Building Archaeology and Seismic Risk:

The Mugello survey

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Abstract: The application to the study of buildings of archaeoseismology, that is the preventive archaeological analysis of historical buildings in areas affected by seismic risk, is nowadays a disregarded field. Nevertheless this discipline requires a close examination from a methodological and disciplinary point of view, considering the frequency and destructiveness of earthquakes. The present work deals with the application of the archaeological methods (stratigraphy, chronotipology, characterization of building techniques, etc.) to the modern methodologies of the tridimensional survey, with the purpose of creating a series of products, as the Digital Elevation Models, Orthophotos, Vertical Architectural Sections, Textured and Wireframe 3D Models, all used to highlight the building and restoration history of the edifices. These products are to be used as a cognitive base of the material structure, of the building techniques and the reparation of a specific context, in order to be of great use for future analyses of vulnerability and restoration. The context selected is an area in the north of Tuscany, considered today at a high seismic risk: the Mugello. This area is characterized by a well preserved religious medieval architecture and was struck by two earthquakes of large intensity since 1542 to our days. These are still traceable in the material structure of the buildings and in the ancient scripts and cartography. Therefore the present paper will focus on the trinomial “technology- archaeology of the architecture- seismic risk” with the intent to bring the scientific community to the attention of the advantages and critic issues of an innovative point of view.

Keywords: Earthquakes, Archaeoseismology, Building Archaeology, Mugello, 3D Models

Introduction

The project “Archeologia dell’Architettura e Rischio Sismico nel Mugello” (Building Archaeology and Seismic Risk in the Mugello area) was born in 2010 from my PhD research in Medieval Archaeology, which I proposed and developed in collaboration with the University of Siena, the University of Florence and the University of L’Aquila. The research project took shape after examining the damages on the architectural cultural heritage, caused by the recent seismic activity in Italy, above all the earthquake in L’Aquila in 2009. The research aims to create an archaeological protocol for the preventive study of areas at seismic risk, by underlining the strength points and type of information achievable through a deep analysis of the buildings and of the contexts more in general. The results of the research are considered in order to be integrated at a later stage with the standard methods of analysis and direct intervention on the artifact, used by other disciplines (geology, geomorphology, structural engineering, architecture, etc.).
The context of study selected is the Mugello area, in the province of Florence, classified as an area at medium-high seismic risk and formed by ten communes located along the borderline between the Emilia Romagna and the Tuscany regions. The area constitutes an ideal context for an extensive archaeoseismic

analysis for two reasons: on one side a well-documented seismic history, on the other side its richness of medieval buildings, especially the religious ones, whose seismic and building history is witnessed not only by ancient documents but also by their own standing structure. After all, earthquakes leave permanent traces on buildings, just as the operations of restoration, demolition etc. Part of the archaeologist's job is to interpret these traces and to transform them into historical processes.
For obvious problems of space and the necessity to conform to the topic of the conference, the present paper will not describe the entire project. It will bring instead more attention on the technologies used for the research, in particular on their application to the measurement of the archaeological evidence of earthquakes on buildings.

Ministerial Guidelines and the Archaeology of Architecture

The will to introduce an "archaeological point of view" in the study of ancient architecture in areas at seismic risk finds a significant point of reference in the procedures indicated by the present ministerial legislation on the seismic risk in Italy:

> "*Guidelines for the evaluation and reduction of the seismic risk of the cultural heritage*".

This publication, developed in 2009 and partly modified in 2011, declares the intention

> "[...] *to define a process of knowledge, evaluation of seismic safety and planning of the possible interventions* [...]" in order to "[...] *express, in the most objective way, a conclusive judgment on the safety and conservation guaranteed by the operation of seismic improvement*"
>
> (MIBAC 2010).

It seems as in these guidelines is missing any mention of the professional figure of the archaeologist. But after a careful reading of the chapter on the procedures applicable for the improvement of architectural vulnerability (chapter four entitled "Knowledge of the artifact"), it is possible to notice the presence of some methods of analysis commonly belonging to the discipline of archaeology. These methods belong precisely to the archaeological study of buildings: definition of the body of buildings, identification of building phases, recognition of the main reconstructive activity, characterization of the constructive techniques. So the first step of the research has regarded these methods listed in the Ministerial Guidelines and the consequent elaboration of an archaeological procedure conforming to them.
Until today, the discipline of archaeoseismology is still not exhaustively studied by Italian archaeologists (at a monographic level). For this reason, it was necessary at first to identify all the means and methods used by other disciplines dealing systematically with earthquakes (in particular structural engineering, history of seismology, geology and geomorphology), to understand how to integrate some procedures to the custom archaeological approach.
As evident from the diagram in figure 1, every discipline (only a part of them has been represented for problems of space) elaborates through its own means a series of products, today completely accepted as

methods of analysis of the seismic risk. The introduction of an archaeological approach and the integrated use of non-archaeological instruments, like for example indirect sources, constitute an innovation in the procedure described above. Precisely, the products elaborated by the different disciplines could be used in the Archaeology of Architecture in the following ways:

- the seismological catalogues could perform a double task, both chronological and historical, to add to the archaeological one, thanks to their database structure (see on this argument GUIDOBONI COMASTRI 2005, BOSCHI et Alii 1997, BOSCHI et alii 1995)
- the dangerousness seismic maps at a national, regional and urban scale, could help in the definition of the context of study
- the damages mechanism abacus could provide the possibility of recognizing punctually the damages on buildings caused by one or more ancient earthquakes
- the digging documentation could provide data in addition to the information collected from vertical archaeology, giving for example the possibility to verify an uncertain or wide-range dating, when written documentation is missing. It is fundamental in fact to underline the difference between horizontal and vertical archaeology, because despite their common approaches (stratigraphy, chronotipology etc.), they produce different kinds of data in archaeoseismology, both quantitatively and qualitatively.

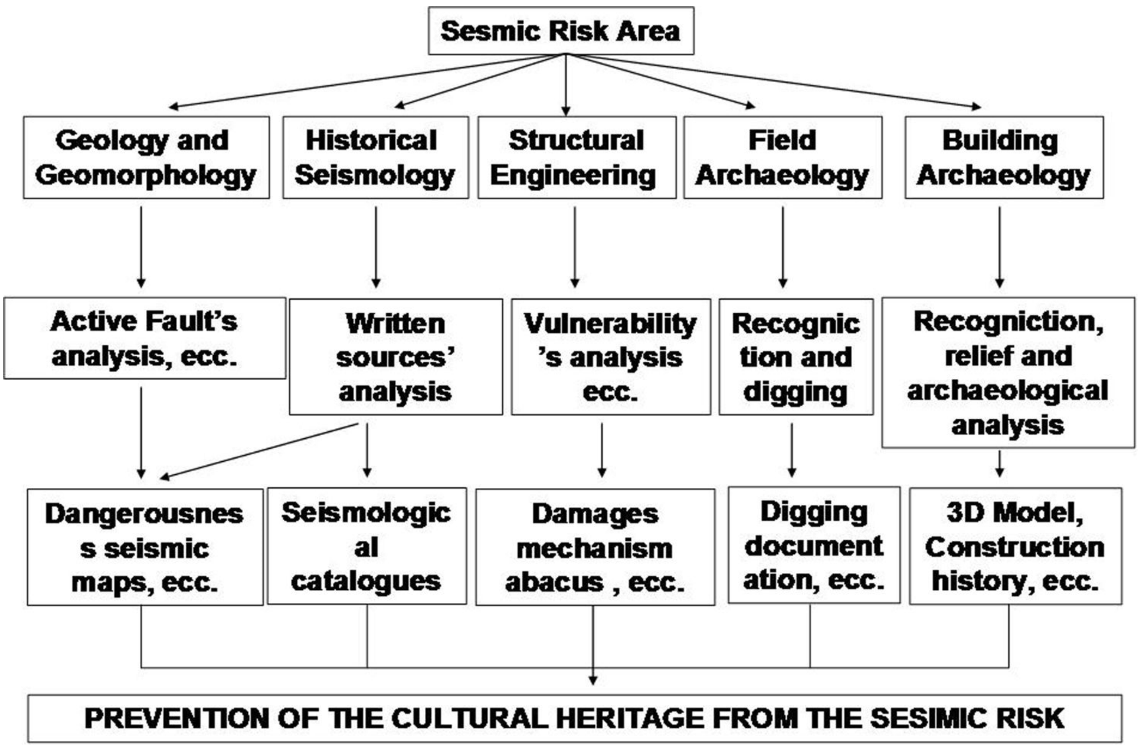

Fig. 1 – Conceptual diagram for the prevention of seismic risk in cultural heritage. The diagram is formed by the integration of two different approaches: the one concerning the analysis of areas at seismic risk and the archaeological one.

