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Giuseppe Amoruso *Editor*

Putting Tradition into Practice: Heritage, Place and Design

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The Architectural Heritage in Seismic Area: Geometrical Survey for Damage Analysis and Strenghtening Design

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Abstract. The consultation of historical archive documents, often combined with a careful visual inspection, can reveal if the masonry structures of historic buildings has been subjected to several repairs, extensions or wheatear a portion was rebuilt after a partial collapse. These events leave indelible marks in the walls, affecting a building's local or even the overall structural behavior, decreasing its level of performance. During the emergency time after an earthquake, fast damages analyses of the architectural heritage are required in order to temporarily preclude their use, fully or partially. To carry out correctly this damage analysis, a precise geometrical survey should be already available as a necessary supporting tool, with all anomalies reported and with minimal simplifications. Some examples are here reported, showing the importance of the use of an available geometrical survey for the damage evaluation of architectural heritage after the 2016 earthquake of central Italy.

Keywords: Historic masonry building · Geometrical survey · Damage analysis · Seismic vulnerability

1 Introduction

The analysis of historical archive documents and, often, careful visual observations are able to detect if the historic masonry buildings has been subjected to numerous repairs, alterations and extensions of different materials or if a portion was rebuilt due to a partial collapse.

These events leave indelible traces in the walls, often affecting a building's local or even overall structural behaviour and resulting in a level of performance that is far from what was designed and implemented at the time of its construction. Often historic buildings turn out to be intrinsically weak and those weaknesses represents their scars, that should be recognized, analyzed and cured. The greater is the number of such scars in the historical buildings and the greater is their vulnerability, mainly to traumatic events such as earthquakes.

Looking at the earthquake that shocked the central Italy in 2016, one of the main causes of historic masonry buildings collapses should not be attributed only to the

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buildings age or to their poor construction quality, but to the high vulnerability acquired over the centuries. The risk becomes higher if transformations or repairs are realized with modern materials and techniques, too different from the traditional ones and so incompatible from the structural point of view [1, 2].

It must be remarked that the value of an architectural heritage is not only related to its appearance, but also in all its material and structural integrity, as a single product of a constructive technology of a specific historical period and place. Preserving the material component means therefore also understanding the logic of its structural system, repairing it with compatible techniques and allowing to be used without changes or substantial additions or substitutions that relegate the original structural material only to an historical backdrop.

In the second half of the XX century, several historic masonry buildings, also architectures of great value, were subjected to structural strengthening through the introduction of modern materials and techniques. The rash use of such techniques, sometimes without rational analysis that simply validates the efficacy and compatibility, turned out to be damaging over time, both for material and for the structure. The conservation of the materials means therefore maintaining their role inside the building, removing, reducing or controlling the causes that have damaged them.

2 The Role of the Precision of the Historic Building Geometrical Survey

When dealing with existing masonry buildings, it is therefore essential devoting sufficient time to the study and knowledge of the structures, above which the new structures will be carried. The historic masonry structures, even the simplest ones, cannot be standardized on a large scale, as can be done for the modern buildings of the post-war period. Each masonry, especially the stonework, is often a unique masonry, because influenced by the construction technique commonly employed in a place and in a given historical period, in addition to the function of the building and the requirement to make it durable. Where changes have occurred, both historical and modern, the building presents geometry variations sometimes noticeable to the naked eye and sometimes evident only through a careful and detailed geometric survey. This survey has not to simplify its geometric complexity, as well as the correct thickness of the walls, their orientation, the correct size of the corners, discontinuities, misalignments, etc.

The building may have had an evolution along the time: born, for instance, as an isolated building, it could have become a row building or a complex one, after the addition of several volumes (Fig. 1). The more complex the building is, the more difficult the detection of its vulnerability is; therefore, its structural evolution should be known as much as possible [3–6]. Thanks to the decay presence, causing partial lack of plaster, or to diagnostic techniques as thermography, it is possible to carry out a volumetric stratigraphical reading and read the different masonry textures that help to understand the characteristic anomalies of an historic building (Fig. 2).

