An integrated Survey Experience for Assessing the Seismic Vulnerability of Senigallia’s Fortress (Italy): Documentation for Conservation and FEM Modeling

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***Abstract*—The paper presents the results of research carried out by an interdisciplinary team at the SAD in Ascoli Piceno in collaboration with MiBACT to verify the seismic safety of national museums. The object of study was the Rocca Roveresca Fortress complex in Senigallia (Marche, Italy), a unique example of a small 14th-century fortress shaped by a series of successive modifications. It currently houses a national museum. An integrated survey based on the acquisition of 3D laser-scanner data and endoscopic investigation was necessary to outline the traces of the stratifications and therefore to obtain different high- and low-poly 3D models useful for different purposes. The main objective was to propose an ideal workflow in developing 3D models that are useful for finite element method (FEM) analysis to detect hidden vulnerabilities in the fortress by evaluating the behaviour of several substructures in the walls.**

***Index Terms*—Integrated research, Point cloud-based Survey, 3D Data Processing, Diagnostics, Seismic Vulnerability, FEM, Structural analysis.**

I. INTRODUCTION

Conservation of the historical architectural heritage should necessarily be based on an appropriate multi-level phase of investigation utilising different areas of expertise. The multidisciplinary aspect is therefore an unavoidable characteristic of the initial phase of cultural good conservation [1], [2] [3]. In order to evaluate the seismic vulnerability of the architectural heritage, in addition to understanding the geometry of building structures, it is also important to investigate construction technology and techniques and the mechanical properties of materials, and to adopt the appropriate methods for structural analysis. Analysing the seismic behaviour of historical masonry buildings, churches, towers, and bridges is facilitated by using both structural analysis methods described in the literature [4], [5] and knowledge of the seismic behaviour typical of these widespread structures [6], [7].

Studying the seismic vulnerability of defensive structures in historical masonry [8] is instead more complex, because of both their construction peculiarities and the difficulty in identifying typical modes of seismic damage. For historical structures characterised by complex geometry, the state of the art includes cases that show how starting with a 3D laser-scanner survey allows for a detailed orientation phase that is also rapid with respect to the amount of data acquired; it is also useful in structural analysis based on FEM models [9], [10], [11].

In this context, research was carried out by a multidisciplinary team at the School of Architecture and Design in Ascoli Piceno starting from a convention with the General Directorate for the Landscape, Fine Arts, Architecture, and Contemporary Art (DG PaBAAC) within the Ministry of Cultural Heritage and Activities and Tourism (MiBACT) regarding verification of the seismic safety of national museums in earthquake-prone areas such as the Marche Region. Those involved in the project come from different fields—architects specialising in surveying and restoration, structural engineers, architectural historians—since risk assessment, which represents the main topic of this research, is typically an interdisciplinary topic.

The work carried out concentrated on the fortified building of the Rocca Roveresca fortress in Senigallia (Italy), which currently houses a national museum. This is a unique example of a small fortress that, starting from a Roman defensive structure, assumed its current characteristic features in the fourteenth century after having undergone important modifications over the centuries to improve its defensive features. This construction offers an opportunity to reflect on the complexity of defensive structures, which present particular design and construction characteristics. In fact, the fortress has structural characteristics that differ greatly from ordinary masonry buildings. The typical robust methods applied to historical buildings and churches can therefore not be used to analyse its structure or evaluate its seismic safety.

One of the main objectives of this research was therefore to propose and experiment with a workflow that, starting from point-cloud data acquired through laser-scanner surveys, would yield two important products: accurate 2D and 3D representations (high-poly 3D model) useful for documenting

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and conserving the fortress; and 3D models (low-poly 3D model) suitable for finite element method (FEM) analysis aimed at verifying the museum structure of the fortress, keeping in mind its specific shape and local seismic response phenomena. The research basically sets out an analysis method by evaluating the behaviour of several substructures in the fortress in search of hidden vulnerabilities that could generate unusual damage mechanisms.

II. CASE STUDY: HISTORICAL BACKGROUND

The Rocca Roveresca Fortress is a monument that encapsulates much of the history of Senigallia, a small fortified centre on the central Adriatic coast. The fortress is located at a strategic point for the survival of the urban centre, which, as important archaeological finds attest, has been inhabited since the very earliest times. It is in fact situated close to the coast, where landings and invasions came from, inserted within the widest fortified walls of the city, which were also expanded and transformed over the centuries. The fortifications characterising this zone of central Italy should be analysed in relation to the important families that stand out in this context, among the most important of which are the Sforzas, Malatestas, Montefeltros, and the Varanos. Such oligarchic groups carried out an important defensive strategy by constructing fortifications that were progressively more effective and updated, an expression not only of military force but also of territorial predominance.

