

Article

Setup Optimization of Experimental Measures on a Historical Building: The Octagonal Hall of the Diocletian's Bath

Silvia Santini , Carlo Baggio, Valerio Sabbatini and Claudio Sebastiani

Department of Architecture, Roma Tre University, 00153 Rome, Italy; carlo.baggio@uniroma3.it (C.B.); valerio.sabbatini@uniroma3.it (V.S.); claudio.sebastiani@uniroma3.it (C.S.)

* Correspondence: silvia.santini@uniroma3.it; Tel.: +39-337675953

Abstract: The growing use of highly specialized tools has led to a better knowledge of the mechanical properties of the structures, reducing the destructive tests. The paper is aimed to identify an investigation method capable of directing staff in the planning of non-destructive test. The experimental campaigns must be planned in order to optimize the number and the type of tests to limit invasiveness and impact. The proposed method has been organized in a logical scheme that permits, in five steps, to predict with a good approximation the critical sections for an optimal setup of testing instruments. This method has been applied to the Octagonal Hall in Diocletian's Bath, to establish a better location for the dynamic endoscopy and tomographic tests. A geometrical model was built using the plans, elevations, sections provided by the National Roman Museum and the point cloud made through a drone. With HBIM (Heritage Building Information Modeling) it was possible to synthesize the information obtained from the geometric and material survey and then to convey it to a finite element model built on Midas Fea NX. Then, structural analyses, both linear and nonlinear, have been carried out for the optimal test setup.



Citation: Santini, S.; Baggio, C.; Sabbatini, V.; Sebastiani, C. Setup Optimization of Experimental Measures on a Historical Building: The Octagonal Hall of the Diocletian's Bath. *Heritage* **2021**, *4*, 2205–2223. <https://doi.org/10.3390/heritage4030124>

Academic Editor: Michele Betti

Received: 9 August 2021

Accepted: 24 August 2021

Published: 6 September 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: Roman masonry; in situ investigation; non-destructive tests; heritage BIM; UAV

1. Introduction

Intervening on buildings with a life history, sometimes centuries old, and that have undergone modifications or structurally stressful events over time requires a detailed local and global knowledge, which can only be achieved through specific on-site diagnostic campaigns aimed at understanding the structural behavior of the entire structure. Given the importance of the historical structure, which is often considered a valuable asset, it is difficult to define a sustainable investigation plan due to architectural constraints that limit invasiveness. Moreover, limited funds and problems related to accessibility in situ make the situation more difficult. The aim of this article is to limit the DT (destructive testing) and to extend NDT (non-destructive testing) by defining an adequate investigation plan for the study of the building, in order to be less invasive and more sustainable.

The application of NDT is often considered one of the preliminary steps. It is therefore necessary to carefully determine the areas of intervention and the most significant positions to reduce the number of tests. Often, this preliminary assessment is carried out with an exclusively visual approach, evaluating the condition of the structure from a qualitative point of view. New technologies such as UAV (Unmanned Aerial Vehicle) surveys with high-performance drones and new methodologies such as HBIM enable the investigation of existing structures in a more sustainable and efficient way. The UAV investigations is aimed at inspecting the structure in order to obtain information fundamental for understanding the geometric characteristics but also for analyzing the current state of conservation of the structure. Using the “Structure from Motion” photogrammetric technique, it is possible to extract high-definition videos, recorded through the flight of a drone, in order to extrapolate data for the creation of the point cloud [1,2]. The point cloud is defined as a digital transposition of building surfaces, consisting of millions of points in space defined by

unique geometric coordinates. The point cloud provides important information for the creation of a three-dimensional model in HBIM [3]. HBIM is a tool applied to existing buildings, monuments, archaeological structures and infrastructures. This tool also extends the use of the BIM to the creation of models of the existing building, both as their digital and geometric rendering in 3D, and as intelligent models rich in information, in which all the parts that compose them are parametric objects. Despite this, the modeling problems compared to the BIM technique are greater, especially with regard to the creation of unique libraries capable of describing each individual component of the structure, as well as with regard to the ability to consider the chronological evolution of the structure over time.

In this study, the main focus is to integrate the mentioned aspects in a logic scheme, in order to identify a methodology to optimize the test setup, including onsite local measures and global dynamic monitoring, to be carried out on a historical heritage architecture. The integration of onsite tests with dynamic monitoring under ambient vibration, allow the tune up of refined finite element models to investigate the local aspects and damages related to the structural behavior and the state of conservation of complex systems such as the monumental ones. In particular, the recording of response accelerations of the building and their processing give the actual properties due to the suffered damage and cracking. To achieve this aim, five different phases have been identified (Figure 1).

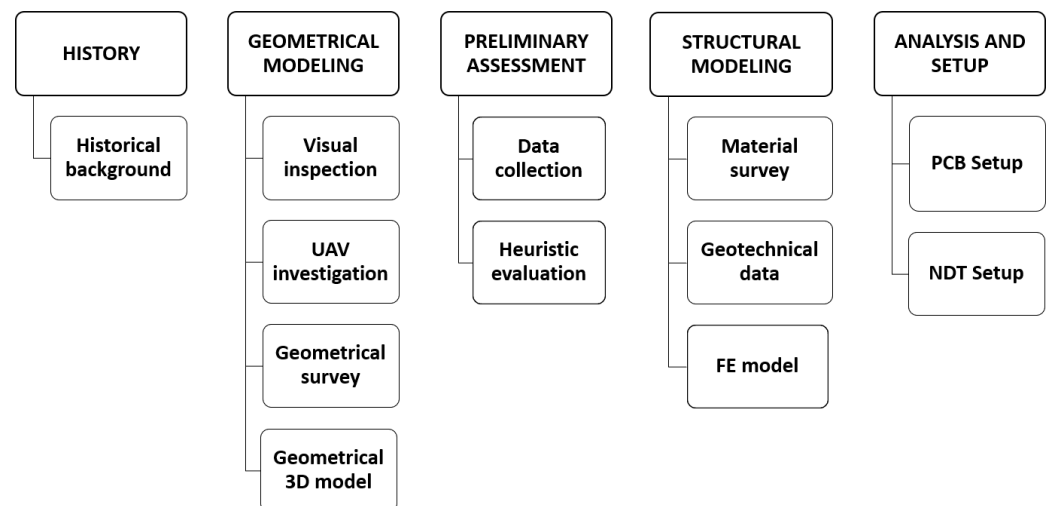


Figure 1. Workflow of proposed methodology for optimization of experimental test setup.