A volumetric stratigraphy (Mannoni 1994) allows the subdivision of the building into homogeneous blocks, characterized by relative chronological relationships. Any

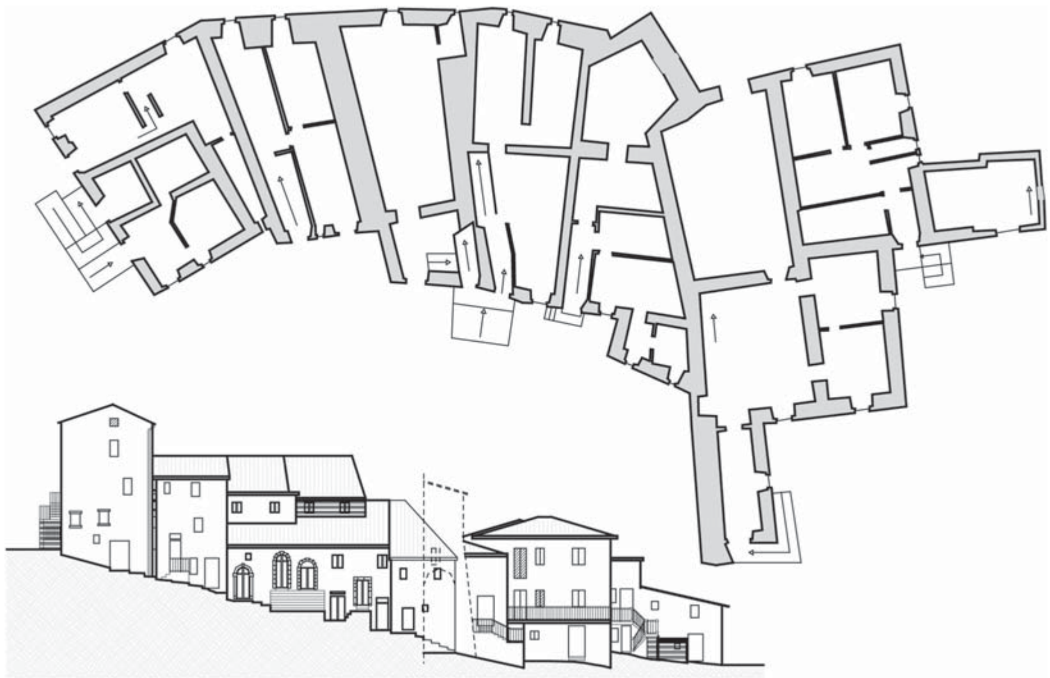

Fig. 1. Example of the map of an historic complex civil building [2, 3].

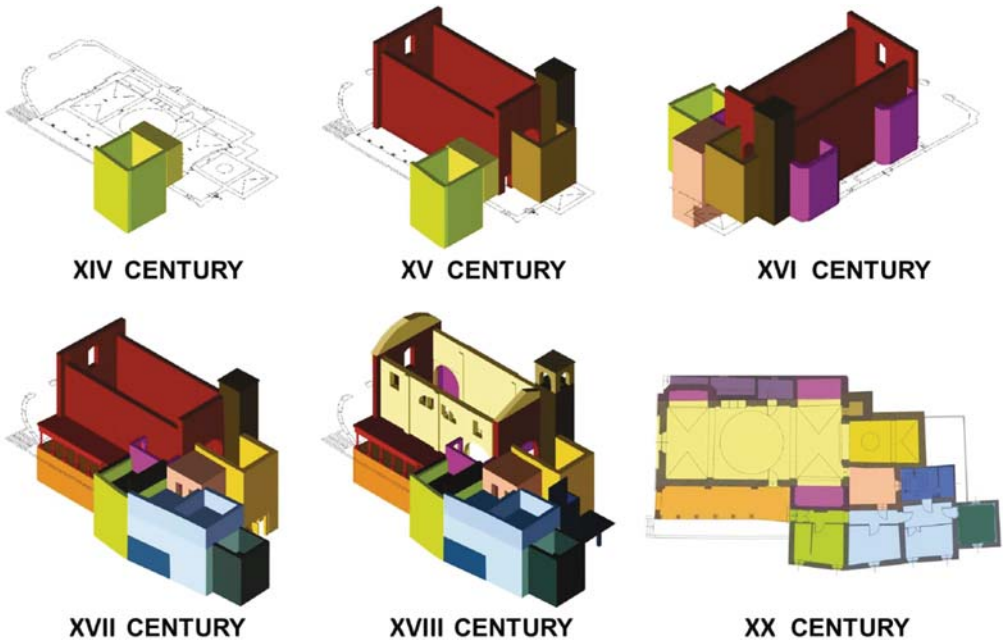

Fig. 2. Volumetric stratigraphic analysis made on volumes for the chronological evolution phases of a complex religious building [4].