The fortress is therefore the manifestation of a complex process of development occurring on the grounds, which confirms the strategic value of the pre-chosen place. Although the prevalent structure dates to the late fifteenth century, at least six main construction phases can be identified. Such phases will be analyzed more specifically through the realisation of 3D models, which, by evaluating its current material consistency and structural behaviour, describes the complexity of the building. In fact, the remains of the Roman fortification, those of the fortress established by Cardinal Albornoz around 1350, part of the construction dating to the Malatestas in the fifteenth century, the transformation by the Della Rovere family from the second half of the fifteenth century, and the signs of use such as a military garrison and prison in the papal and post-unification age make it the “summit” of almost all the power that in subsequent eras determined the fate of Senigallia.

III. DESCRIPTION OF ARCHITECTURAL COMPLEX

The architectural typology of the Rocca Roveresco Fortress of Senigallia constitutes a characteristic model of military fort in the field of plain fortresses. The shape of these fortresses is effective amid the flat orography of the place, which allows regular, symmetric forms.

The fortress is a large square building with a cylindrical bastion situated at each of the four corners. The complexity of the structure lies within, where the separation of spaces is labyrinthine and distributed over different levels. Its current form dates from the end of the fifteenth century at the behest of Giovanni Della Rovere (Fig. 1).

Fig. 1. Senigallia's Fortress: the external shape

The construction works were initially entrusted to Luciano Laurana, who designed the residential part of the fortress and the drawbridge. Building continued under Baccio Pontelli, who surrounded the residential part with a real defensive structure. The fortified structure is entered by crossing a drawbridge that leads into a large internal courtyard, whose northern part is occupied by the residential zone. This is building has three levels above ground as well as an underground level, all accessed by a main dual staircase in the east and a spiral staircase in the northeast. The residential zone is composed of a series of environments with large, predominantly pavilion or groin-vaulted ceilings, while the underground levels are covered mainly by brick barrel vaults. The rest of the structure is substantially composed of barrel-vaulted passageways connecting a series of irregular-shaped rooms situated within the bastions (Fig. 2).

Fig. 2. Senigallia's Fortress: examples of the types of spaces within.

IV. DATA ACQUISITION: PLANNING THE INTEGRATED SURVEY

Given the field in which this experience is situated and the professionals involved, (surveying architects, structural engineers, restoration experts) the objectives identified are to obtain: i) a series of appropriate 2D and 3D representations of the current state of the fortress; ii) a feedback of stratifications that have occurred over time by comparing the survey results to archival sources; iii) an understanding and analysis of the structural system derived by superimposing the historical modifications, which can be used to interpret the behaviour over time.

An in-depth survey was therefore made in order to make preliminary observations regarding the dimension and overall layout of the architectural structure and the morphological characteristics of the site.

The Rocca Roveresca Fortress is situated at a lower elevation than the surrounding buildings and is surrounded by an open garden that separates the two. In contrast to the apparent uniformity of the exterior, the fortress presents great internal geomorphological complexity as a result of successive fortifying retrofits throughout the centuries.

Based on such important observations and a series of basic 2D graphics provided by the authorities, the work, which was coordinated among the experts involved, allowed the following to be defined: i) the most appropriate methods and instrumentation for the different types of surveys; ii) planning the data-acquisition phases; and iii) identifying the accuracy (metrical precision) of the data acquired in order to obtain subsequent graphics on multiple levels of detail (scales from 1:100 to 1:50) according to the size/object of the representation.

Procedures related to the geometrical/metric survey were therefore developed for both the interior and exterior with instrumental surveying techniques using 3D laser-scanner technology; in particular, two different instruments were used. For the exterior, an additional dedicated photographic survey was made to process digital photogrammetry of the external surfaces of the fortress with structure-from-motion (SFM) systems.

A material survey (mapping the stonework and structural elements to evaluate their inspectability, morphology, and construction) was then made both inside and outside, along with an analysis of the crack pattern/state of structural and material degradation. As well, focused endoscopic investigations and non-destructive tests were made to study the non-visible parts in terms of the construction, stratigraphy, and material techniques used, since these are fundamental aspects in identifying the local and global vulnerabilities of the fortress.

All of this was used to outline the resistant structure in order to identify the geometry of the analysis model (globally and for substructures). The different survey campaigns were carried out between March and April 2014 in various phases, each of which required several days of specific work.

V. RANGE-BASED AND IMAGE-BASED SURVEY

The range-based survey used to acquire geometrical/metric data regarding the fortress was made with two different instruments: the Leica P20 TOF laser scanner enhanced by Waveform Digitising (WFD) technology and the Leica HDS 7000 phase-based laser scanner, which was used in particular for some interior scans.

For the exterior, a total of 12 stations, complete of RGB data, for scanning using the P20 were established. This instrument was also used for a more detailed survey of the following interior areas of the fortress: the internal courtyard (4 scanning stations); the embedded Roman tower (12 scanning stations); a particular interior walkway on the first level connecting the two sides of the internal courtyard (3 scanning stations); the level of the roof (10 scanning stations).

For the interior, the HDS 7000 was used to survey: the different vaulting systems in the rooms of the residential area, situated on three overlapping levels (30 scanning stations) and the rooms on the underground levels (11 scanning stations) (Fig. 3).

