sous la direction de
LAMIA HADDA
SAVERIO MECCA
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Villages et quartiers à risque d'abandon

Stratégies pour la connaissance, la valorisation et la restauration

TOME 1

FIRENZE UNIVERSITY PRESS

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La série de publications scientifiques Études Euro-Méditerranéennes a le but de diffuser à l'échelle internationale les études et les recherches résultant de la coopération scientifique et culturelle entre le Maroc et l'Italie dans le cadre de la Déclaration conjointe du 6 Juillet 2016.
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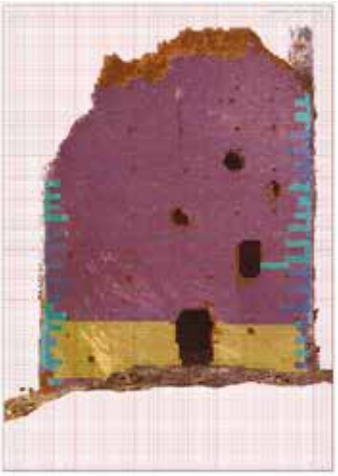

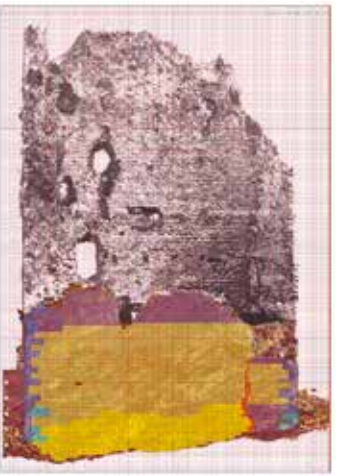

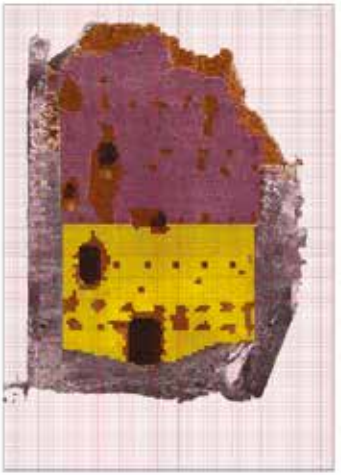

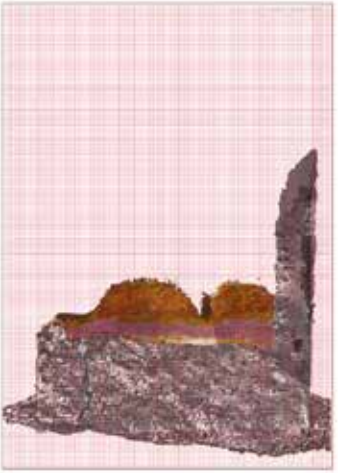

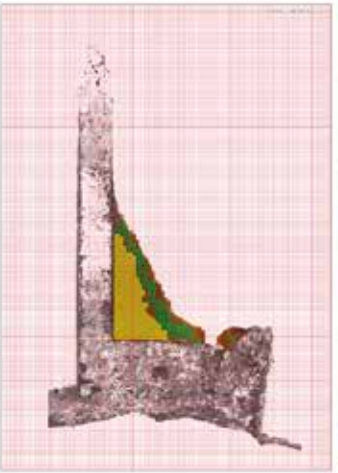

THE SAFEGUARD OF BUILT HERITAGE IN ARCHEOLOGICAL SITES, AN INTERDISCIPLINARY APPROACH BASED ON LIGHT-WEIGHT UAV PHOTOGRAMMETRY AND TERRESTRIAL LASER SCANNING SURVEY: THE CASE STUDY OF MONTE LUCIO

Carlo Costantino, Angelo Massafra, Davide Prati, Simone Garagnani, Giovanni Mochi
Università degli studi di Bologna-Italia

Elevations-characterization analysis of "Monte Lucio" tower, from top left: east elevation; north elevation; west elevation; south elevation; internal east elevation; north internal elevation; internal west elevation; internal south elevation – (Graphic Elaboration, 2018 © Paolo Faccioli).