block corresponds to a unique building phase, recognized by the observation of constructive details; its relationship with the other blocks may be "preceding" or "subsequent", often with no possibility of an absolute dating. Critical connections between blocks need to be investigated, so to clarify the phases of expansion and transformation of the complex and so the most vulnerable points. The study can be then completed by the investigation of dated elements like the brick type and dimensions and by the chronological characterization of the construction techniques and masonry details, beyond the survey and characterization of the different masonry typologies.

These anomalies should not be considered just as historic constructive mistakes or survey mistakes, whereas they should be stressed. Serious mistakes can occur when those traces in the masonry structure are not examined carefully before carrying out repairs, reinforcement works, adding new structures or making structural changes, especially in earthquake zones, as well as adding provisional works.

3 The Analysis of the Crack Pattern

An effective approach to the historic masonry constructions study has to start from the knowledge and understanding of their structural logic, with all their specific peculiarities and intrinsic weaknesses, as well as the global damage and all the visible cracks. The crack pattern survey must be carried out in order to interpret the type of damage and its causes. The damage survey, followed by a correct analysis and investigation of the damage causes, helps in recognizing the cracks that are indicators of a local or global suffering or future possible collapse mechanism [3, 4, 7]. That damage causes could be due to a sudden traumatic event or to some events still active. Damages which are frequently attributed to the earthquake can have a different nature and can be caused by excessive dead load or soil settlements, or simply to lack of maintenance. All cracks should be clearly represented on the buildings elevation drawings, with their correct location and shape. In case of stone masonry, the load bearing capacity depends strictly on the deficiency of the constructive details, which may be the cause of a local mechanism. At last, with different crack patterns surveyed at different period of time, it is possible to observe the evolution of the cracks (Fig. 3).