This instrument was also used to survey the following areas in greater detail: the double staircase connecting the three residential levels (7 scanning stations) ; the spiral staircase situated near the northeast bastion (1 scanning station); the trussed ceilings in the volume that emerges in the roofing (7 scanning stations).

Given the overall characteristics of the building, the survey was designed to adopt multiple resolutions. Therefore, different scan settings (sampling densities) were used with respect to the level of detail/geometrical complexity of the areas being surveyed and the distances to the surfaces. The resolutions adopted were:

- 12.5 mm at a distance of 10 m (positions of the scanning stations < 10 m from the surfaces);
- 6.3 mm at a distance of 10 m (positions of the scanning stations 10–20 m from the surface).

The entire range-based surveying campaign allowed for a total of 97 scans, yielding an entire dataset of 1676 million points (Fig. 4).

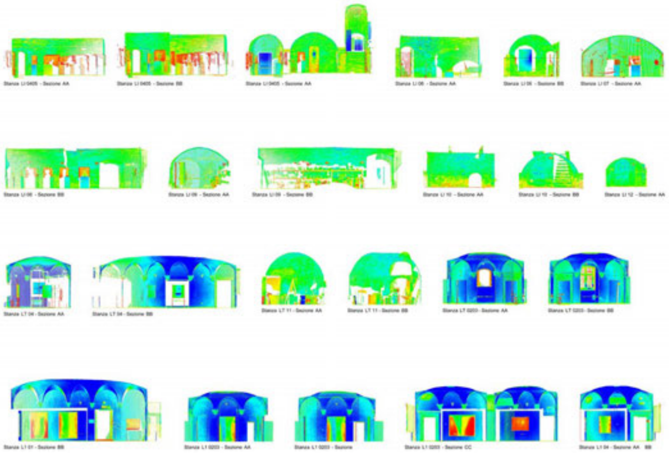

Fig. 3. Laser scanner survey: different vaulted systems in the rooms within.

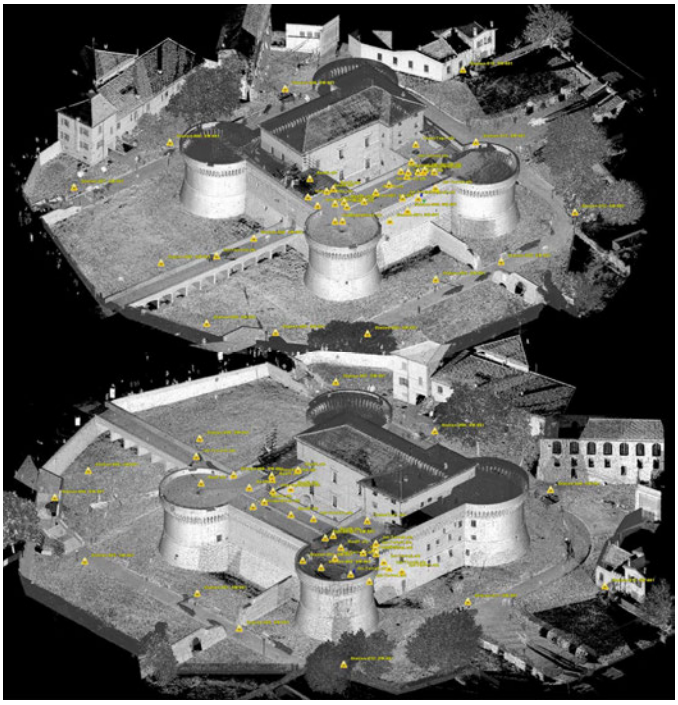

Fig. 4. Image of the entire range-based surveying campaign.

For the image-based survey, which was aimed at subsequent processing using SFM software, a Nikon D300 camera equipped with an APCS-C size CMOS-type sensor (23.6 x 15.8 mm), with a maximum resolution of 4288 x 2848 pixels and a pixel size of 5.50 micrometers, was used. The camera was mounted with AF-S DX NIKKOR 16-85 mm f/3.5-5.6G ED VR lens. All snapshots were made with the minimum focal length, i.e., 16 mm.

The photography campaign was carried out with a wide-field photography scheme, with an average object distance of 12 m, and a shutter speed of 1/100s, F-number f/9, and ISO 200. The entire campaign produced a total of 115 snapshots with an average distribution of about 28 snapshots for each of the main external façades.

VI. RANGE AND IMAGE DATA PROCESSING

To manage and share the enormous quantity of 3D data acquired with everyone involved (engineers and restorers), a data-sharing platform was first set up, which could be accessed both on- and off-line by using the TruView visualisation plug-in.

The platform, composed of all the point clouds acquired, allowed users to easily explore both the entire set of clouds, which were registered and aligned with all scanning positions indicated, and the different individual scans.

The data-processing phase yielded a series of 2D drawings directly from the point cloud using the CloudWorx application for AutoCAD. In particular, scale representations of the geometries of the different vaulted systems present in the different rooms on the various levels were created, allowing the main profiles (cross-sections) for each to be rendered reliably in the two orthogonal directions (Fig. 5).