History collects the main historical events of the building with particular attention to the structural modification for a long period (Section 2).

Geometrical modeling includes different phases as visual investigation (Section 3.1), UAV flights that allow for the extraction of high-definition videos (Section 3.2), geometrical surveys of the construction through plans, sections and elevations (Section 3.3), geometrical 3D models and HBIM (Section 3.4).

Preliminary structural assessment consists of a heuristic evaluation of the structure that synthetically brings together information from all the collected data (Section 4)

Structural modeling consists in materials (Section 5.1) and subsoil (Section 5.2) and finally structural modeling through a finite element model (FEM) (Section 5.3).

Analysis and optimal setup consist of a modal analysis to predict the relevant displacements to figure out the best positioning for dynamic sensors (accelerometers PCB and/or MEMS) (Section 6.1) and a pushover analysis to individuate the most stressed sections to figure out the optimal on site non-destructive and semi-destructive tests (Section 6.2).

The proposed method has been applied to the case study of the Diocletian's Baths, in particular on the Octagonal Hall (OH) and the adjoining church of Saint Isidoro (SI) and the masonry Wall fragments of Gymnasium (WG) (Figure 2).



Figure 2. Three-dimensional view of the Octagonal Hall (OH), the church of Saint Isidoro (SI) and the Wall fragments of Gymnasium (WG).

2. Historical Background

Part of the original huge complex is preserved due to a series of historical events that have partly changed its original plan. Regarding the portion under investigation in the present paper, the most significant transformation is the construction of the first public granary in Rome by Gregory XIII in 1575 to solve the food needs of the city [4]. The four thermal halls were well suited to the needs of capacity and efficiency of the granaries, characterized by an elongated shape on three levels (top floor, middle floor and unloading floor) with large openings functional to the wheat drying process. The growing demographic and economic development of the city led to the need to expand the granaries already in use and to build others: first with Paul V, who built a new building perpendicular to the Octagonal Hall between 1609 and 1621, and then with Urban VIII, who, in 1640, extended the complex until the Strada Pia (Figure 3).

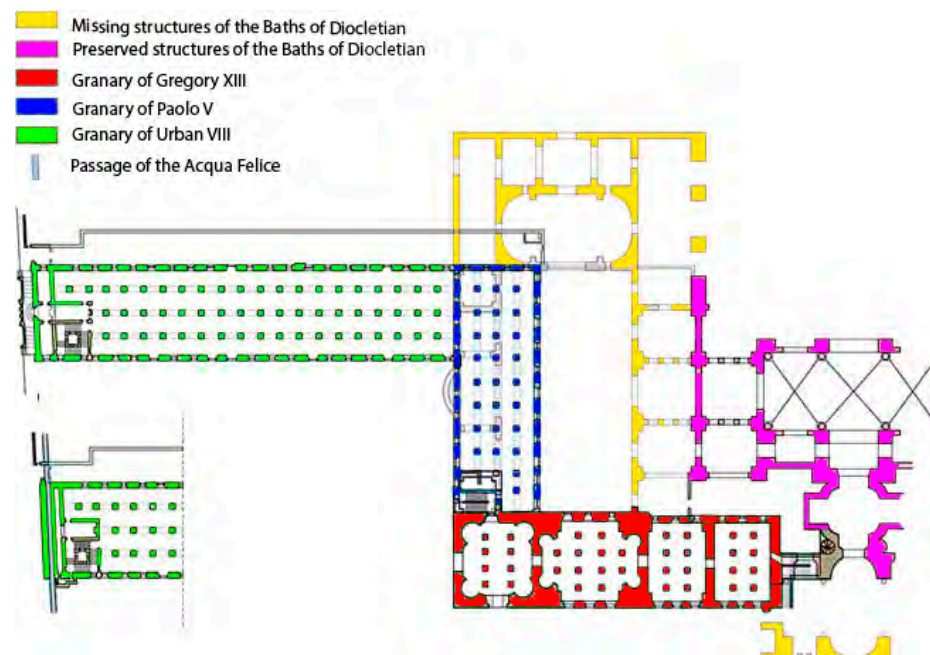


Figure 3. Historical phases of the granaries of Rome.

The Octagonal Hall was used exclusively for a functional reuse of the existing wall structures; consequently, new floors were built, new windows were opened and the brick curtains were covered with plaster. The large side arches were closed, and the dome

was covered with a roof. The image of the monument changed drastically, completely transforming its internal and external appearance. With the suppression of the wheat and oil Annona wanted by Pius VII and with the opening of Via Cernaia in 1878 at the service of the new Ministry of Finance, the hall became partially isolated from the thermal complex, which, in 1890, became the Roman National Museum. In 1936, demolitions were started to eliminate what remained of the granaries. After the Second World War, the Octagonal Hall remained an isolated building. Significant evidence of the changes can be found in Paulin's plates made by the end of 1879 [5], which illustrate the original plan of the baths in the Roman age (≈ 300 d.C), the plan in its current state at the time of the drawing and the southeastern elevation where it is possible to observe the gutting that has created Via Cernaia and the appearance of the octagonal hall still in the configuration of the granaries [5] (Figure 4).