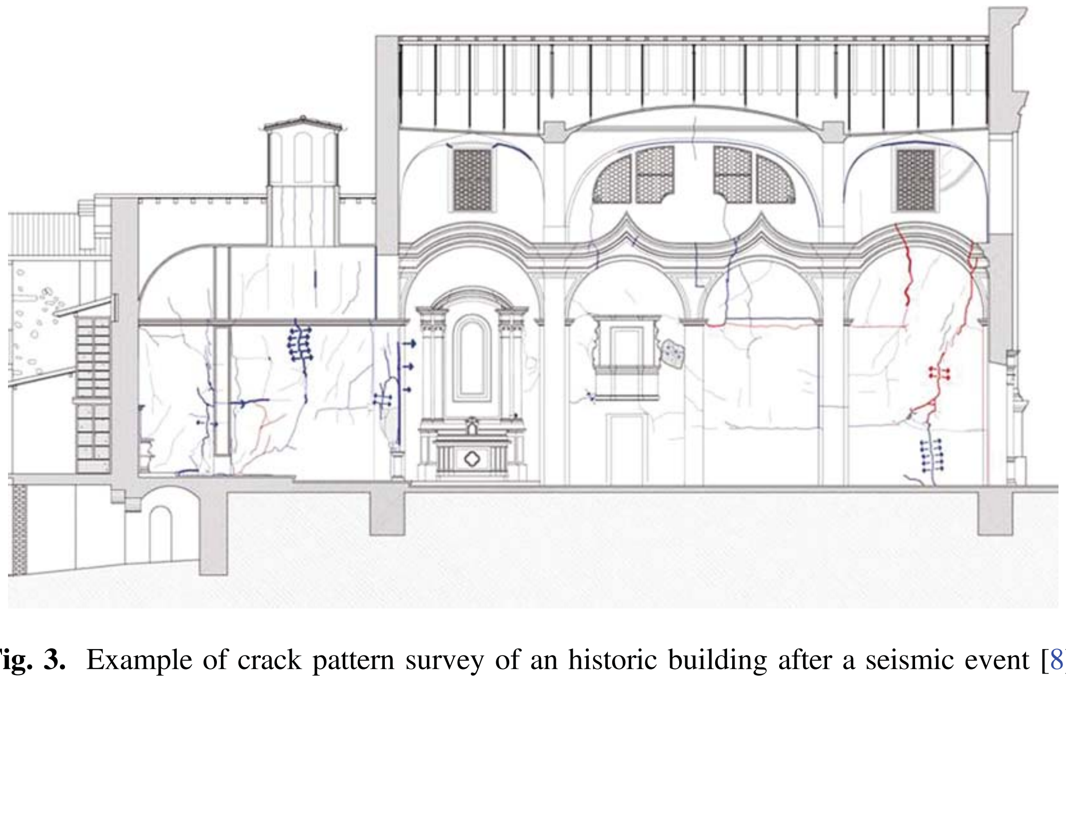

Fig. 3. Example of crack pattern survey of an historic building after a seismic event [8].

The damage and the crack pattern survey becomes an essential topic in a preservation project, in order to distinguish the recent arisen problems from the already existing ones and never fully solved. Cracks usually form where the structure is already fragile and in detail where discontinuities are present. Therefore their analysis helps in setting up a strengthening design, which should be effective and durable. Also a monitoring design of correctly selected cracks is able to define the evolution of the damage and its velocity.

Earthquakes usually put in evidence already existing damages. If an historic building was built following the rules of art, presenting a compact and regular geometry, and, substantially, if it has not been modified over the centuries, it is more homogenous and presents less damages, compared to the similar building that had transformation, reconstructions and strengthening. The incompatible strengthening interventions realized in the last forty years were one of the major cause of damages, as observed after the seismic event that hit the Central Italy in 2016.

4 Some Examples of Incorrect Interpretation of Historic Buildings Evolution and Damaged After a Seismic Event

Every seismic strengthening intervention should take into account the historic and constructive evolution of the building, all its modifications occurred over the centuries, till the more recent ones. The presence of such discontinuities makes the historic building much weaker than a similar one but homogenous and compact and often concurs to add irregularities both in plane and in height.

Also the application of provisional strengthening systems should take into account, in addition to the observed damages, the preexisting weak points, the discontinuities and the constructive evolution. This has the aim to avoid wrong or needlessly invasive interventions on architectural heritage, as observed in the historic center of L'Aquila after the 2009 earthquake.

Three different cases are here reported.

4.1 Complex Masonry Building in Recanati (MC)

The case of an historic building in the center of Recanati is here presented. The building has an unknown origin and is characterized by an articulated geometry, due to the addition of three brick masonry volumes of three/four- storey, with masonry vaults on the basement and placed on a high sloped ground.

This construction was damaged after a first seismic event in 2016 and, according to the risk of overturning of the North façade, the municipality decided to close the below street, till the necessary protection and safety works were realized. Those works were realized after a short time and nowadays the building presents the last upper floors fully chained up with two series of iron ties rods (Fig. 4).

From the on-site visual inspection of the damage, after subsequent earthquakes, and from the analysis of the geometrical survey (supplied by the owner), it was observed that the main cracks were located only in one portion of the North façade: this portion