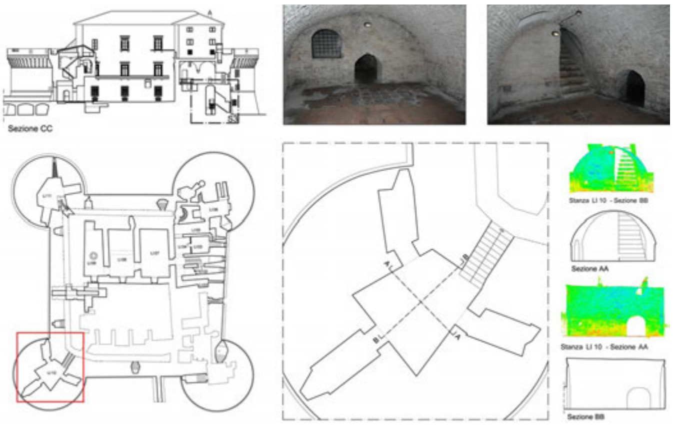

Fig. 5. Scale representations: plan and cross-section of the Fortress and the system of vaulted rooms.

In addition and more generally, this phase allowed various aspects to be verified and redefined: the characteristics of the horizontal elements (thickness of the slab floor and vaulted systems); the vertical elevation of the floors; the position, size, and shape of the main niches and cavities in addition to openings present in the walls and the rooms situated in the bastions; the verticality and alignment of the walls; the thickness of the supporting walls and spine walls. All of these are important aspects for verifying the seismic safety of the building.

The data from the photography campaign of the exterior were processed with Agisoft Photoscan software using 110 of the 115 snapshots made (5 were discarded because they were out of focus). After the orientation and auto-calibration phase, a dense point cloud of 6.8 million points was extracted along with 616,000 features (tie points) with an average alignment error of 0.45 pixels.

The dense point cloud was then transformed into a polygonal model using an interpolation-based proprietary algorithm included in the software. With the same software, the model was then scaled and aligned on the point cloud acquired from the laser scanner using a series of points distributed on the different sides of the fortress. These points were recognisable both in the point cloud and in the model reconstructed with Photoscan, i.e., various points whose coordinates were obtained from the laser scan were inserted as markers. The average alignment error was calculated directly in Photoscan and was equal to about 2 cm.

Finally, the photo reprojection phase was carried out in order to obtain a texturised model of the external surface of the fortress, therefore generating orthographic images of the facades with high geometric/metric and chromatic resolution (Fig. 6). The images also contain an accurate measurable resolution of the architectural details and wall structures, which is useful for analysis and mapping (wall material analysis) or for defining the crack pattern. In agreement with structural engineers, parts of the fortress were chosen for structural verification using FEM models, and several substructures were marked for analysis. The procedure for generating than one of these models is explained in section VIII.

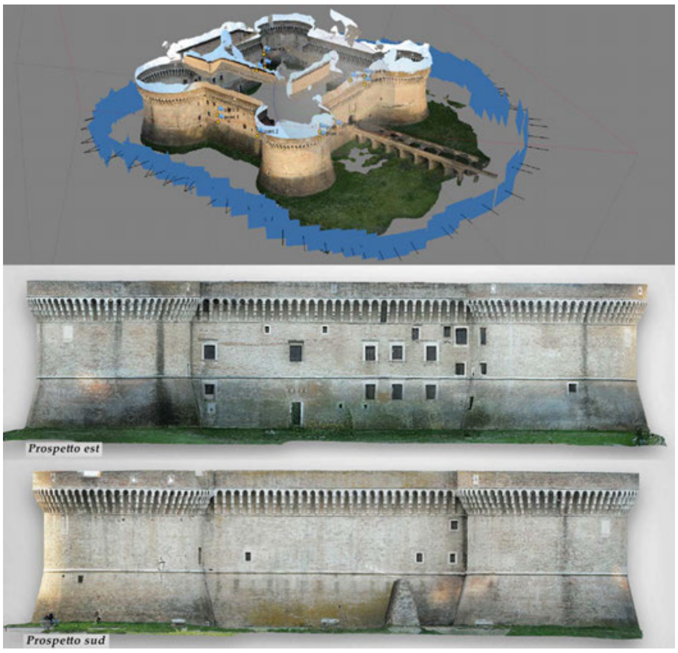

Fig. 6. Orthographic images of the facades elaborated with SFM systems.

VII. HISTORICAL RECONSTRUCTIVE 3D MODELS

The surveying campaign, combined with historical critical analysis, produced specific observations and integrations pertaining to the reconstruction of historical phases of the fortress, thereby allowing concise but exhaustive 3D models to be obtained.

The models pertained to the six evolutionary phases, allowing portions that were homogeneous in their construction techniques and materials to be associated.