This paper introduces a well-defined working pipeline oriented to a multidisciplinary approach to analyze the structural behaviors of the Archeological Heritage through complementary and integrated studies. The geometrical and deterioration data pertaining to a medieval tower in "Monte Lucio" (Reggio Emilia, Italy) were joined in an accurate 3D model to be used for structural analysis, starting from the complementary use of a terrestrial laser scanning (TLS) with UAV air photogrammetry. Meanwhile, an interdisciplinary collaboration between different professional figures such as archeologists and chemists was established to get information relating to masonry stratigraphy and mortar typology. This allowed the material characterization fine-setting for parameters then embedded into structural models, usually the most complex operation in historical buildings. This led to classify the different brick typologies and the elevations' characteristics in a 10x10 cm pixel matrix, identifying each slice uniquely by using different colors. The matrix was then imported in MATLAB, assigning coordinates and mechanical characteristics to each pixel, according to material typology. Finally, the model was imported in Abaqus Unified Fea to perform "Pushover analysis" and to calculate the distribution of horizontal forces to evaluate possible prevention measures to be taken. In conclusion, through the adoption of different combined digital survey technologies and multidisciplinary data sharing, the proposed workflow proved to be efficient in the case study presented.

Keywords: Cultural Heritage, Terrestrial Laser Scanning, UAV, Aerial Photogrammetry, Archaeological Site

Introduction

State of the art

Restoration of Cultural Heritage is a complex theme, especially when it affects archeological ruins. It requires close collaboration among various professional figures in order to get a complete and reality-based cognitive framework about the examined objects and to develop analysis models that respond to the actual building's behavior (Dall'Asta et al., 2018). Historical masonry ruins are challenging because of many factors: only a few fragmented and disconnected structural elements often remain, geometries of buildings are usually irregular, a careful historical analysis is essential to determine construction phases and related vulnerabilities, mechanical properties of deteriorated materials are not known, and in-depth studies

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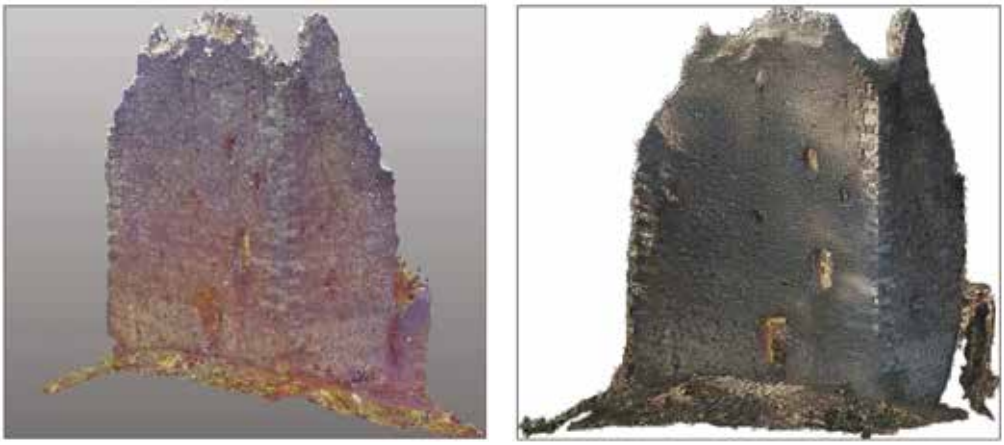
The tower of "Monte Lucio" ground and aerial pictures. – (Photos, 2018 © Davide Prati and Simone Garagnani).

are necessary to estimate them. Due to these reasons, an accurate but simple analysis is essential to understand all the possible variations and uncertainties of the parameters that describe the problem (Lourenço and Roque, 2006).

There are numerous studies in the field of vulnerability analysis of historical buildings that use innovative tools, software, and procedures (Yekrangnia and Mobarake, 2015; Valluzzi, 2006; Lourenço and Roque, 2006; Betti and Vignoli 2011; Galassi et al., 2019), but in most of them, the building is interpreted as a unique case that needs a specific interdisciplinary study.

The progressive development and dissemination of digital survey techniques permitted to know in-depth historical buildings identifying anomalies, organization, and state of deterioration of their elements, providing very accurate data and obtaining results that correspond as much as possible to the effective structural behavior (Fregonese et al., 2013; Prati et al., 2019). The use of photogrammetry and terrestrial laser scanning has been extensively investigated over the years (Koch et al., 1998; Bucksch et al. 2007; Pfeifer et al., 2007; etc.). Recently, the spread of UAVs (Unmanned Aerial Vehicles) proved to be effective in the field of photogrammetry (Murtiyoso et al., 2017), so several studies explored the potentialities of its complementary use with a terrestrial laser scanner (Pueschel et al., 2008).

Comparison between the two point clouds: realized in Faro Scene from data acquired by the terrestrial laser scanner, (on the left); Created in Agisoft Metashape using the acquired aerial images (on the right) – (Graphic Elaboration, 2018 © Paolo Faccioli).