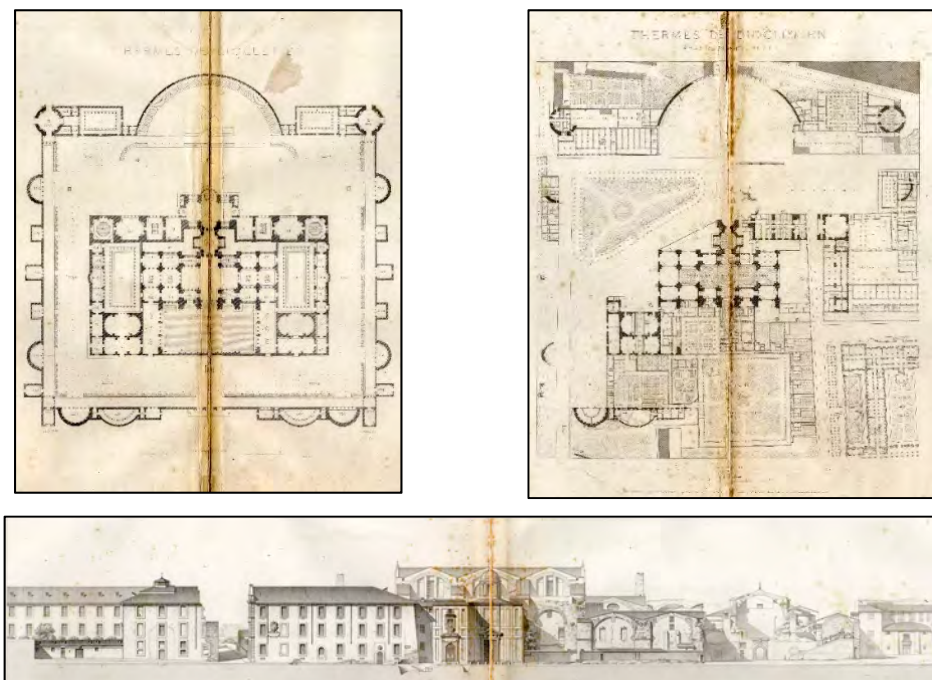


Figure 4. Edmond Paulin, 1890 [5].

In 1928, a metal dome was built, which led to the use of the hall as the planetarium of Rome [6]. The planetarium was decommissioned in 1983, and subsequently, some restoration and consolidation work began that involved the dome, the ground floor and the vaults supporting it.

3. Geometrical Model

3.1. Visual Inspections

An inspection was carried out inside the Octagonal Hall, the adjoining church of Saint Isidoro and the masonry Wall fragments of Gymnasium. The Octagonal Hall is the corner hall of the west side of the entire complex of the Diocletian's Baths. Through a visual inspection and with the help of photographic surveys and drones, it was possible to preliminarily investigate the structure, note the different materials and make initial assumptions about the state of conservation of the structure. In Figure 5, a section of WG shows the inside core made of "*opus caementicium*" and exterior panels built in "*opus testaceum*". This technique represents the main Roman construction method in the Imperial Age.

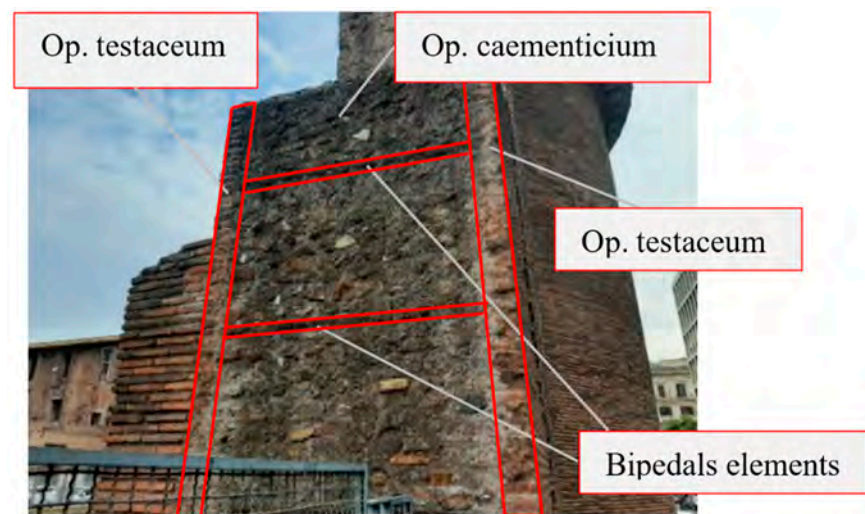


Figure 5. Section of masonry Wall fragments of *Gymnasium* (WG).

Looking closely at the complex, it is possible to observe damaged areas and portions with some repairs over time that are distinguished respect to the plain masonry (Figure 6). This subdivision, identified on site by visual inspection, could suggest a modeling with three different types of masonry defined as plain masonry, repaired masonry and damaged masonry.



Figure 6. The main damaged parts (highlighted in blue) and the visible restorations (highlighted in red).

The exterior appearance is a consequence of the interventions carried out after the disposal of the Granaries (Figure 4). It is therefore obvious the importance of verifying the

consistency inside of the wall, through in situ investigations (tomography and endoscopy) and collecting data into HBIM useful to a well-founded maintenance.

Entering the Octagonal Hall, the main building of the examined portion, including SI and WG, it is possible to see an octagonal dome that has a diameter of about 22 m with an open oculus at the top with evident traces of degradation. The degradation was also confirmed by the presence of little pieces of plaster and bricks fallen on the floor from the dome, which encouraged the investigation of the internal state of the dome and the iron fuller dome, which makes it difficult to visually inspect the surface of the vault.

3.2. UAV Investigations

A survey of the intrados of the dome was carried out through a drone. The investigation is aimed at inspecting the interior of the dome to obtain a point cloud, useful to understand the material state of the inner surface but also for analyzing the progressive losses of material over time. Through the UAV flight, high-definition videos were recorded to obtain a better knowledge of the state of conservation of the masonry and details for the creation of a three-dimensional model in HBIM. Figure 7 shows the interior of the Octagonal Hall and trajectories of the drone inside the dome.