Phase 1: Roman Period. On the underground level, stone-block masonry can be observed in the ruins of the foundation of the Roman tower. Figure 7 model (a).

Phase 2: Low-Medieval. The first easily recognisable intervention consists of the first fortifications made by Cardinal Albornoz, partially erected on the Roman ruins. The walls in this phase roughly outline the current internal courtyard. Figure 7 model (b).

Phase 3: Malatesta Period. The fortress was expanded, taking on a quadrilateral shape with rectangular bastions on the corners and lead brick curtain walls with corbels and Ghibelline merlons. Figure 7 model (c).

Phase 4: Sigismondo Malatesta. A reinforcement scarp in sandstone was added to the perimeter walls. It is visible today underground and in some openings in the robust thickness of the walls. Figure 7 model (d).

Phase 5: Giovanni Della Rovere. A new fortress encompassing the Malatesta phase was designed with earthen infill and four scarped circular corner bastions. Construction of the spiral staircase in Istrian stone also dates to this period. Figure 7 model (e).

Phase 6: End of the 15th century. Internal reinforcement was built above the main entrance on the defensive wall along with the arches in the courtyard. Figure 7 model (f).

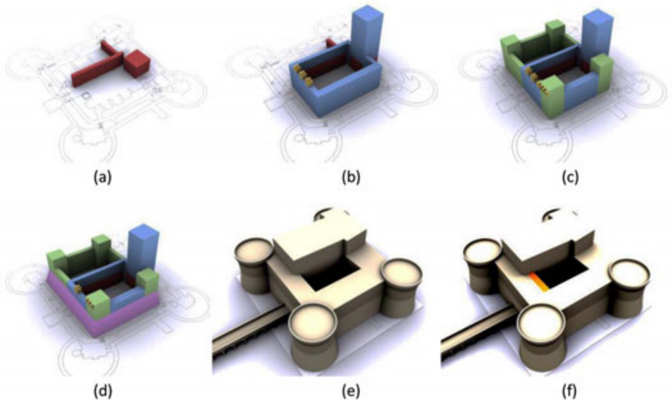

Fig. 7. The six historical phases of the Fortress.

The series of building phases led to a system characterised by notable discontinuities within the massive walls; this represents the salient characteristic of the building regarding its static and seismic behaviour. It also warranted endoscopic investigations (Fig. 8), not only of walls built in different eras, but also of contemporaneous parts in order to evaluate their internal homogeneity, allowing them to be carefully positioned at important points based on the historical reconstruction made.

VIII. FEM ANALYSIS METHODS AND 3D RECONSTRUCTION

As already discussed, the Rocca Roveresca Fortress is a very particular example of military architecture in which a sequence of retrofits were implemented over the centuries in order to make the structure capable of withstanding fire from improved offensive weapons. The structural system is characterized by architectural stratification, with large masonry elements with sharp discontinuities and stone rubble infill. A narrow passage runs along the defensive walls connecting the four bastions situated at the corners of the square fortress. The bastions are characterized by a double order of small inner rooms protected by very thick infill with external masonry. Masonry walls, for which in-plane and out-of-plane behaviours may be studied separately, are present only in the raised part of the residential building, whereas the aspect ratios of the main components of the fortress are such that they cannot be modelled as surface elements.

Despite the apparent regularity of the fortress, due to the previous considerations, an overall behaviour of the system is not reliable and the usual approaches to analysing masonry structures are not suited for this kind of system. Instead, 3D FEM models must be adopted that are capable of describing local effects induced by inner discontinuities in the walls and the complex system of inner rooms and wall openings. Because mechanisms related to local critical situations are expected to form, the fortress can be analyzed by considering suitable substructures (macro-elements) in order to reduce the analysis run-time. In particular, the following substructures were defined: (i) the defensive wall, in which internal discontinuities between the masonry curtain walls and the infill were modelled; (ii) a portion of the defensive wall strengthened with buttresses overlaid by barrel vaults; (iii) a bastion; and (iv) the raised part of the residential building (Fig. 9).

Fig. 8. Performing endoscopic investigations and non-destructive tests.

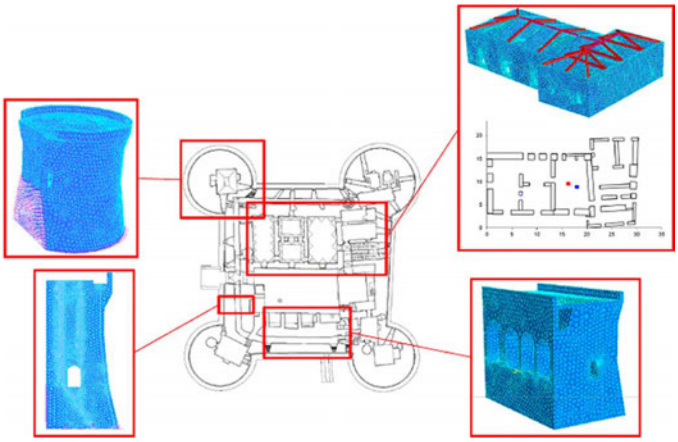

Fig. 9. Fortress substructures (macro-elements) considered and relevant FE models.