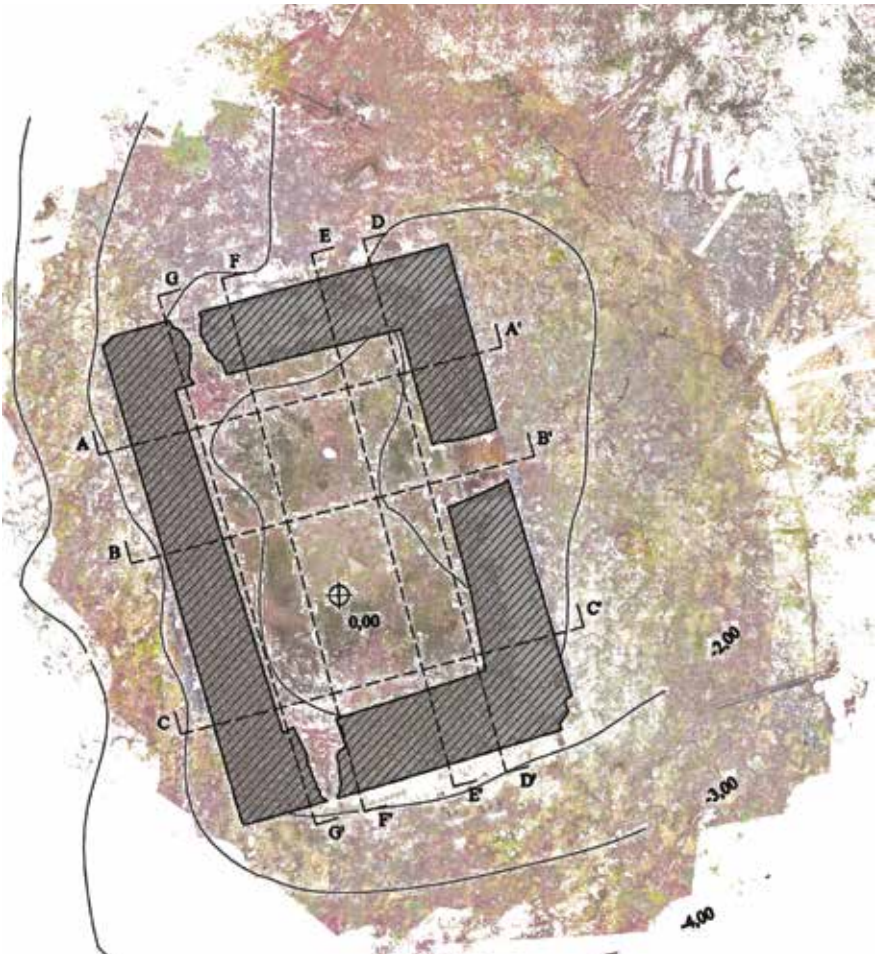


Historical investigations and tests on materials are also fundamental to gain a detailed knowledge of archeological sites. Investigations allow reconstructing the evolution of the building phases to make qualitative hypotheses on the organization of materials in stratigraphies while tests give quantitative information about the mechanical properties of materials, which can be integrated with geological analyses.

The Case Study: The Tower of "*Monte Lucio*"

The case study presented in this work consists of a medieval tower located on the top of "*Monte Lucio*", one of the four hills between the Po Valley and the Apennines, south of Quattro Castella in the province of Reggio Emilia, Italy. Thanks to their strategic position, these hills are characterized by a significant amount of medieval buildings, such as rural houses, towers, villages, and fortifications, many of which are in a state of ruin.

The scarce archival sources on "*Monte Lucio*" mention a first village over the hill, probably devoted to military function, around the end of the 13th century (Salimbene, 1882; Bandieri, 2017). The original construction of the tower might be dated back to that period and it was probably inspired by the castle or of the medieval tower-house, a typological multi-level dwelling that was commonly used to control the area since the 12th century militarily (Fabbri F., 1960). In the following centuries, different owners followed one another to manage the fortress of "*Monte Lucio*", changing its role from a military outpost to an agricultural center, until it was restored in 1497. However, it seems that the site fell into disuse between the 15th and the 16th century, slowly reaching the current state of ruin (Bandieri, 2013). Since 2011, an archeological two years long excavation project has been carried on to