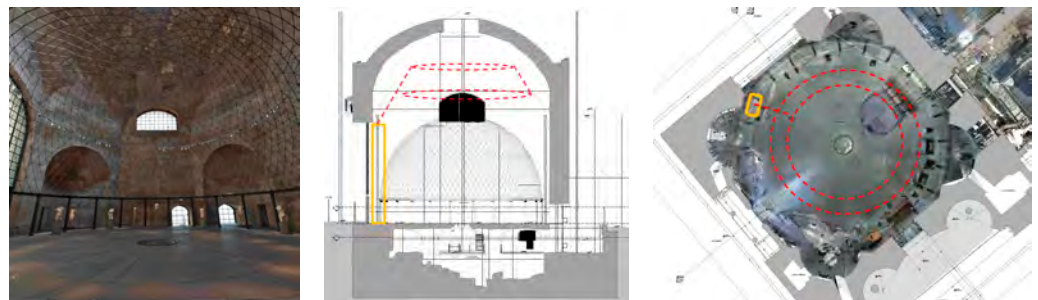


Figure 7. Interior Octagonal Hall and trajectories of the drone inside the dome.

Some significant frames were extracted from the high-definition videos and a three-dimensional model of the inner surface of the dome was built using the “Structure From Motion” photogrammetric method [1–3]. The model built using the Metashape software [7] should be a reference for identifying the alterations of the dome.

The Figure 7 shows the point cloud of the interior of the dome, where it is possible to highlight the presence of areas with a probably different behavior. From a careful study of the point cloud, together with the drawings available from a previous survey of the Octagonal Hall, the dome is made of eight veloidic masonry elements, joined together to obtain a “melon shaped dome”. In fact, the eight elements, being synclastic elements, have a parallel curve and a meridian curve, both with an internal concavity [8].

Figure 8 shows the generation of a melon-shaped dome. Inside each veloidic elements there are brick ribs embedded in the masonry [9]. Their execution, therefore, proceeded with the casting in “opus caementicium” and was used to contain the great mass of Roman opus.

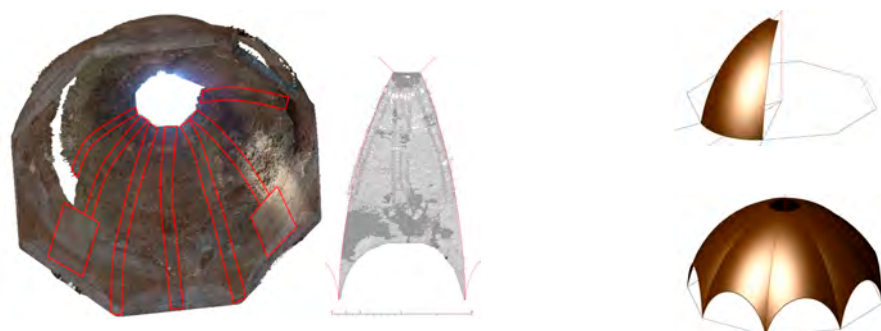


Figure 8. Point cloud in Metashape software (left) and melon-shaped dome (right).

3.3. Geometrical Survey

The UAV videos have been integrated with drawings available from surveys executed in 1978 [10], in 2011 by Monica Cola and in 2020 [5] and collected in the archives of the technical office of the Baths. Some of the plans and elevations commissioned by the Roman National Museum are shown in Figure 9.

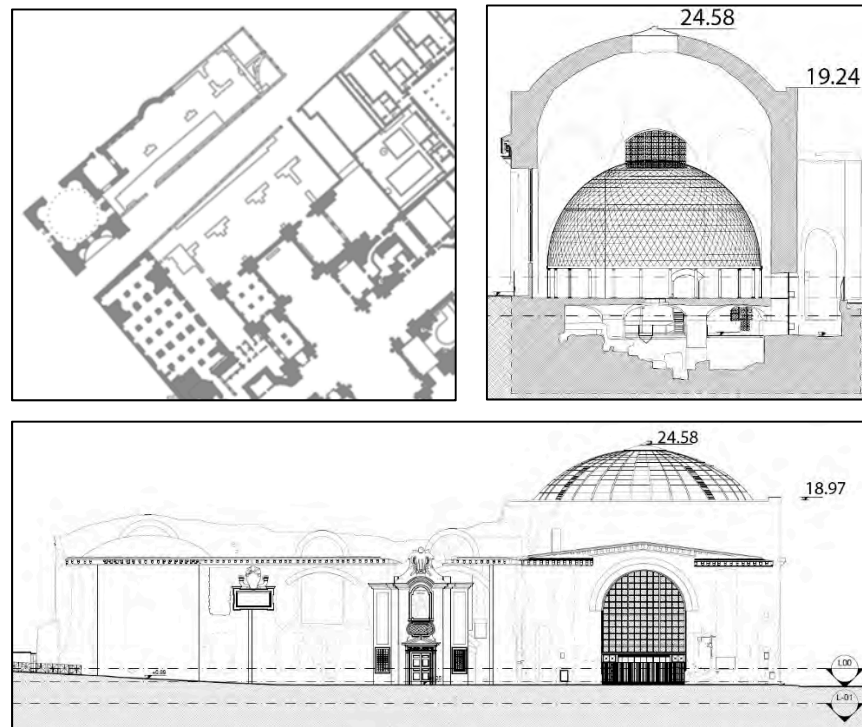


Figure 9. Plan, elevations, sections provided by the Museo Nazionale Romano.

The hall has a square plan externally and an octagonal plan internally using semi-circular niches.

The original floor is located at a lower level ($\cong 1.78$ m below the present ground level), consequently bringing the structure to a height greater than the current one.

