, e doppo esso due altre braccia per la terza cannoniera: e così delle 30 braccia ne avremo consumate 29, cioè 23 per li due cerchi, che ci rappresentano due merloni, e 6 per le tre cannoniere; e quel braccio che avanza, servirà per risalto o spalletta. [...] La lunghezza della piazza non si farà meno di 40 braccia, facendola pendere un poco verso la fossa, acciò che anco dall'estremità di dentro possa fare effetto; e perciò si faranno le cannoniere senza soglia o scaletto.

From Galilei G., *Trattato di Fortificazione*, 1593

Fig. 8.

Modern way of planning fortifications. Geometry and structure

The formal symmetry, proportion and regularity of new fortifications surely reflected the Renaissance culture and aesthetic canons. Otherwise, their conformation to geometry was justified by precise military reasons. The bastion was the most important structure of this complex system, where each element was deeply connected to the others by principles of reciprocal defence.

In its simplest configuration, this system was principally formed by two adjacent ramparts and the walls between them (fig. 5). The profile of each element was generated by precise method of planning, based on the trajectories of projectiles, assuring the defence of walls between ramparts and the reciprocal defence between ramparts, and cancelling any “dead ground”.

The rampart showed a great planimetric symmetry, linked to the bisecting axis – called *asse capitale* – of the corner it was built to defend. It had five sides: two fronts, two lateral flanks and the ideal internal one called the *gola* (literally, throat).

Generally, firearms were put in two levels of fire. A first level was constituted by the *piazza di sotto* (lower square), one for each flank, sometimes in the form of one or two levels of casemates, symmetrically opened in the flanks, near the walls, with two embrasures each for the grazing defence of the walls. A superior level was represented by the *piazza di sopra* (upper square), a large, open-air square, with embrasures opened along all the perimeter.

Inside the body of the rampart, at the level of foundations, a vaulted gallery ran all along the perimeter, with air vents for the ejection of the smoke from the firearms.

This gallery had a double function: like a real casemate along the flanks, it had many harquebus slits; along the fronts it permitted inspection of the perimeter (countermine gallery), against possible enemy mines.

Outside, a large moat ran along all the perimeter; its form responded to the same methods of planning. Over the ditch was the *spalto*, a flat space wider than a mile, without trees, building or any other elements that could offer repair to enemies.

The boundary was made of brick or stone walls, reinforced inside by counterforts. These were rectangular in plan or, as suggested by Galilei, pentagonal, in order to maintain the earthen ramparts in case of breach.

Foundations were usually built of fired bricks, hard bricks or hard stone, because of their excellent structural resistance and resistance to humidity.

For external wall surfaces, on the other hand, green (less baked) bricks or sandstone (*pietra morta*) were used, because they better absorbed cannonball shots. Where it was damp, fired bricks were preferred only for the external wall surface, or generally on the inclined surface of parapet, being more resistant to rain and natural agents.

The filling between counterforts was made with tamped clay. The earth inside the ramparts was generally made stable with branches of chestnut, oak or of any other water-resistant quality of wood.

In the second half of the sixteenth century, this first model of bastion *all'italiana* (in the Italian way) showed its vulnerability. In fact, with the evolution of fire-arm technology and pyrotechnics, using brick or stone became dangerous, because, when such walls were hit by projectiles the fragments that flew into the air were almost as dangerous as the projectiles themselves.

Moreover, the practice of digging underground tunnels to reach the bastions⁹ was more frequently used. So in order to defend ramparts from enemy attacks and mines, new defence structures were built in and outside the ditch (*mezzelune, falsebraghe*, etc...).

By the end of the sixteenth century, the Italian model of ramparts was definitely substituted by French or Flemish ones, made completely of earth, limiting walls to the basement.¹⁰

From ideal to real town. A case study: Leghorn

Between the end of the fourteenth century and the first half of the fifteenth century, very significant changes occurred. The protectionist economy based on medieval corporations gradually ended. International trade improved in consequence of the discovery of the New World. Moreover, a process of centralization of territories and powers gradually occurred, with the birth of national and regional monarchies.