Testing photogrammetric technologies in the analysis of historical buildings in seismic risk areas

It is useful, before describing the technologies used in the Mugello area, to introduce a short reasoning on how an archaeological survey in seismic risk areas should be characterized. This reasoning derives from the experience gained after the earthquake in L'Aquila in 2009 and also from the project that is still taking place in the Mugello. Despite their different context (different safety conditions, surveying speed, landscapes etc.), both areas present common problems, regarding the kind of instruments to be used for surveys and the papers to produce. The instruments to be used for an archaeological survey should present the following essential characteristics: speed and ease of transport and assemblage; speed in surveying and in elaborating data; the feature of creating tridimensional models in a correct metric, geometric and chromatic scale and possibly connected to a texture; the feature of producing an output usable by different disciplines; the possibility to document also the "fourth dimension", that is time, obtained from archaeological analysis. Moreover, the study and the documentation (and not only) of the historical architectural heritage in seismic risk areas require the correct codification of rules. In this regard, the guidelines on data feedback in photography and graphics, formulated by the English Heritage in "*Metric Survey Specifications for Cultural Heritage*" (ANDREWS 2009), result interesting. These guidelines in fact, permit to develop results at a standard European level, which can be handed, in a second moment, to the responsible of direct analysis of the material structure of the buildings.

The Menci Software ZScan was used for the surveys preceding archaeological analysis in the Mugello buildings. This software is a kind of photogrammetric technique that develops tridimensional models in a texturized RGB point clouds, throughout the elaboration of photographic triples (ARRIGHETTI-CAVALIERI 2013). This process can be divided in two phases: the survey on site and the elaboration of data in laboratory. The second phase is, in addition, characterized by two different operations, that are the creation of 3D models and the elaboration of a final model, complete with outputs that are connected to several other softwares:

- ZScan: this software transforms single photographic triples in tridimensional models, throughout several operations, all directly controlled by the software user, during the elaboration of the model. This direct control is essential, because it allows to generate outputs in a particular resolution and different densities, in relation to the final requirements of the research project.
- ZMap: this software generates a mosaic from the 3d models (the mosaic can be created manually or automatically, if Ground Control Points are provided by total station), digitizes the model and creates outputs (3D wireframes drawn directly on the 3D model, orthophotos, Digital Elevation Models and section lines characterizing the surface of the objects surveyed) to be used for several types of analysis.

The models generated permit a clear understanding of the material structure of the building, thanks to their precision and reliability at a metric, geometric and chromatic scale. Furthermore, the application of the texture to the 3D models allows an interpretation and a stratigraphic characterization of the building analyzed, both from a macroscopic (for example the reconstruction of building phases and agency) and a microscopic (for example the identification of the detachment of plaster from walls) point of view. These elements are fundamental to understand and record the history of a building and its context, so they match perfectly with the requirements of an archaeological survey.

Also the ZScan Micro technology was used in the Mugello area (ARRIGHETTI et alii 2012, FREDIANI et alii 2010, TIANO et alii 2008), in collaboration with the architect Rachele Manganelli del Fà of the Institute for the Conservation and Enhancement of the Cultural Heritage, part of the CNR in Florence. Methodologically similar to ZScan, this other software develops models and outputs of a higher accuracy and definition, with a level of precision arriving up to 50 micron. ZScan Micro was tested during the monitoring of damage on certain buildings studied.

Some examples of the surveys conducted in the Mugello area

The Mugello area is located along the Apennine ridge, dividing Tuscany from the Emilia Romagna region. As evident from the National Map of Seismic Danger, elaborated by the National Institute of Geophysics and Volcanology (fig. 2), this territory is classified at a medium-high level of seismic risk. In addition, if we take a look at the map of seismic micro-zones, elaborated by the Tuscany Region and divided in all the Communes occupying this territory (fig.2), it is evident that the Mugello is located in an area classified as 2, the highest level in Tuscany and the second highest in all Italy (level 1 includes for example the area of L'Aquila).