3.4. Geometrical 3D Model

For the HBIM of the Octagonal Hall all the information was used and have been included in the model, the plans, elevations, sections provided by the National Roman Museum, the historical photos and the point cloud built through the flight of the drone on the intrados of the dome. The data was imported into Autodesk Revit 2019 software [11] and was appropriately scaled and positioned in order to have more points of view of the structure. Figure 10 illustrates the insertion of all the drawings and the point cloud.

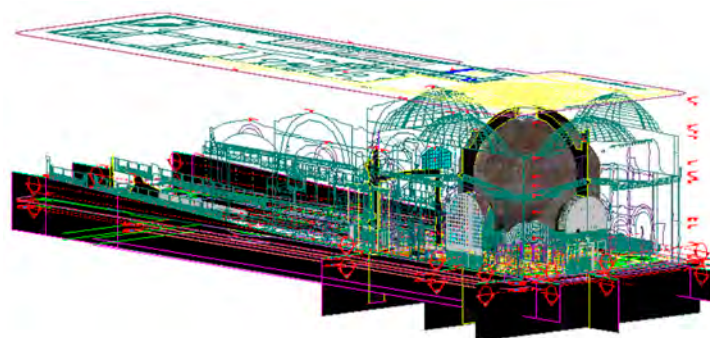


Figure 10. Import of plans, sections, elevations and the point cloud into Revit 2019.

The octagonal dome was built through a rotation, on the octagonal plan, of a profile calculated through the point cloud and sections of the structure. This extrusion was built into the point cloud in order to highlight the material differences. In particular, with the information obtained from the point cloud analysis, it was possible to create the HBIM model of the dome with 16 ribs and 4 remakes positioned at the base of the dome.

Subsequently the main elements of the Octagonal Hall were modeled, considering all the information at the same time. In Revit, these elements were built as “a Wall local elements”. Through this construction method proposed by the software, it is possible to model the main wall elements as a solid element. Once the main structural components were built, the facade of the church of Saint Isidoro and the different portions of masonry due to renovations or more deteriorated and damaged areas have been included in the model. These areas of different material reflect the historical evolution already described (Section 3.1) and show the structural changes that the monument has undergone, due to the transformation in Gregory XIII’s granaries (Section 2). Figure 11 shows the construction process in HBIM of the Octagonal Hall.

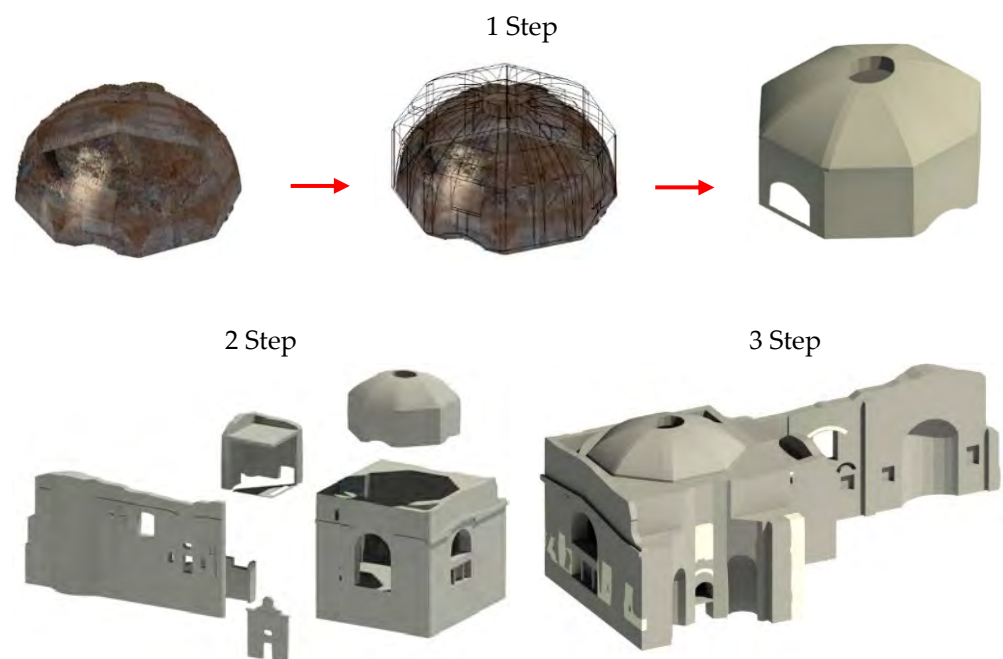


Figure 11. Construction process of the dome of the Octagonal Hall.

4. Preliminary Structural Assessment

The collected data allow a heuristic evaluation of the structure, preliminary to its numerical modeling and synthetically brings together information from the history, the overall geometry, from the visual inspections, however conducted.

The vulnerability of the complex depends both on the changes that have taken place over a very long period and on the initial consistency of the various constructive elements that compose it.

The Octagonal Hall is now an almost complete and well-preserved building. The corner building is even originally less vulnerable than the adjacent structures, however, it has undergone some considerable changes. Its use as a papal granary led to the opening of windows which were then plugged up after its dismission. Furthermore, masonry vaults were built to support the floor at the road level. These seventeenth-century vaults have recently been badly consolidated and therefore required a loading test (a large cushion filled with water) to assess their vertical limit load (Figure 12a). The opening of Via Cernaia interrupted the structural continuity, causing a visible crack in an adjacent room (Figure 12b). Due to the intense vehicular traffic and the nearby subway line, static monitoring and dynamic ambient vibration monitoring were performed (Figure 12c). A chain was inserted

to control the opened crack on the exterior wall on the side of Via Cernaia (Figure 12d); the brick wall facade, which seems original, is made with triangular bricks typical of the Roman construction technique of the Imperial Age.