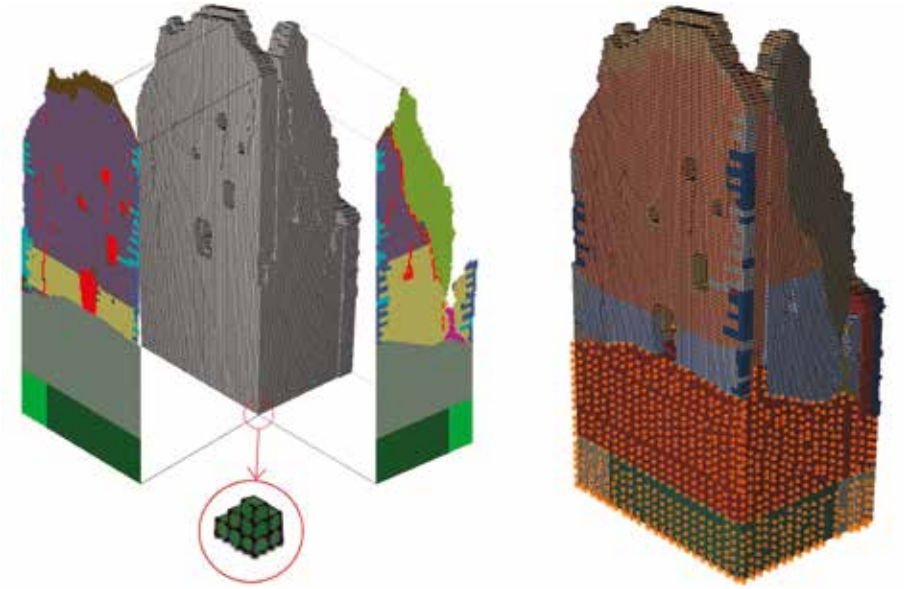


The tower of "Monte Lucio" ground and aerial pictures. – (Photos, 2018 © Davide Prati and Simone Garagnani).

Creation of the Matlab model starting from the elevations-characterization analysis (on the left) Finite element model in which the different materials and the ground and foundation bonds are applied (on the right) – (Graphic Elaboration, 2018 © Paolo Faccioli).

provide important information about the historical site, encouraging different research activities (Augenti et al., 2012).

The tower is located on the highest point of the area, about 309 meters above the sea level, in a predominant position over the other ruined buildings. It has quite a small rectangular plan, about 5.8 x 8.6 meters, and a maximum height of about 13 meters. Nevertheless, the original construction was likely 16 meters high (Ballardini, 2016). The building is currently in critical condition: large portions of masonry from all four facades, the roof, and the internal floors fell to the ground. In addition, an evident material



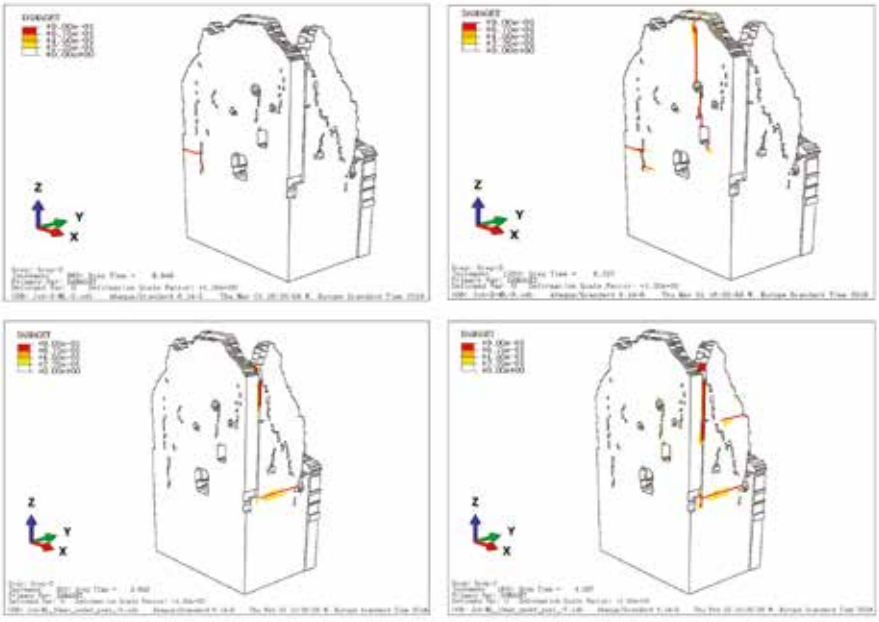
detachment is shown on the north and south facades, walls display a series of vertical cracks, and one of them is strongly inclined towards the outside. Most of these problems are caused by the position near the hill slopes, where the ground is gradually collapsing down to the valley.