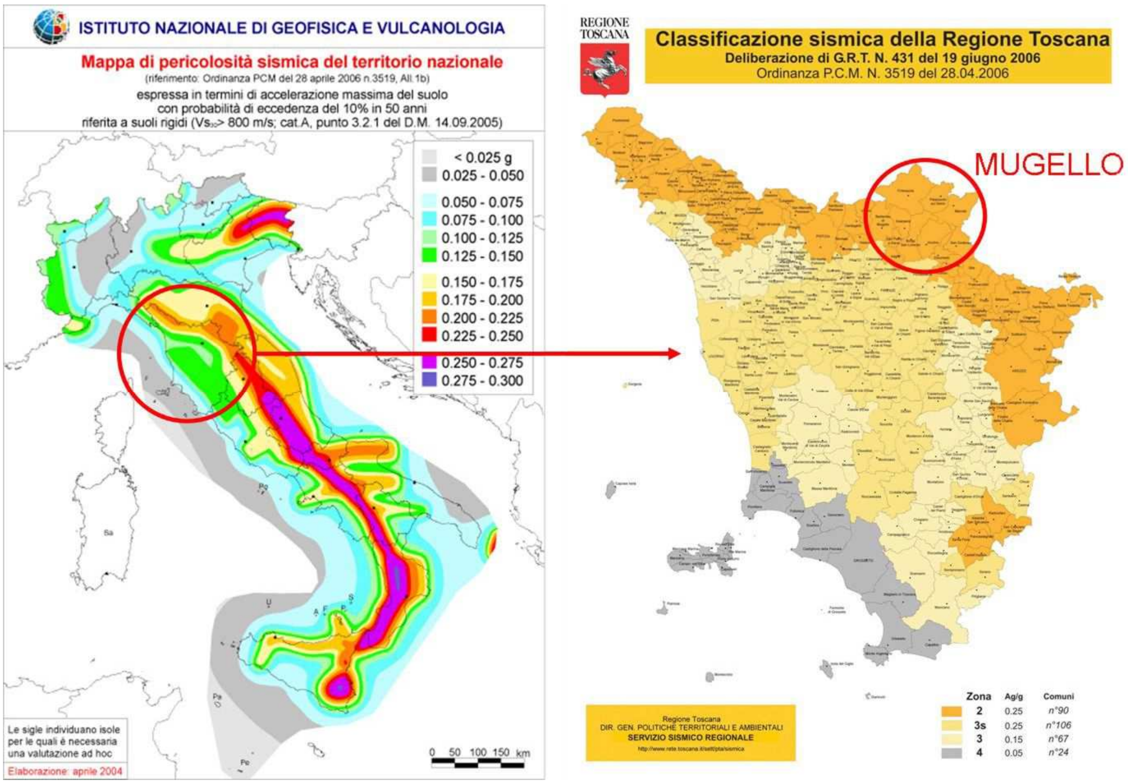

Fig. 2 – National Map of Seismic Danger elaborated by the INGV
(open source: http://zonesismiche.mi.ingv.it/mappa_ps_apr04/italia.html) and the Map of Seismic Classification of the Tuscany Region (open source: http://www.rete.toscana.it/sett/pta/sismica/03normativa/classificazione/classificazione_toscana/index.htm).

By observing the list of earthquakes in fig. 3, derived from the seismic catalogue of the INGV, it is possible to notice that several earthquakes took place in the Mugello area during the modern age. Among these, two earthquakes of 9th grade intensity happened in 1542 and 1919. The catalogue also shows how, according to the historical sources, no earthquake took place before 1542. But this fact should be reconsidered due to the results obtained by the archaeological surveys on the buildings in the Mugello area. The surveys in fact highlighted the presence of earthquake damages previous to the 16th century.

Fig. 3 – List of earthquakes happened in the province of Florence from 1000 to 1920 (data obtained from the seismic catalogues of the IGNV). The list includes dating, epicenter (blue for the earthquakes in the Mugello and red for the ones in Florence and its province) and Estimated Intensity. All earthquakes of intensity inferior to the 7th grade have been removed from the list, for it has been calculated that only earthquakes over that grade bring a certain amount of damage to buildings.

After selecting the area to study, a systematic survey of all its medieval buildings was started, proceeding in a concentric way from the epicenter of the earthquake in 1542 (between Scarperia and Galliano) to the hypothetical “borderline” of the 7th grade intensity (the distribution area has been analyzed by some geologists of the INGV and published in FERRARI MOLIN 1985). The parameter used for the selection of the context and the buildings to analyze was obtained by the comparison between the seismic wave of 1542 and the evidence found during surveys and from the historical sources available. With this method, 20 buildings have been spotted in the territory, 18 of these being churches, presenting entirely or in part their material structure and being in this way easily readable from a stratigraphic point of view. The buildings also presented seismic damages and a quite considerable amount of historical documentation.
In every building selected, the most interesting sections were surveyed, in order to obtain a detailed and reliable documentation, to use for archaeological investigations. The surveys were mainly conducted on the outside of the buildings, the bell towers and only in part on the inside of the buildings (all in great part plastered). The most difficult aspect of the survey was the height of the buildings in relation to the small space available on the ground for the photographic shots; this brought several times to shoot pictures with the lens of the camera strongly inclined, causing a big distortion in the models generated during the post processing phase. In addition, the presence of projecting elements (for example canopies, balconies, frames, etc.) created in the models shadows that were too large to be corrected. For this reason, sometimes