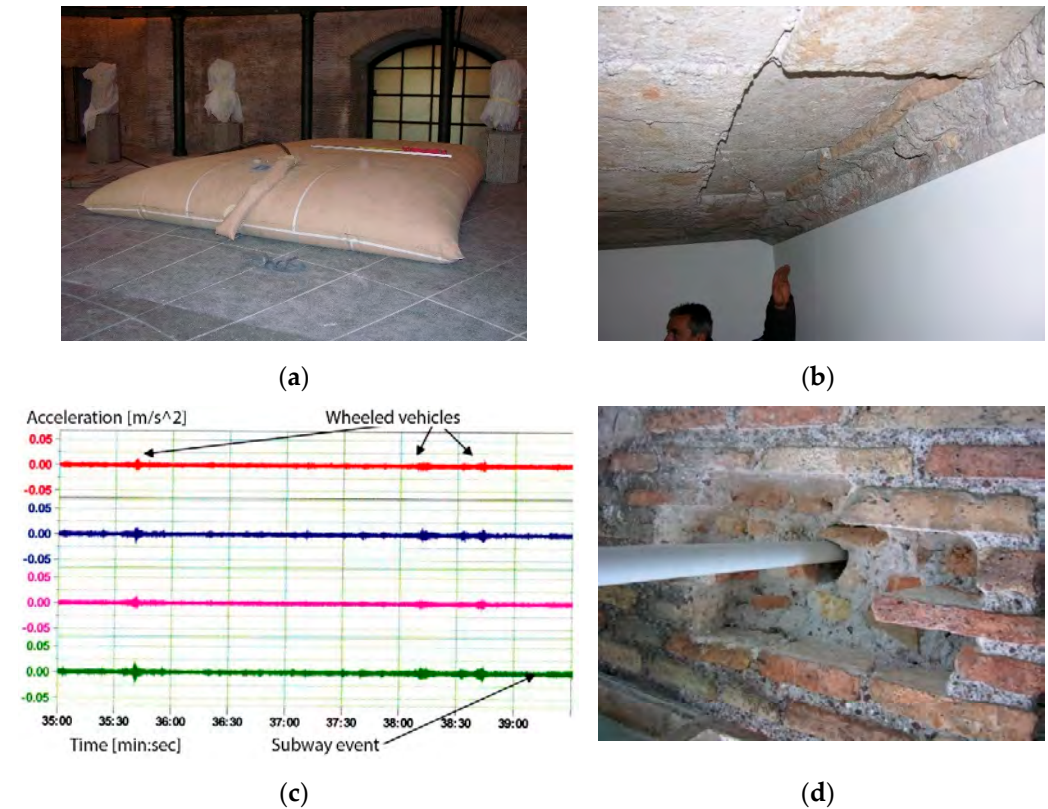


Figure 12. (a) Local test on the Octagonal Hall, (b) a visible crack, (c) monitoring of the vehicular traffic and the nearby subway line, (d) a chain inserted to control the opened crack.

The most vulnerable part of the complex is the high isolated wall fragment of the Gymnasium (WG). This is affected by reinforced concrete structures that support the adjacent Via Parigi, which is also subjected to heavy vehicular traffic (Figure 13). The influence of these structures should be evaluated in FEM modeling.



Figure 13. The fragmented wall of the gymnasium and the reinforced concrete slab supporting Via Parigi.

Saint Isidoro could be of medium vulnerability considering its smaller mass and continuity with the Octagonal Hall and the isolated wall.

In modeling, the uncertainty about the depth of the wall restorations after the removing of the granary facies should also be considered, as well as the state of the intradosal material of the dome.

This preliminary assessment integrates the data collected to build an effective HBIM model useful to plan a sound maintenance of the complex; moreover, it is crucial for the implementation of a thoughtful FE model for structural evaluations.

5. Structural Modelling

5.1. Material Survey

For the purposes of structural evaluation, the appearance of the external skin is not significant, it is necessary to know thicknesses, stratigraphy, any cavities. To this end, investigations such as endoscopies and sonic tomographies could be necessary as well as the relative humidity map as a measure of the predisposition to degradation.

The masonry of the Imperial Age is realized by a core in "*opus caementicium*" made of rubble tufa stones, bound by a mortar of lime and pozzolana, protected by two external facing in "*opus testaceum*". In the wall, so built, some layers of bipedal bricks are inserted to mark horizontal planes. In the masonry mass of the dome, eight ribs are inserted at the intersection of the sails and another eight ribs in the middle of the sails themselves. There is no agreement among scholars on the function of these ribs.

The knowledge of the construction techniques of Roman masonry of the Imperial Age is well known, but unfortunately, the knowledge of its mechanical properties is still insufficient due to the lack of experimental data. In this paper, the mechanical characterization of Roman masonry has been assumed from the few available data provided by Samuelli Ferretti [12] and Philip Brune [13].

5.2. Geotechnical Data

The study of the soil characteristics of the Baths of Diocletian was carried out thanks to the geological and geoarchaeological report prepared for the Soprintendenza Speciale per i beni archeologici di Roma and delivered by the Roman National Museum. Figure 14 shows the plan and sections of the reconstructed stratigraphy near the Octagonal Hall based on the cores extracted.

The values used for the characterization of the soil refer to the boreholes closer to the Octagonal Hall. The most significant data obtained from a sample extracted at 28.4 m are: Unit Weight $\gamma_v = 19.3 \text{ kN/m}^3$, an Oedometric module $E_{ed} = 35,706 \text{ kPa}$, a Coesion $C = 43.9 \text{ kPa}$ and a Friction angle $\varphi = 23.2^\circ$. The data thus obtained were used to describe the behavior of the soil in the finite element model. This information was compared with the geological maps of the city of Rome made by Ugo Ventriglia published for the Provincial Administration of Rome in 1971 [14] and with the maps of the Geographic Information System of Metropolitan Cities of Rome Capital [15]. The objective of this comparison is to provide a general procedure capable of providing information on the type of terrain in the city of Rome for preliminary analyses. Thanks to the sections made by Ventriglia near the Octagonal Hall, it was also possible to hypothesize part of the stratigraphy of the soil [14] and to compare the results with the experimental tests carried out. Consequently, the presence of a superficial layer of Pozzolana and a more important layer of underlying lithoid tuff was hypothesized. The comparison shows that the data obtained from Ventriglia are very general and less detailed, but still a very good guide in the absence of experimental geotechnical tests. Figure 15 shows part of the plan and sections of the Geological Map of the Ventriglia with the positioning of the Octagonal Hall.