This paper focuses on the model of the bastion in order to demonstrate the importance of 3D modelling in evaluating local stresses in the materials. The bastion geometry is characterised externally by surfaces that can be approximated as portions of cylinders and truncated cones, and internally by rooms covered with stone vaults that are irregular both horizontally and vertically.

The layouts of these inner rooms cannot be superimposed, which means that the walls of the upper rooms are supported by the vaults of the underlying room without any apparent specific reinforcement measures. Cannon loopholes are also placed sporadically, creating discontinuities in the curtain walls.

The geometry of the bastion was obtained from the point cloud acquired in laser-scanner survey, maintaining all the inner rooms and cavities but roughly simplifying the stone corbels sustaining the upper battlement.

The presence of such irregular rooms within the bastion made it necessary to concentrate on the union between the different internal and external surfaces of the bastion when constructing the geometric model in order to correctly generate the mesh. The correct geometrical modelling of the surfaces is in fact fundamental in obtaining a regular mesh both for 2D models with simple surfaces and for 3D models with complex curvilinear surfaces and internal cavities.

McNeel Rhinoceros was used to realise the FEM model. The portion of the point cloud resulting from the laser-scanner survey that described the parts to reconstruct was thus isolated. This portion was decimated with a sampling of 40 mm. A polygonal model was obtained from this one decimated point cloud using the proprietary WRAP algorithm in Geomagic.

With the same software, an additional decimation was made with curvature priority in order to obtain a reference mesh model. This model was then used to obtain, in Rhinoceros, the main curves necessary for generating the mathematical surfaces that described the masonry volumes.

The aim was to use second-degree curves in most cases. The work was carried out in meters, with an absolute tolerance of 0.01 m and the parts modelled were simplified on the order of 0.1 m. A unique closed polysurface was thus obtained, which represented the volume of the bastion and the internal rooms (Fig. 10). This polysurface was exported in ACIS format and imported into Straus.

The bastion substructure is separated from the fortress where it interfaces with the defensive walls. This section is expected to be the one with the least resistance due to the presence of openings and inner passages.

Fixed restraints were placed at the base of the bastion whereas simple restraints to prevent horizontal displacements were placed orthogonally to the vertical surface for the portion in contact with the back soil. No restraints were placed on the upper part of the bastion since it is assumed that the defensive walls do not constitute an effective restraint for the bastion.

The FEM model of the bastion is composed of 122,455 four-nodes tetrahedral brick elements (Tetra4) with linear shape functions, yielding a total of 76,000 degrees of freedom. The maximum length of the element edges is 0.50 m (Fig. 11).

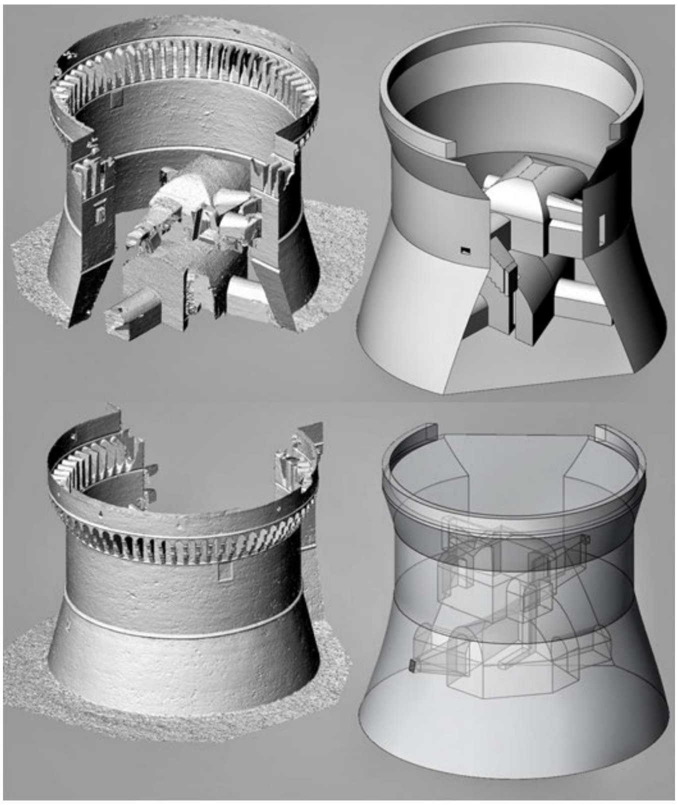

Fig. 10. Left: mesh model derived from downsampled scanner data. Right: NURBS model obtained from curves traced using the mesh model as reference..