the “plain” orthophotos has replaced the tridimensional model, even if this brought to an inevitable loss of information due to the absence of the third dimension.
Once the surveys on the buildings were conducted, a series of outputs were generated (Digital Elevation Models, 3D models, surface sections, orthophoto plans, etc.) that could best form a base for recording and documenting the construction history of the buildings, the case studies of damage (that were activated by the different earthquakes) and the possible restorative measures carried out in past.
The stratigraphic survey on the structures, closely connected to the case studies of damage activated, was conducted both on the tridimensional models and on the “classic” orthophotos. Regarding this, it is important to underline the close connection between the kinematics of cracking and the interfaces between the different building phases or SU (Stratigraphical Units). The millimeter accuracy of the perspective drawings, orthogonally adjusted, allowed to work easily on the spot and to report on the final papers the stratigraphy of buildings. In this way, it was just as accurate to identify the damages caused by earthquakes and the methods of reconstruction or prevention adopted. An example is showed in figure 4, where the stratigraphic survey on the façade of the Parish Church of Saint Agata has underlined the presence of 5 macro-phases of construction related to earthquake damages or restorative measures. One of these phases, probably dating to the 13th century for its building technique and located in the central part of the façade, results stratigraphically previous to the earthquake documented by the written sources.

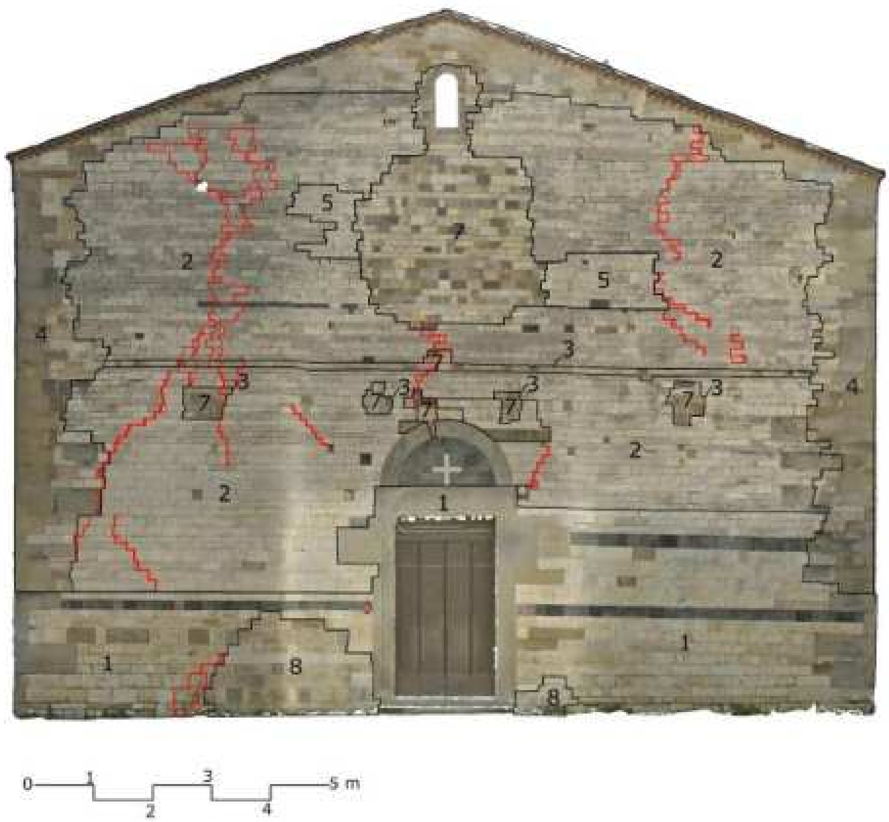

Fig. 4 – Example of orthophoto plan with a stratigraphic survey in phases (black lines) and crack framework (red lines) of the entrance façade of the Parish Church of Saint Agata in the Mugello. It is interesting that several damages run along the interfaces dividing different building phases. It is also interesting that some of these damages are concentrated only on some of the building phases rather than on others. This helped to date the phases and agencies found.

In this case, the evidence on a single building of a certain amount of damage, dated to a specific period, leads to a consideration: this damage was caused by several factors, both natural and artificial. But from the comparison with the results obtained from the survey on other buildings in the area, an intense constructing activity consequent to large damage and dating to half of the 13th century results evident. So to verify the hypothesis of an earthquake in absence of written sources, the only useful way could be an archaeological excavation. But excavations in the present are still focused on later chronological phases.
As already explained, the ZMap software offers also the possibility to draw directly on the texturized cloud of points, allowing to generate a 3D wireframe of the structures. The procedure consists in the identification of the different reference planes of the objects to draw and in the digitization of the models with a toolbar similar to the one of a CAD software. This permitted a considerable improvement in the completeness of recording the structures and in the overview of the building phases of the architectural complexes.