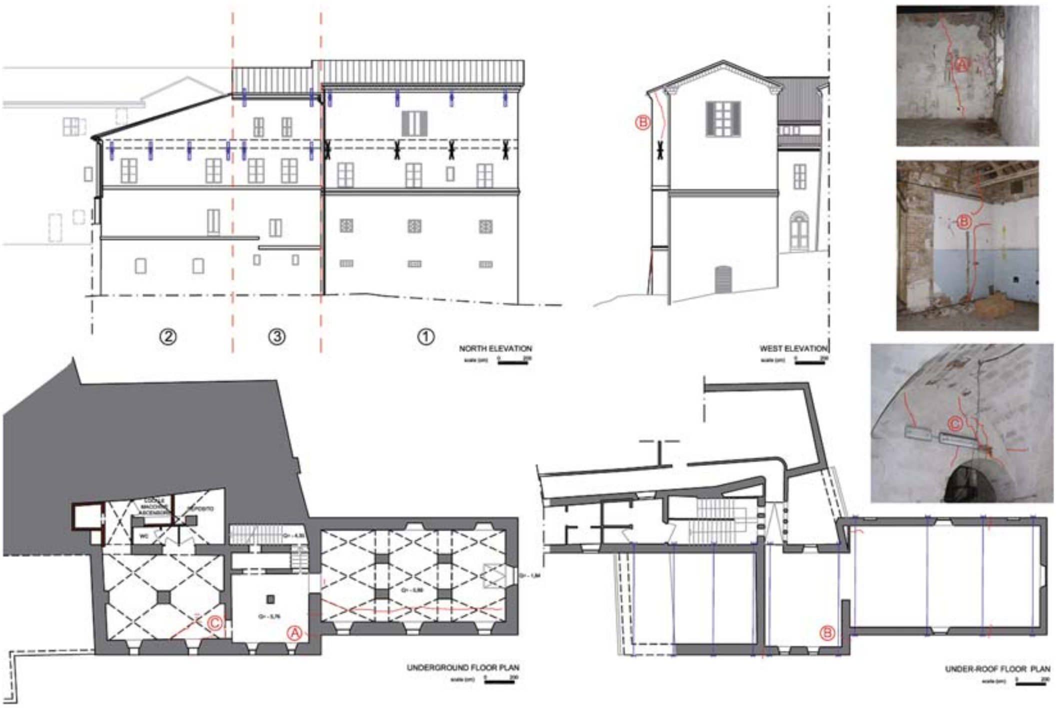

Fig. 4. A complex historic building damaged by the earthquake: crack pattern and provisional intervention on the North facade.

corresponds to a subsequent constructive phase that joined two existing volumes, localizing the main internal stairs. It has a different wall thickness and horizontal floor. Cracks are localized mainly in the corners, where walls are not aligned and can be hammered, mainly in the upper floor. Probably far from the emergency time, this observation could have reduced the number of iron tie rods inserted to the real necessary ones, with the aim to avoid the overturning of only this added façade portion.

Such a massive safety intervention was certainly able to avoid collapses during the last seismic events, but has unnecessarily created additional manipulations in the structure, hard to repristinate after their removal. In addition, the overall provisional intervention did not avoid the formation of new cracks in the basement vaults, where maybe tie rods should have been added, together with the intervention in the ground soil, carried out only below one of the three volumes.

The complex geometry of the building with its historical evolution, together with the recent provisional safety works (excessive iron tie rods number and localized ground soil intervention), contributed towards a more vulnerable building, also when it will be definitely restored.

4.2 Church of Santa Maria in Piano in Loreto Aprutino (PE)

The second case here presented is a religious Romanesque building, strongly transformed over the century. Although some evidences of a monastic structure, together with a church, traced back to the IX century, the current building dates back to 1280, when the church was enlarged and restored following the "Bourguignon" style (the

Cistercian style coming from Bourgogne). The plan is rectangular with a unique nave (1), divided in five bays through big gothic arches, which springers go above half-columns protruding from the side-walls and bear the visible wood roof. The beauty frescos and the bell tower, built on a preexisting tower near the church, dated back to the first restoration realized in 1429.

In XVI century the porch (2), strongly adjusted in 1955, and the octagonal apse (3) were added. In XVIII the dome with a cylindrical drum was added above the apse. Observing the damage together with the geometrical survey, the historic evolution and stratification correspond to a clear overlapping of different structures. This is the case of the dome vault, built over the octagonal apse and the back wall of the church of the XV century (maybe of XIII century).

After the seismic event of 2016, a serious crack pattern was observed, mainly due to the different structures reaction (church back wall, apse and dome vault) to the seismic actions: the three structures adjacent but not interlocked caused general hammering, damaging seriously the back wall. In addition soil settlement effects are visible (Fig. 5).