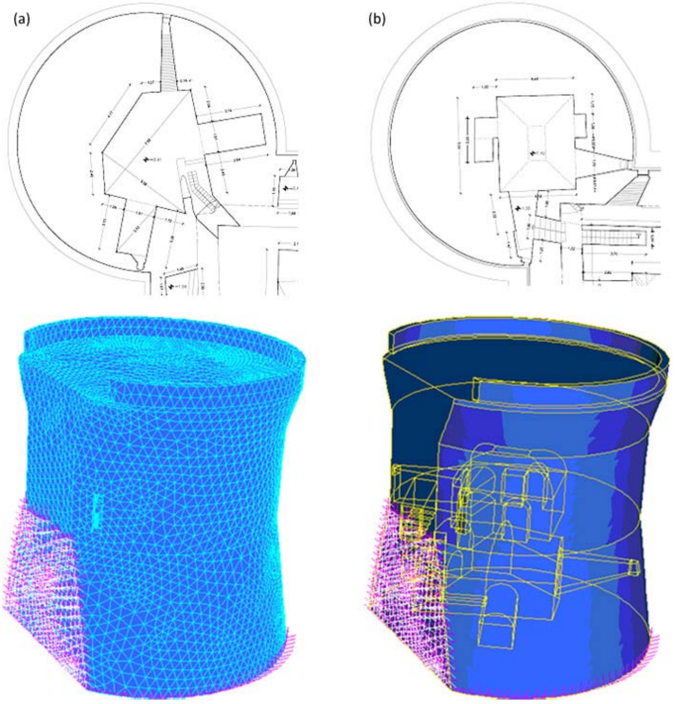

Fig. 11. Top: plans of inner rooms: basement level (a), ground level (b). Bottom: FE model with the inner rooms and wall openings.

IX. ANALYSIS RESULTS

The model was used to assess the linear response of the bastion under gravitational and seismic action in order to evaluate stress concentrations in critical regions. The principal vibrational modes of the bastion, corresponding to periods of 0.161 s and 0.139 s, are typical for stiff systems (Fig. 12). As expected, the longer period is obtained for vibrations orthogonal to the diagonal of the square shape of the fortress due to the interaction of the structure with the back soil in the other direction. The irregular inner rooms do not have any apparent influence on the principal modal shapes.

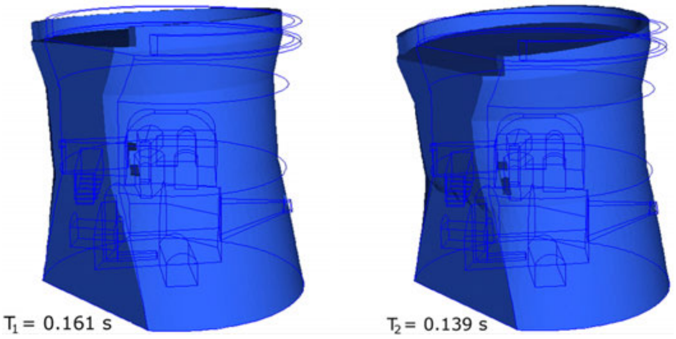

Fig. 12. Values of the vibration period of the bastion: the first mode shape (left), and the second one (right).

The vertical stress distributions for some horizontal and vertical sections demonstrate the formation of load paths, with stress concentrations at the bottom of the bastion for the portions near the defensive walls. The effect of openings and irregular inner rooms on stress concentrations is mainly evident in the horizontal sections, while moderate tractions (white fields) arising at the vault keystones are evident in the vertical sections (Fig. 13). As for the distribution of vertical stresses for the two seismic situations, horizontal actions superimposed on gravitational actions produce non-symmetric stress distributions, with some concentrations at the edges of the walls of the inner chambers (Fig. 14). The results obtained demonstrate the capability of the technique described to develop the structural model of architectural systems characterised by massive, irregular geometries.

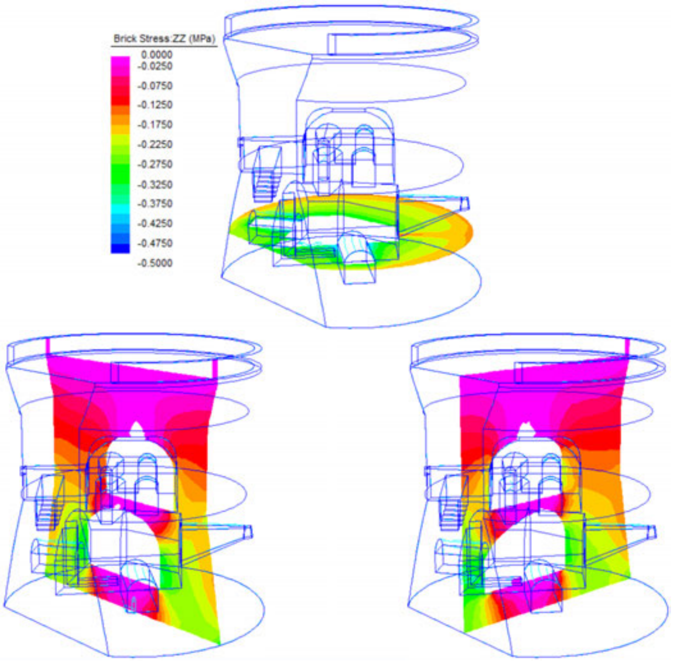

Fig. 13. Stress state under gravitation loadings: horizontal section (top) and vertical one (bottom).