In this context, medieval towns were subjected to rigid control by the central government. The medieval urban structure, with its "labyrinth" made of narrow streets, surely did not respond to this necessity.¹¹

The consequent regularization of the shapes of towns was certainly produced by the new Renaissance culture, where nature was subjected to geometry and the architectural language was definitely codified in accordance with the classical principles of symmetry and proportion.

However, military exigencies certainly played an important role in defining the Renaissance model of the star-shaped town. Large streets, in fact, permitted the rapid deployment of men and weapons during sieges. The wide central square, symbol of political power, both civil and religious, was also used as parade-ground in war periods. Finally, the star-shaped boundary walls, with ramparts and external defensive structures, clearly showed the military character of the Renaissance town. The removal of the defence-line as far as possible from town centre sacrificed outer-wall suburbs and lands to the exigencies of war, irremediably changing the ancient relationship between town and country-side.

Actual examples, such as Palmanova, ideal ones, such as *Sforzinda* (Filarete, 1460) or utopian ones, such as *Christianopolis* (J.V. Andreae, 1619) showed that geometry and regularity, apart from respecting principles of formal perfection, responded to precise functional exigencies, assuring the town's defensive efficiency.

As an example of the new urban design related to military necessities, we choose to introduce the first urban plan of Leghorn, drawn by Bernardo Buontalenti in 1576 (fig. 9).

Fig. 9.

The plan had a mostly regular pentagon shape. The irregularities derived from the presence of the western old town, with the fortress drawn by Giuliano da Sangallo near the port. In the new plan, the old fortress was placed in one of corners of the defensive boundary and the old town was fortified with ramparts.

Along the perimeter, Buontalenti projected five new bastions: Ascension's Bastion at the southeast, Santa Barbara's Platform¹² at the northwest, St. Andrew's Bastion at the southwest, St. Julia's Bastion at the east and St. Francis's Bastion at the north.

Defence lines measured no longer than 750 ells. The fronts of bastions were unusually designed on defence lines starting from the corner of perimeters and not from the corner between flanks and walls.

In the middle of each side of the perimeter, Buontalenti built some secondary defensive structures, called *cavalieri*, (knights) for shooting outside the city and defending the nearest ramparts from the middle of the curtain.

The scheme of orthogonal streets permitted soldiers to cross the city quickly. The principal axis was represented by the main street, 14 ells wide. It had an inclination of 30° with respect to the North, in order to optimise the effects of sun and wind.

The main square in the centre, with the Cathedral, was really a parade ground, directly connected with the trapezoidal service square behind the *gola* of Ascension's Bastion.

The "Via Giulia", the other main street, orthogonal to the one mentioned above, served commercial and military purposes, connecting the two most important city gates – Porta a Mare and Porta a Terra – placed near the flanks of bastions and efficaciously defended by their embrasures.

A circumvallation 20 ells wide ran inside along all the defensive perimeter and permitted troops to reach ramparts by a complex system of rhomboidal-shaped ramps.

Conclusions

So, did a relationship exist between mathematics and military architecture in the sixteenth century? If so, Euclid surely presided over it. And, more generally, if the scientific approach is based on analysing the relationship between causes and effects of any possible phenomena, in the “modern” way of planning defences, the regular and geometrical shape of fortifications was surely conceived to respond to concrete exigencies. That was really a modern attitude, where shape and function lived in perfect equilibrium, so deeply characterizing the face of cities and their civil organization from the sixteenth century onwards.