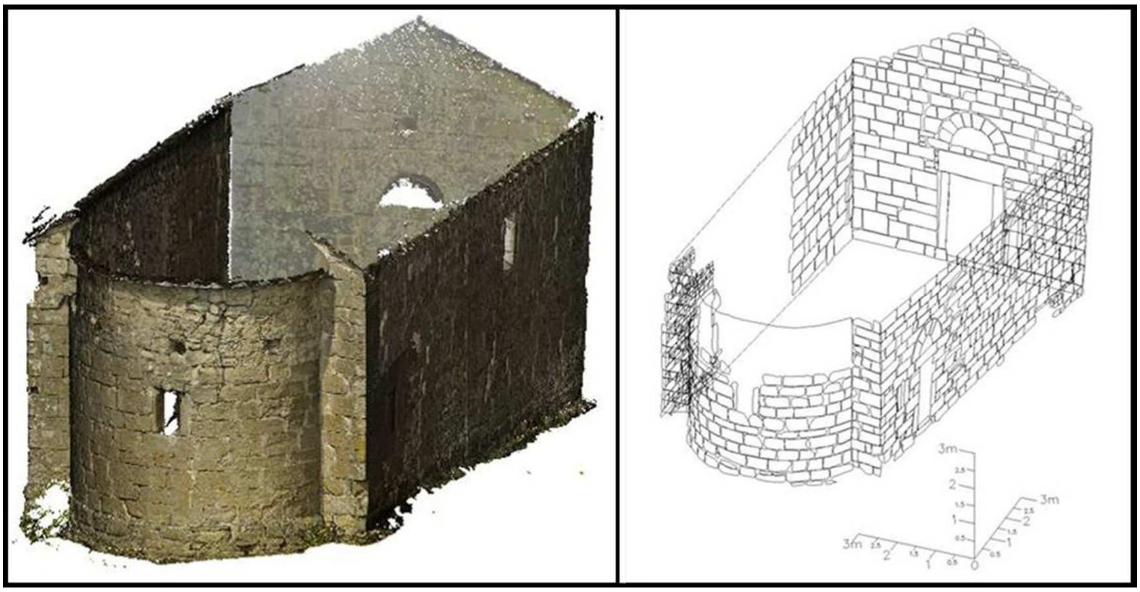

Fig. 5 – Example of three-dimensional model and of digitization in a 3D wireframe of the external façades of the church of Santa Maria a Fabbrica a Vicchio.

Another important aspect emerging from the surveys in the Mugello area was the difficulty of recording and classifying exactly and accurately some particular case studies of damage, activated on the structures by earthquakes or other natural phenomena, as a bulging or out of plumb condition. In this case, the problem was solved throughout the use of ZMap. Precisely this software transforms the tridimensional models in Digital Elevation Models that is chromatic maps representing through colors the position of the photographed surfaces in relation to a vertical plane of reference. In addition, the possibility to obtain surface sections on the DEM (lines traced through points predefined by the software user, these represent the outline of the surfaces of objects) allows to display and measure with a millimeter accuracy the deformations of the surfaces recorded (fig.6).