The Equipment: Terrestrial phase-shift laser Scanning and UAV air photogrammetry

The difficulties in accessing the tower by land have led to the complementary use of terrestrial laser scanner with UAV air photogrammetry:

A "Faro Cam2 Focus 3D 150" laser scanner was used for the terrestrial survey. The contained size (24 cm x 20 cm x 10 cm) and the outstanding portability of this tool (5 hours of autonomy and 5 kg of weight) allowed surveying the tower quickly, despite the difficulty of operating in this area. The instrument offers accurate geometric data (linear distance error of ± 2 mm for a measure among object and scanner in a range between 10 m and 25) with the possibility of obtaining the detailed coloring of the point cloud.

A DJI Phantom 4 was used to carry out the aerial photogrammetry. This is a small drone (29,0 x 29,0 x 18,0 cm), 1380g in weight (battery and propellers included) with a maximum load of 300g, enough to fit a GoPro Hero 5 action camera with digital gimbal stabilization. Although this camera is characterized by an ultrawide field of view (FOV) considered in lens



Pushover analysis in Abaqus Unified Fea: upper, the analysis carried out in the x-direction; below, the analysis carried out in the y-direction – (Graphic Elaboration, 2018 © Paolo Faccioli).

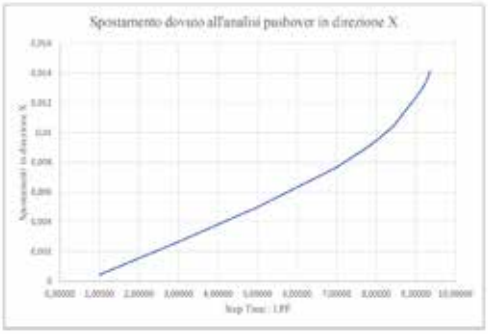
calibration, the 4K highest resolution ensured an ideal outcome by overlapping the pictures of at least 50%, with a proper resolution for photogrammetric purposes.

The workflow

This study illustrates an interdisciplinary workflow for vulnerability and safety analysis of ruins in archaeological sites, based on the collaboration between different figure to obtain the following complementary studies:
The Survey of the Ruins (Planning, acquisition, modeling);
Archeological Study, Historical Investigation and Material Analysis;
Structural Modelling and Analysis.

The Data Collection: The Ruin Survey

The main obstacles to survey operations were the remote location of the hilltop and the presence of invasive shrubs. Consequently, the survey was carried out at the end of autumn to minimize the vegetation interference.
The complementary use of terrestrial phase-shift laser scanning with UAV air photogrammetry has permitted to obtain a highly detailed 3D model: the terrestrial laser scanner, at