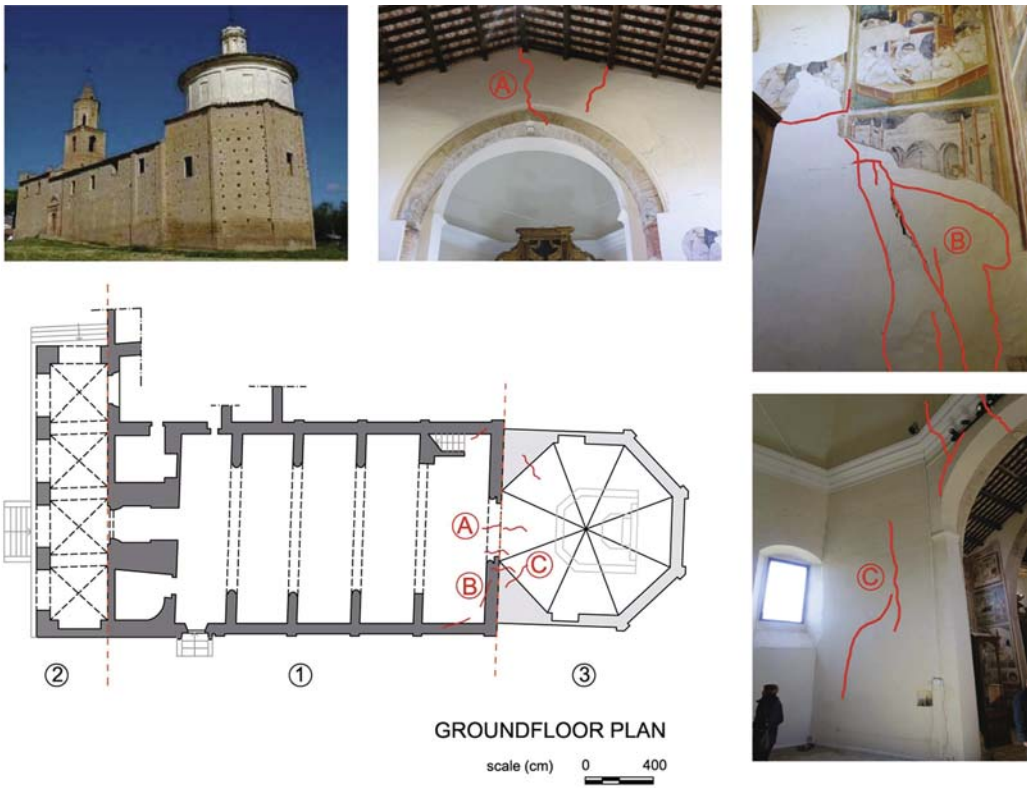

Fig. 5. The earthquake damages on the Santa Maria in Piano's Church dealing with its vulnerability.

This is the case of a seismic damage strictly correlated to the compositive complexity of the building, due to the articulated structural evolution over time. This should be taken into account before its restoration in order to better analyze this weak points showed by the earthquake and design an intervention aimed not only to repair the structures but to overcome these vulnerability elements.

4.3 Defensive Building Named Forte Malatesta in Ascoli Piceno (AP)

The construction was built over a roman thermal complex, at the gates of the city, near the *Castellano* river side and is a fortified work of urban defense of Ascoli Piceno. After several demolitions and reconstructions, in 1349 it was strengthened, becoming a typical medieval fortress with the new name of Forte *Malatesta*, taking its name from the captain who encouraged this renovation. Other demolitions occurred till the beginning of the XVI century, when, above the ruins, a church was built with a dodecagonal shape and devoted to Saint *Maria del Lago*, still visible nowadays in the central body of the construction. Under the commission of Pope III *Farnese*, Antonio da San Gallo *il Giovane* in 1543, on the same site, raised a new fortress with an irregular star shape, including also the deconsecrated church and conveniently transformed in bastion. Additional changes occurred over the centuries, till 1828 when the Forte *Malatesta* was completely restored and used as a judicial prison till 1978. Currently a recent restoration transformed it in a museum.