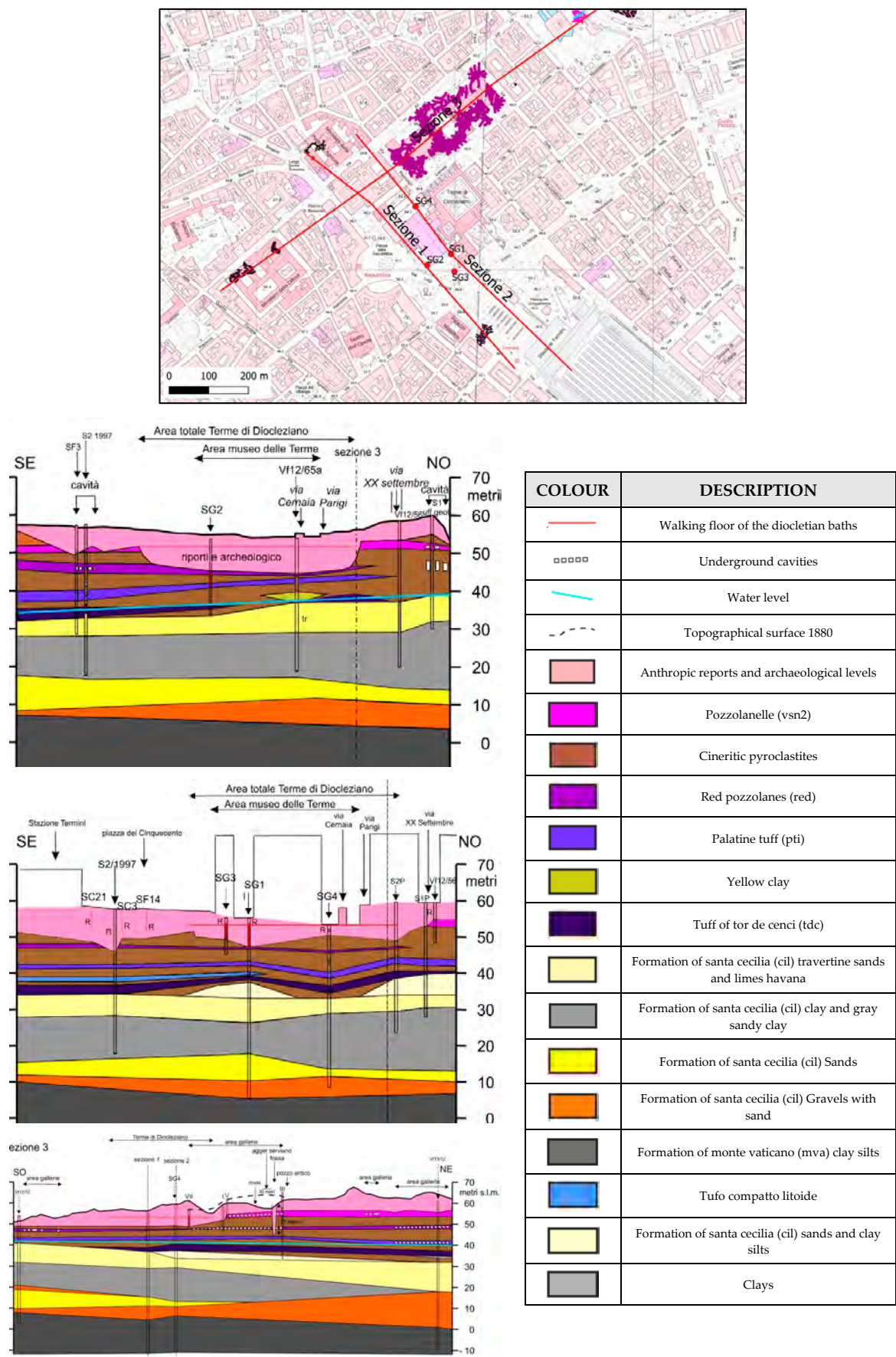


Figure 14. Geotechnical sections of experimental tests carried out by SOGEA srl.