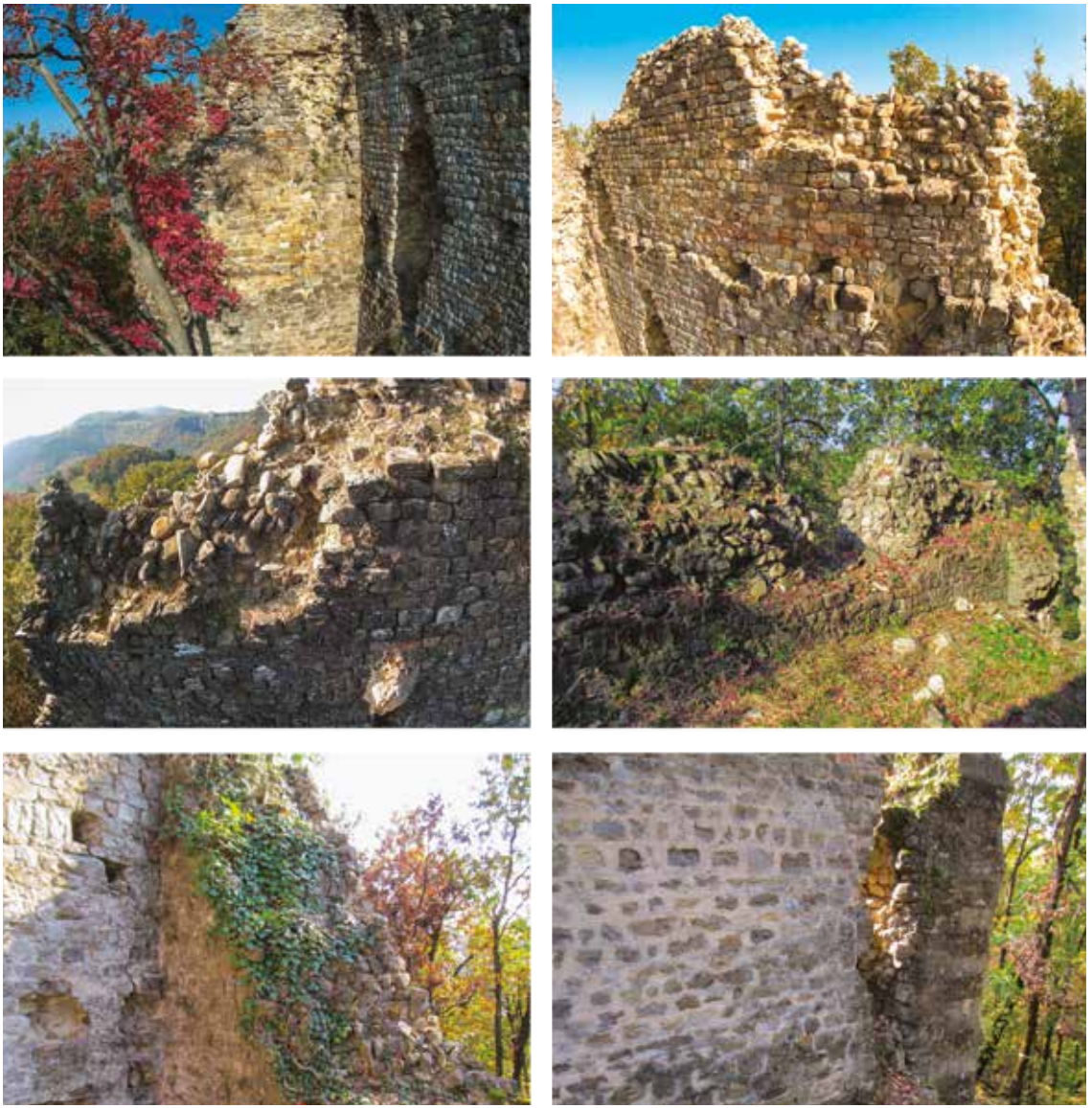
a close distance from the tower, offers extremely accurate geometrical data of the basement, becoming less accurate on the upper parts; on the opposite, the UAV air photogrammetry provides highly defined 3D model of the top of the tower. In order to minimize accuracy gaps in point clouds authored with different techniques, some ground control points were measured to evaluate their mutual distances and to set their coordinates for the aerial photogrammetric survey. Thus, alignment and registration of the upper point clouds and the lower ones were successful, with a satisfactory RMS value for each aligned scan.

This survey approach has allowed a deep understanding of the construction concerning wall thickness and masonry stratigraphy. It has also highlighted the anomalies and irregularities in element laying and allowed locating openings as well as possible. The final data merging of both the point clouds in a 3D model has been employed to produce the façade elevations as the structural analysis starting point.

The Archeological Study, Historical Investigation, and Material Analysis

The stratigraphical analysis of "*Monte Lucio*" was key to recreate the original aspect of the building. Probably the tower contained three wooden ceilings, and its height allowed the visual contact with the surrounding settlements of "*Monte Zane*" and "*Bianello*". The walls, which taper towards, are characterized by the presence of numerous putlog holes, placed at approximately one meter between one row and the other. The current access of the tower is not the original one that probably was located in the south or west wall of the building at a higher place through a drawbridge.

Two main masonry typologies are present in the tower of "*Monte Lucio*". The first, most common, is contemporary to the settlement on the hill, according to literature sources, during the 13th century. The brickwork consists of local sandstone cobblestone, not manufactured or only splitting, laid on horizontal mortar beds of variable size. The corner quoins,



The current wall condition of the tower of "Monte Lucio" – (Pictures, 2018 © Davide Prati & Simone Garagnani).

instead, are made up of sizeable squared sandstone elements hewn by expert stonemasons. The core of rubble masonry is characterized using similar sandstone in regular courses, unlinked to the outer shell. In the south wall, affected by notable collapses in the 14th century, the second masonry typology is present, made up of waste material from the previous collapse alternated with new bricks, arranged chaotically (Augenti, 2012).