Notes

1. Nitro-glycerine was first obtained by the Italian scientist Ascanio Sobrero in 1847, and then perfected by Alfred Nobel in 1866 with the introduction of dynamite.
2. The present-day composition is: saltpetre 74.64%, sulphur 11.85%, coal 13.51%.
3. In Italy, the first use of bombards is attested in 1331 in the siege of Cividale. Firearms have been illustrated in codices ever since 1325. A document about *Provvisione* of the Florence Republic (dated 11 February 1326) is perhaps the first to talk about firearms.
4. The flanking principle of defence was already present in the Roman age. According to Vitruvius, in fact, summarizing Greek and oriental details, towers must jut out over the walls in order to strike enemies sideways, and the longest possible distance between towers was based on the range of arch arrows.
5. The typical harquebus slit had, outside, the shape of an upside-down keyhole and permitted a range of fire 20° wide. The hole was for lodging the barrel of the harquebus, while the vertical slit was for aiming the shot. Inside, it had a simple splay, showing its direct derivation from the loophole.
6. One of the most representative examples of this type of fortifications is the Medici Fortress in Volterra, planned by Francesco di Giovanni di Matteo Francione in the 1472. The fortress is constituted by two parts joined together by two long walls. The eastern one, called *Mastio* or *Maschio* (the Male), has a quadrilateral perimeter with cylindrical towers at the corners and a big cylindrical tower in the centre, overlooking the town centre and built against possible rebellions of its citizens. The western one has a semi-cylindrical tower (called the Female) and a great arrowhead fortification toward the valley, a sort of big polygonal armed square – quite a bastion – looking outside the city.
7. Some of the most important treatises in military architecture:
Roberto Valturio, *De re militare*, 1472.
Antonio Corazzano, *De re militaria*, 1493.
Giovanni Battista Della Valle di Venafro, *Vallo*, 1521.
Niccolò Machiavelli, *Arte della Guerra*, 1521.
Albrecht Dürer, *Etliche underricht, zu befestigung der Stett, Schloss, un flecken*, 1527.
Nicolò Tartaglia, *Nova Scientia*, 1537. *Quesiti et invenzioni diverse*, 1538.
Giovanni Battista Belluzzi, 1545-98.
Pietro Cataneo, 1567.
Giovanni Battista Zanchi, 1554.
Francesco De Marchi, *Architettura militare*, 1565.
Giacomo Lanteri, *Del modo di fare le fortificationi di terra intorno alle città, & alle castella per fortificarle. Et di fare così i forti in campagna per gli alloggiamenti de gli esserciti; come anco per andar sotto ad una terra, et di fare i ripari nelle batterie*, 1557.
Francesco De Marchi, 1599.
G. Maggi-I. Castriotto, *Della fortificatione della città*, 1564.
Girolamo Cataneo, *Libro Nuovo di fortificare, offendere et difendere con alloggiamenti campali*, 1567.

- Galazzo Alghisi, 1570.
 Domenico Mora, *il Soldato*, 1570.
 Gabriello Busca, *Della espugnatione delle fortezze*, 1585.
 Galileo Galilei, *Breve istruzione all'architettura militare*, 1592-93. *Trattato di fortificazione*, 1593. *Del compasso geometrico e militare*, 1606.
 Bonaiuto Lorini, *Le fortificationi*, 1597.
8. *A ragionar del modo di disegnare le fortezze secondo Euclide* [Lanteri G., *Del modo di fare le fortificationi di terra intorno alle città*, 1557].
  9. A special corps of sappers, digging a gallery underground, reached ramparts and made them explode with gunpowder.
  10. Galileo showed in his treatise the way to compress earth by using wooden chains and to protect rampart's external surfaces by turfing or using sun-dried clay blocks. Even if the Flemish models better responded to the new techniques of siege, they required more upkeep and were more subject to deterioration.
  11. In 1475 Ferrante d'Aragona, king of Naples, defined narrow streets a "danger for the State".
  12. Platforms were similar to bastions but they differed in being placed in the middle of defensive perimeter and not in the corner.

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Marco Giorgio Bevilacqua earned his degree with honors in 2003 in Civil-Structural Engineering at the University of Pisa. Since 2004 he has been working on his doctorate in "Science and Techniques for Civil Engineering" at the same university. His thesis is entitled "La fortificazione della città di Pisa nel XVI secolo. Il primo fronte bastionato". He is part of various national and international research projects on the subjects of the designing and surveying of architecture. He collaborates in teaching projects for architectural design in the first years of the degree program in structural engineering-architecture at the University of Pisa. Beginning this year, he has a contract to teach a laboratory for CAD applications. Only in his spare time is he a "real" engineer.