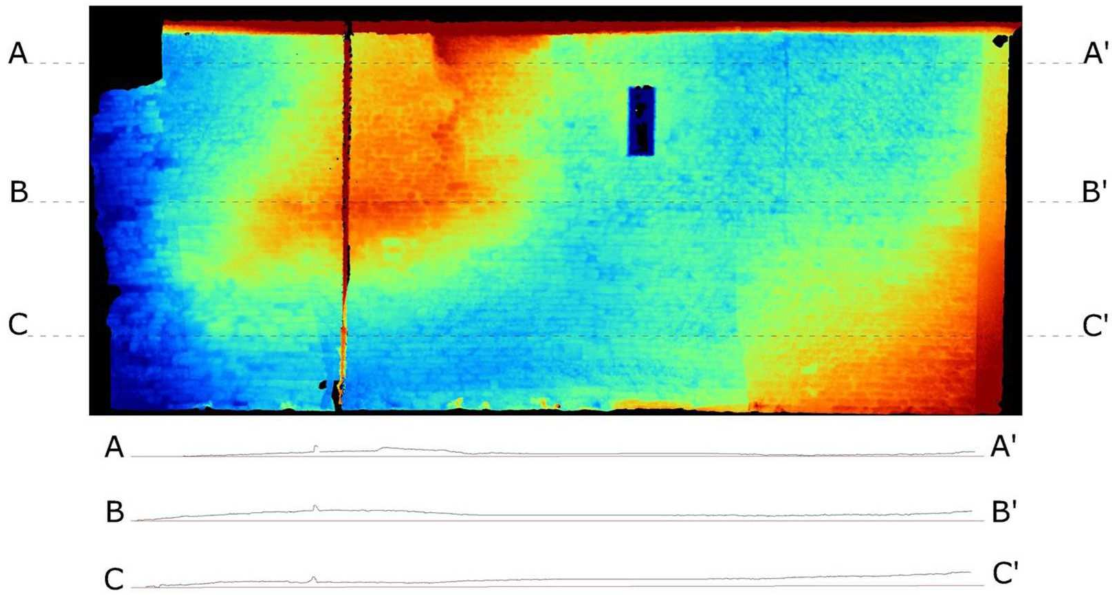

Fig. 6 – DEM and surface sections of an external façade of the Chiesa Vecchia di San Michele in Ronta. It is easy to distinguish in the image the changes of directions in red and yellow from the vertical plane in blue. Moreover, the three section surfaces traced on the DEM (A-A', B-B' and C-C') allow a clear overview of the direction and intensity of movements at a millimeter-scale, thanks to the characterization of the superficial deformations in relation to a horizontal surface of reference, as evident in the diagram below the DEM.

Finally, the ZScan Micro technology has been experimented only on two buildings, to monitor any possible movement of damage in time (for now surveys have been conducted in September 2011 and September 2012). This paper will present the results of the monitoring of part of the parish church of Saint Gavino Adimari, precisely its corner combining the front of the building with its side. The damage consists in a quite ancient crack, that was restored in past by inserting some stone chains, probably after the earthquake of 1542. Maybe due to the earthquake of 1919 and/or to the movements of earth under the church, the crack recently opened again. For this reason the church of Saint Gavino was ideal to experiment a kind of monitoring through differentiated temporal scanning.

Thanks to the ZScan Micro technology, the lesion was measured in September 2011 and September 2012 and a 3D model was generated from the measurement both times. Each model was used to produce a Digital Elevation Model, on which some surface sections were traced, along specific points of the crack (fig.7). The four curves generated from these sections were then overlapped to verify if there had been any changes in time, to prove if the crack had moved (fig.8). In this case, no changes were noticed, so we can affirm that the lesion in the wall did not move in the period between September 2011 and September 2012.

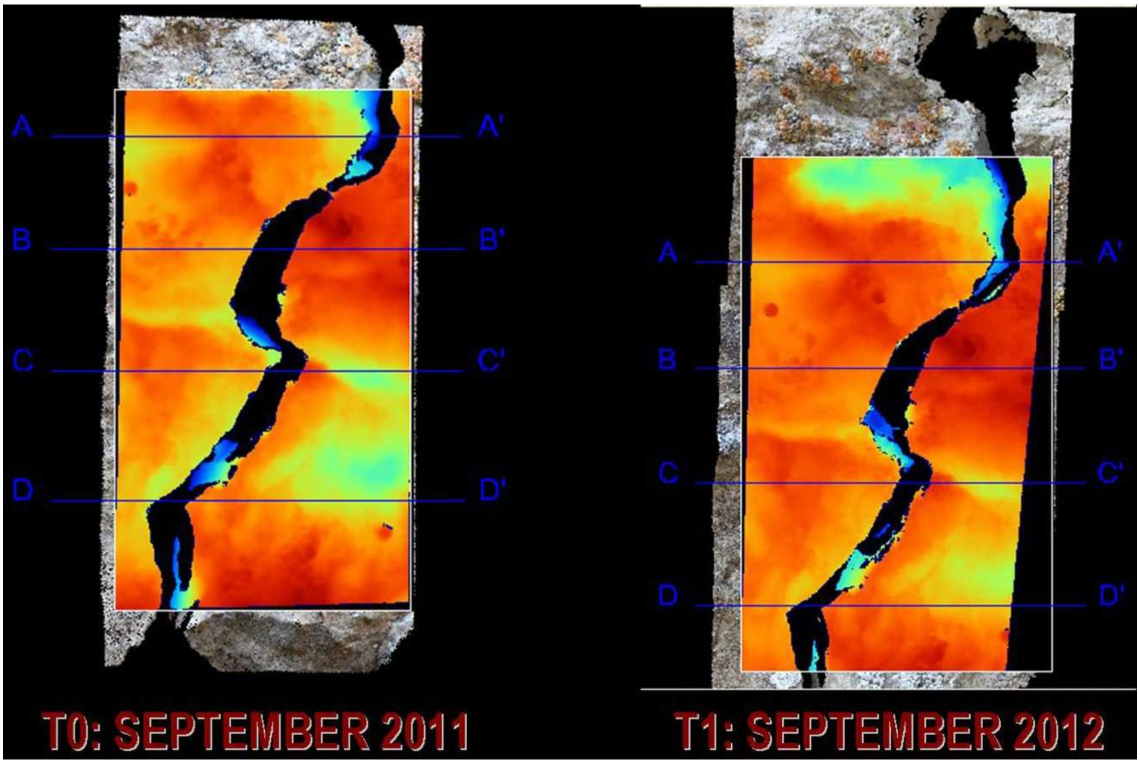

Fig. 7 – 3D models, DEM and sections of the crack in the church of Saint Gavino Adimari, all obtained through the ZScan Micro technology.