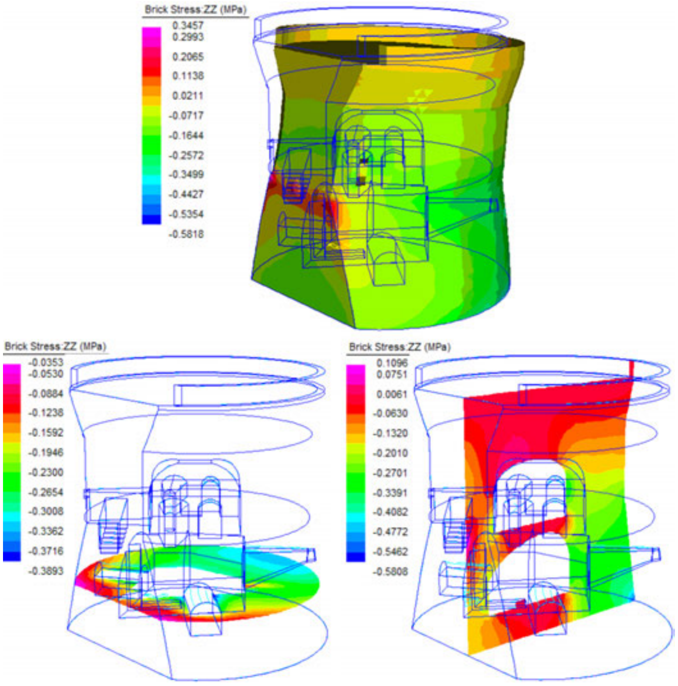

Fig. 14. Stress state due to the superposition of gravitational loads and seismic action in the diagonal direction.

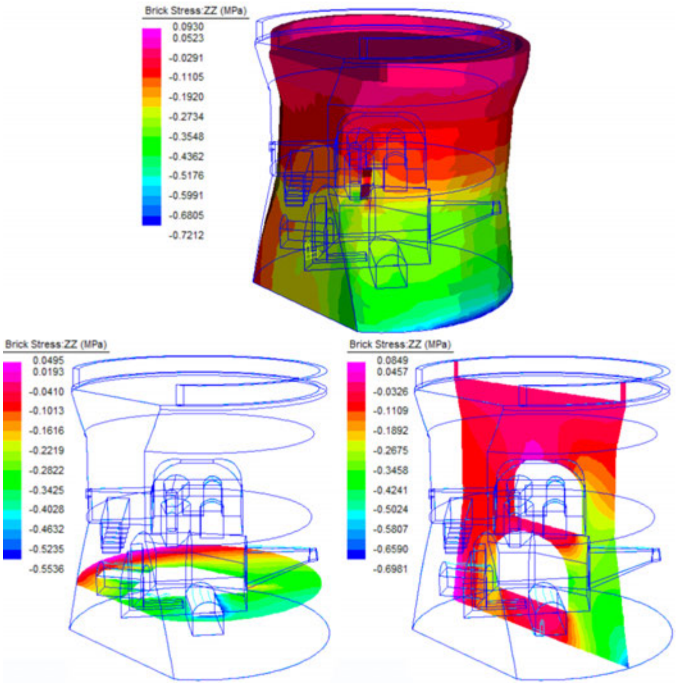

Fig. 15. Stress state due to the superposition of gravitational loads and seismic action in the transverse direction.

X. CONCLUSIONS

The central objective was to propose and test a workflow in order to define a method, i.e., an operational process, that could be used to study the seismic vulnerability, not only of the Rocca Roveresca Fortress in Senigallia, but also in other similar architectural contexts. The different phases of the workflow were described: data acquisition, data processing with different analytical analysis made by different members of the team of scholars, and the elaboration of FEM models for structural tests.

As for the specific case illustrated (bastion substructure), it is clear that given the internal complexity of the spaces in this element, an initial laser-scanner survey was fundamental in beginning tests on the tensional state. In fact, the density of initial digital data allowed the point cloud to be decimated appropriately, which was necessary to generate the FEM model, thus reducing the uncertainty.

More generally, one can say that starting from high-level digital data definitely allows the data to be dealt with in different ways. In other words, in carrying out the experimentation, models with different levels of refinement can be derived, therefore making it possible to further refine the analysis, going more into detail. With respect to the bastion, additional localised analysis can be made to build upon this research, considering, for example, how particular elements such as the projecting corbels work structurally. This would also allow for further verification of the validity of the approach and the potential of the method's various phases with respect to the quality of the results obtained.

While this paper concentrated on illustrating the workflow as applied to the substructure of the bastion, other analysis has already been carried out on a portion of defensive wall (linear and non-linear static analysis). The process certainly needs improvement, but in its current state, the approach tested and all the analysis made to date has given good results with respect to the predefined objectives.

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