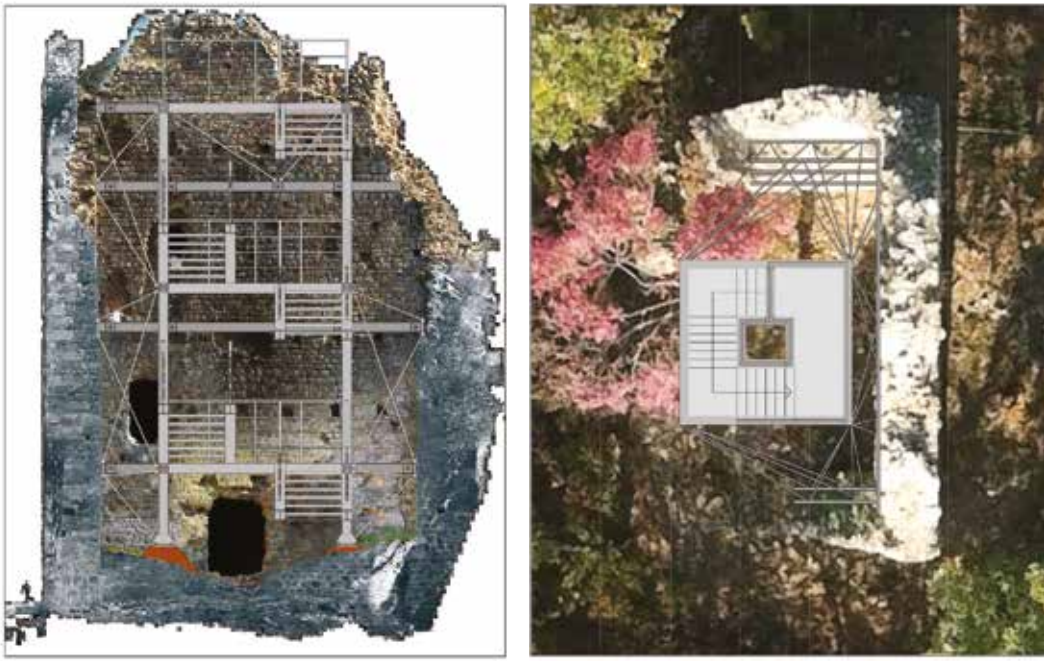
Following the stratigraphic analysis, five mortar samples were collected. These samples were taken to carry out the chemical and petrographic analysis from the corresponding different stratigraphic units of the tower. The samples collected from the north wall, reveal an unusual feature in medieval times, the use of hydraulic lime mortar, obtained from the calcination of local limestone with high clay percentage. The mortar samples taken from the south wall, in which the second masonry typology of the 14th century is present. The courses are bounded with aerial lime-based mortar of medium-low quality, produced with local raw materials and traditional methods. The third mortar typology has been identified as a modern product of the industrial age between the XIX and the XX century, consisting mainly of a mixture of lime and cement, probably used to fill the collapse of some sandstone elements (Bandieri, 2016).

Structural Modelling and Analysis

The external and internal elevations of the tower were produced from the 3D TLS survey. The masonry was divided within a 10 x 10 cm grid, based on the different brickwork, on the typology of elements, and to the state of conservation, using different colors. Therefore, the masonry parts, preserved in the best possible way with limestone elements and the abundant presence of hydraulic mortar, were diversified from the wall portions in which the mortar is less used. Afterward, the squared sandstone quoins bounded as orthogonal devices with heading and stretching stones. were diversified from those significantly damaged and less resistant. Then, the portions present in the north and south facades were detected, where fallen materials filled the large cracks caused by the beginning of the west wall overturning.

Another color was linked with the masonry portion of the north facade rebuilt after the collapse, characterized by a mixed composition of recovery-collapsed materials and bricks, bounded by a not particularly resistant mortar. Finally, the significant cracks, the partial collapses, and the missing stone elements were detected along with the presence of putlog holes and the masonry invaded by vegetation.

The matrix was further simplified to use the elevations in structural software, removing the background photo of the tower and approximating the Intermediate situations to worse conditions. Accordingly, using MATLAB, the elevation images were transformed in a matrix, in



Design of the new steel truss-tower. Section view (on the left); **Top view** (on the right) – (Graphic Elaboration, 2018 © Paolo Faccioli).

which each element of 10cm x 10cm side was reduced to a point with geometric coordinates and mechanical characteristics corresponding to the type of material to which it refers. Each elevation was then inserted in a three-dimensional space, obtaining the walls thicknesses by reproducing the images in succession along the z-axis, till reaching the opposite façade. The software automatically creates the model in CAE (Computer-Aided Engineering) format so that it can be used in Abaqus Unified FEA (Finite Element Analysis) in order to carry out the structural analysis.