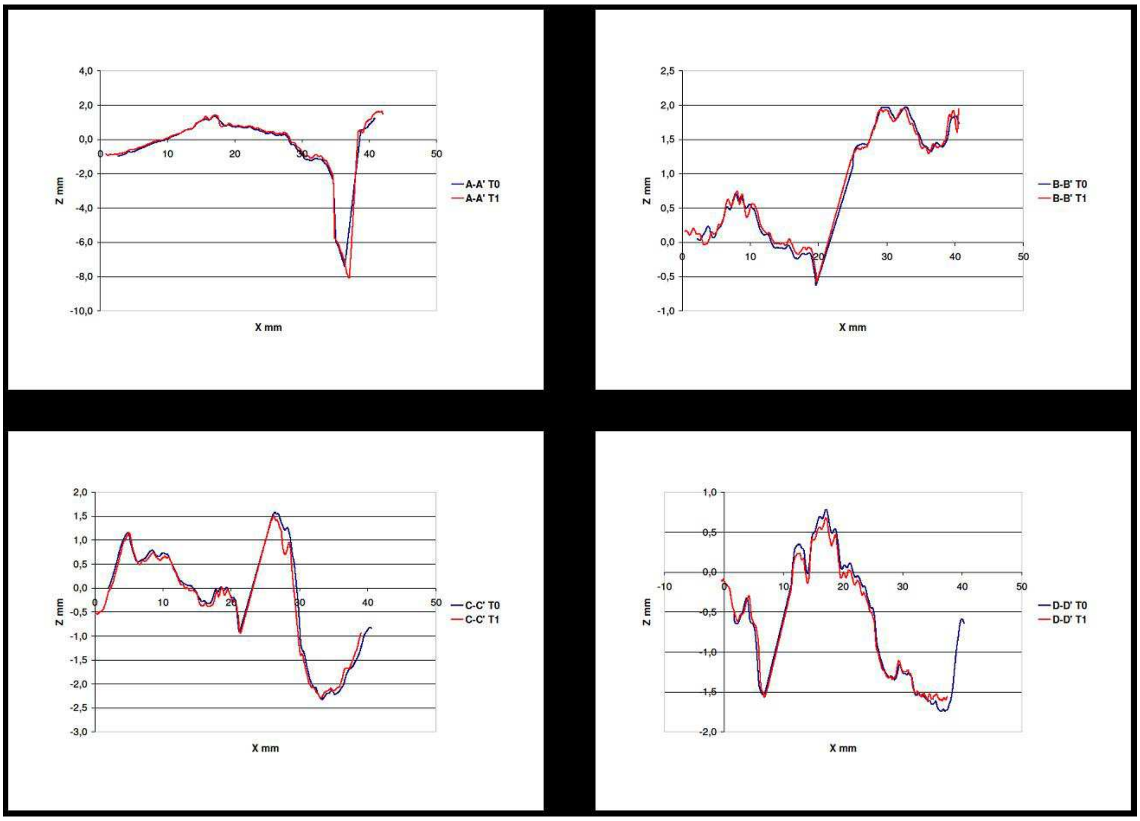

Fig. 8 – Overlapped sections of the crack measured in September 2011 and September 2012 with ZScan Micro technology (parish church of Saint Gavino Adimari).

Conclusions

The survey in the Mugello area has underlined the necessity of working at a multidisciplinary level on seismic risk territories, to prevent as much as possible earthquake damages on historical buildings through their study. In fact it is this knowledge of the buildings, considered fundamental by the ministerial guidelines, that allows to identify the most correct intervention in each context, an intervention that should take place before any other earthquake makes it impossible. This research has underlined the importance of archaeology in a prevention survey on an artifact. This discipline provides in fact important data that results often essential to integrate the studies by other disciplines and to understand where and how to operate. For example a stratigraphic survey can accurately identify the interfaces between different building phases of a structure, that could be weakness points in a wall if not well clamped, causing small or serious damage in case of an earthquake.

It is obvious that a careful archaeological study brings to the necessity of a structural measurement as much as careful. The testing of ZScan and ZScan Micro in the Mugello produced satisfactory results, both quantitatively and qualitatively, and allowed to achieve the following objectives:

- Working on site in a safe, rapid and non-invasive way
- Working on textured 3D models, generated with accuracy and reliability through outputs directly controlled by the software user
- Identifying accurately and quickly any possible bulging or out of plumb condition in the buildings
- Monitoring in the short and long term any possible movement of damage in any direction.

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