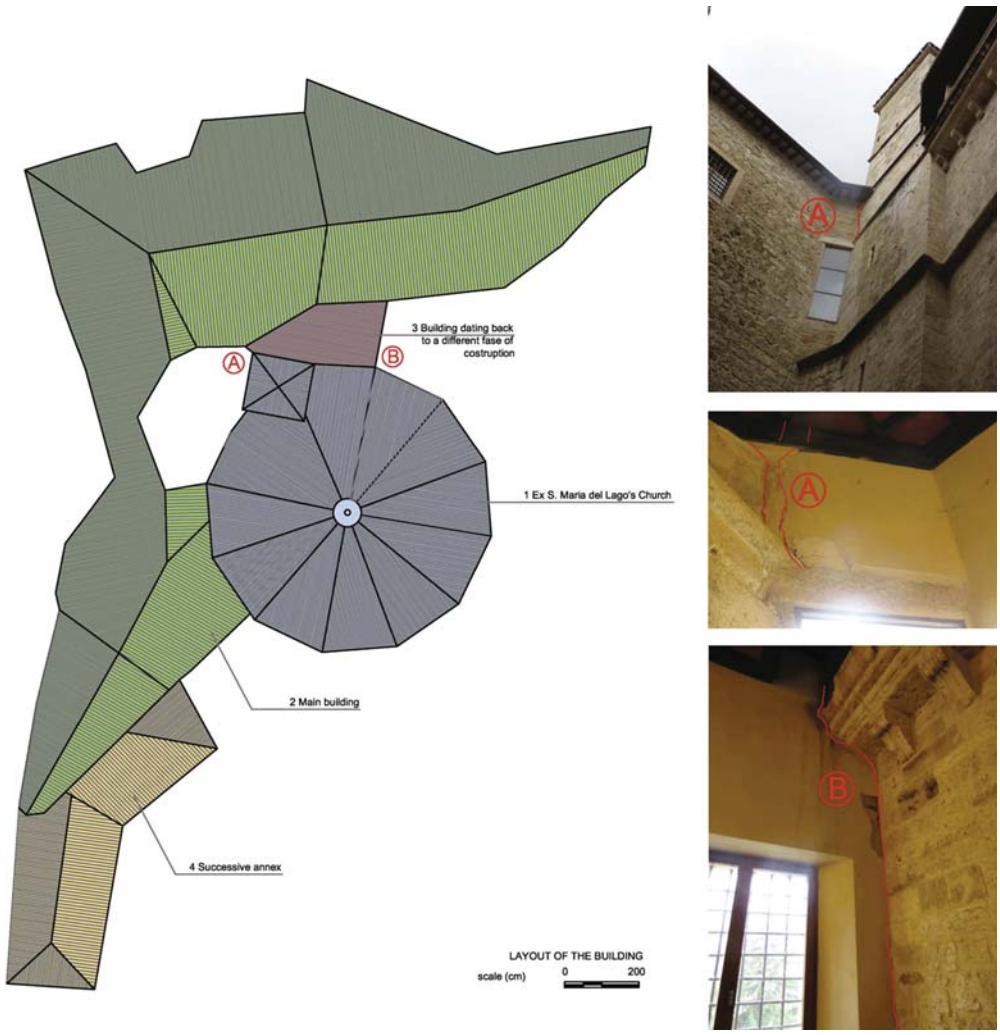

Fig. 6. Malatesta's Fort layout and damages caused by the earthquake on the weakest part of the building

As in the two above mentioned cases, also in this case the earthquake put in evidence the vulnerable points of a such complex building, made by annexing and filling spaces among preexisting structures but always military and so statically massive.

The main damages are localized in the weak points of the building and referred to the interventions made after 1543, such as “shiner” brick masonry vaults, internal partitional walls and external wall boards, overlapping with non-homogenous materials. In details, a passing-through crack with stone material ejection concerned near the tower: from the historic-stratigraphical analysis of the building it is clear that this portion is a connecting volume filled between the tower and the fortress, made with external wall boards not interlocked with the lateral walls. The walls with higher mass and more compact hammered and detached those connecting walls (Fig 6).

5 Conclusions

Some cases have been here discussed to highlight the close relationship between a correct graphical representation of the geometrical surveys and the analysis of the damages caused by an earthquake. The geometrical survey of historic buildings, when well detailed and showing all real anomalies present in the constructions, can be a valuable tool to understand the complex configuration of architectural heritage in their current shape and their vulnerable points. Historic buildings are often the results of several transformations occurred over centuries, as well as they can also show deformation and damages not necessarily due to accidental events. Of course, the geometrical survey alone is not able to supply an enough level of information and knowledge of a building, able to guide the restoration work, but it is certainly the first essential step. A precise geometrical survey of architectural heritage should already be available as a necessary supporting tool, with all anomalies reported and with minimal simplifications, so to let the recognition of the historic- constructive evolution marks. In post-earthquake emergency, geometrical surveys of complex buildings are an helpful tool for the fast analysis of the damages and for the identification of the possible collapse mechanisms. This helps in designing a correct and necessary intervention of provisional works.

This geometrical survey is a tool able to recognize in a short time the vulnerable points of the building, allowing the design of correct provisional works, preventing urgently further damages and so the loss of the architectonical heritage. Unfortunately, those interventions, as well as the definitive retrofitting, when not correctly designed, can, on the contrary, contribute to increase the already existing vulnerabilities present in the existing historic buildings, instead of helping them in preventing further damage.

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