Afterward, the ground and foundation bonds are applied in the finite element model along with the loads to carry out the analysis: a linear analysis, both static and dynamic, was performed to observe the building response to seismic actions and to verify the model and data correctness. Subsequently, the non-linear static analysis was carried out applying an inverse triangular profile load, first in the X direction than in the Y direction, increasing the horizontal acceleration from 0 to 10 m/s2, a very high value in order to provide an amplified view of structural behavior.

By confirming the hypothesis on the building structure, the analysis has highlighted the north and east walls possible overturning risk toward the outside of the tower, suggested

by the crack formation along the weakest portions of masonry (already damaged portions or near the openings). The presence of overturning mechanisms has been further confirmed using the linear kinematic analysis in accordance with Italian law in the field of structural safety (Norme Tecniche delle Costruzioni, 2018), which demonstrated the need to insert tie rods in a hypothetical restoration project in order to guarantee seismic safety.

The enhancement and renovation project proposal

The presented analysis shows that the tower's most significant problem consists of the possible overturning of the north and east walls toward the outside of the building. Moreover, the timber ceilings are completely missing inside the fortress, and masonry walls are, in general, not attached to the other ones. Another critical issue is the degradation on top of the walls, where some stones could involve dangerous situations in case of strong wind or seismic events.

In order to limit the danger caused by the top-stones possible collapsing, the protection on top of the walls should be realized by using a thin layer of fiber-reinforced mortar, reinforced with a fine stainless-steel net, to give tensile strength and to improve the connection between the walls at the top.

The construction of a stainless-steel truss-tower inside the historic building is considered to solve the wall overturning (Jurina, 1996). The new structure, with a square base of side 3.5 meters and a maximum height of 10.5 meters, contributes to stability transferring the loads that were previously supported only by the historic building. A 1-meter gap is left between the two structures, the masonry one and the steel one, to insert four bond-beams and connect them to the towers. These elements improve the joining between the walls, their collaboration, and the entire building's structural behavior in case of seismic loads. The bond-beams are connected to the masonry through many anchor plates placed 10-15 centimeters inside the putlog holes, so that the anchor plates of the tie rods are not visible on the external facades (Jurina,1996). The rigid tie rods connecting the two structures absorb the horizontal actions both in the external and internal direction of the building. The anchor's insertion in the masonry involves the hydraulic mortar injection, with a composition similar to the original one, which also improves the overall masonry strength.

Inside the steel structure, the realization of a metallic staircase allows reaching all three different floors that would be used both for studies and maintenance interventions. The stair furthermore offers the possibility to the public to visit the historical tower and enjoy a panoramic view of the surrounding area. Thanks to the use of steel elements, the whole intervention is almost entirely reversible and modifiable.

Conclusions

This paper illustrated an integrated multidisciplinary approach to analyze the structural behaviors of the Archeological Heritage, involving engineers, architects, archaeologists, historians, and chemists with the aim to achieve a full knowledge of the studied ruin through complementary studies concerning of geometrical shapes, building evolution, masonry and stone stratigraphy, characterization of the materials properties.

The proposed methodology was applied to a complex case study that required an exhaustive research; the medieval tower located in the archaeological site of "*Monte Lucio*". The complementary use of terrestrial phase-shift laser scanning with UAV air photogrammetry allowed to obtain accurate dimensional data, including the detailed information on the inaccessible tower top; An exhaustive stratigraphic analysis was carried out through laboratory tests on the mortar that made it possible to date the different construction phases of the tower and to obtain the characterization of the properties of the materials. All this information was transformed in MATLAB and was used in *Abaqus Unified Fea* to perform structural analysis in order to evaluate possible intervention strategies to be taken in the enhancement and renovation project proposal.

In conclusion, the exposed approach introduces a well-defined working pipeline oriented to a tight collaboration between different disciplines to produce digital models to perform in-depth vulnerability analysis of ruins. The relative cheapness of equipment and the reduced time spent in surveys and elaborations guaranteed by the use of well-integrated software suggest that the presented multidisciplinary approach represents an efficient approach in damage prevention for archaeological sites and enhancement strategies.

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Villages et quartiers à risque d'abandon sont aujourd'hui une problématique commune à des nombreuses régions de la Méditerranée, considérée comme un point stratégique dans les nouvelles politiques européennes. L'abandon progressif des zones internes est une constante dans les pays caractérisés par le sous-développement économique, avec les phénomènes d'émigration et de fragmentation du patrimoine culturel. Cela entraîne des problèmes d'architecture et de gestion du territoire. L'objectif principal de ce travail de recherche est de créer un espace de discussion qui comprend l'étude du patrimoine architectural et du paysage ainsi que les témoignages démo-ethno-anthropologiques.

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