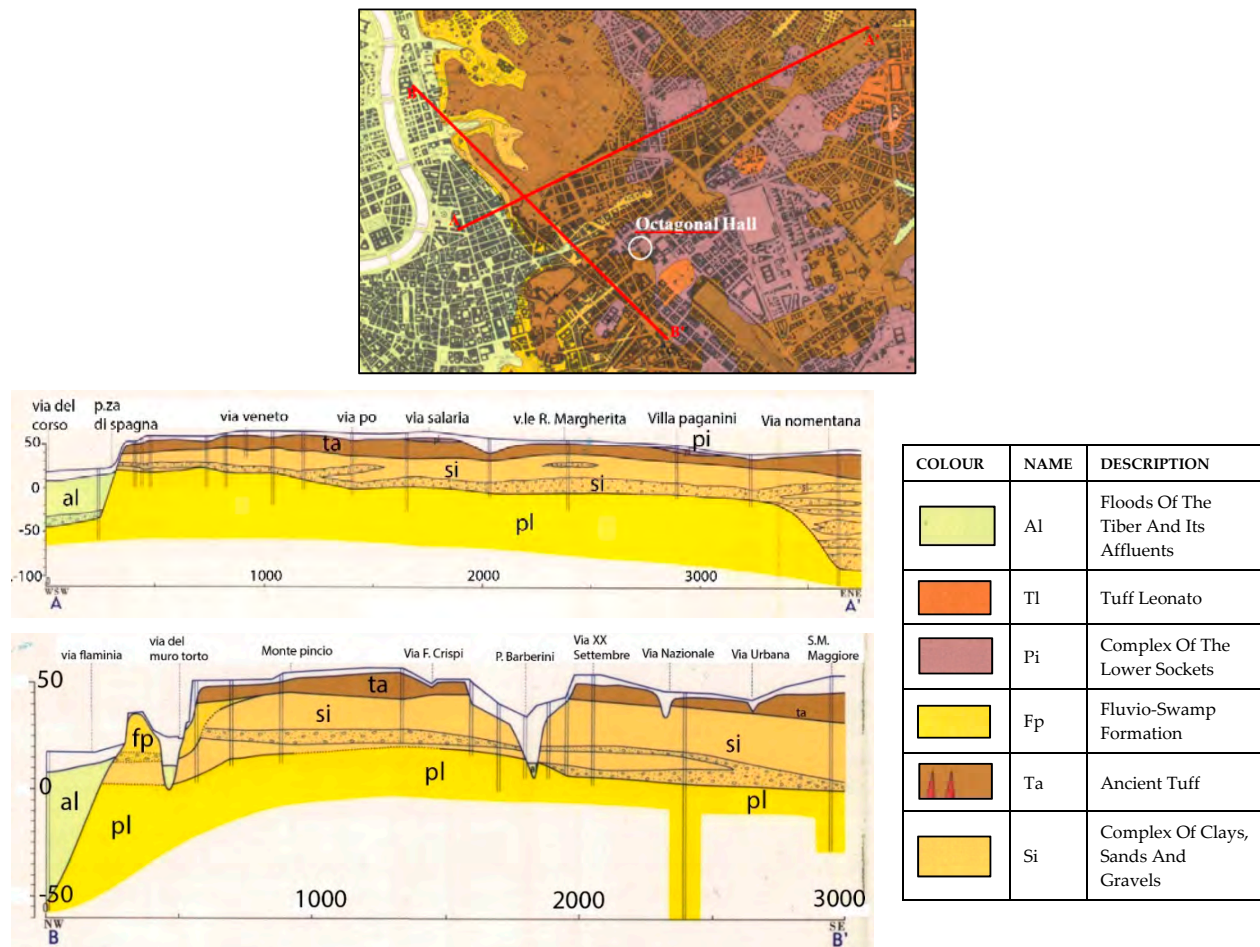


Figure 15. Plans and Sections of Rome made by Ventriglia.

5.3. FE Model

Once the 3D model in HBIM was completed, the information of the structure was exported in the Midas Fea NX software [16,17]. The model in Revit has been subdivided according to different mechanical properties. Then, the mesh has been obtained by automated generation process available in Midas Fea [17] NX, with a total of 694,102 elements and 136,205 nodes (Figure 16).

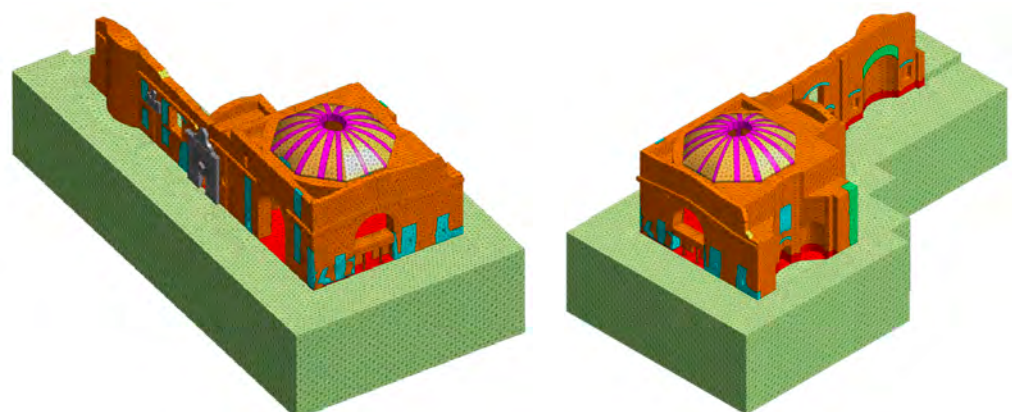


Figure 16. FE model of the Octagonal Hall.

The structure was joined in continuity to the soil at the base and on the lateral surfaces. The connection between the structure and the ground was realized using an “interface element” capable of restoring the interaction between the different materials. The general practice in many roman structures was the use of materials with different densities, heavier in the foundations and lighter in the upper structures and in the vaults. Consequently, it is possible to assume that the density of the cement decreases with the increase of the height.

Elastic moduli and densities assumed in the model are listed in Table 1. The colors used in the Table 1 represent the different portions of material used in the finite element model. In order to differentiate between damaged masonry and repaired one, it was decided to apply a coefficient of variation equal to 20%. The constitutive model for the “*opus caementicium*” is given using Samuelli Ferretti’s data in compression and the approximate bilinear behavior proposed by Brune in tension [11]. The constitutive model is shown in Section 6.2

Table 1. Mechanical characteristics of the materials defined in the FE model in Midas Fea Nx.

Color	Name	Elastic Modulus E [MPa]	Poisson ν [-]	Unit Weight γ [kN/m ³]
	Plain masonry—lower	2600	0.2	18
	Plain masonry—medium	2600	0.2	16
	Plain masonry—upper	2600	0.2	14
	Ribs	3120	0.2	16
	Repaired masonry	3120	0.2	16
	Damaged masonry	2080	0.2	16
	Soil	26.52	0.3	19.3

6. Analyses and Results

Once the finite element model was developed, different analyses were carried out to identify the optimal setup for the positioning of the dynamic tests and the non-destructive tests. With the modal analysis (Section 6.1), it is possible to obtain information on the dynamic behavior of the structure and figure out an optimal configuration of the accelerometers based on the most significant displacements. With the pushover (Section 6.2) on the other hand, it is possible to obtain information on the most critical sections and consequently define the position of the non-destructive tests to better characterize the behavior of the structure.

6.1. Modal Analysis and Accelerometer’s Configuration

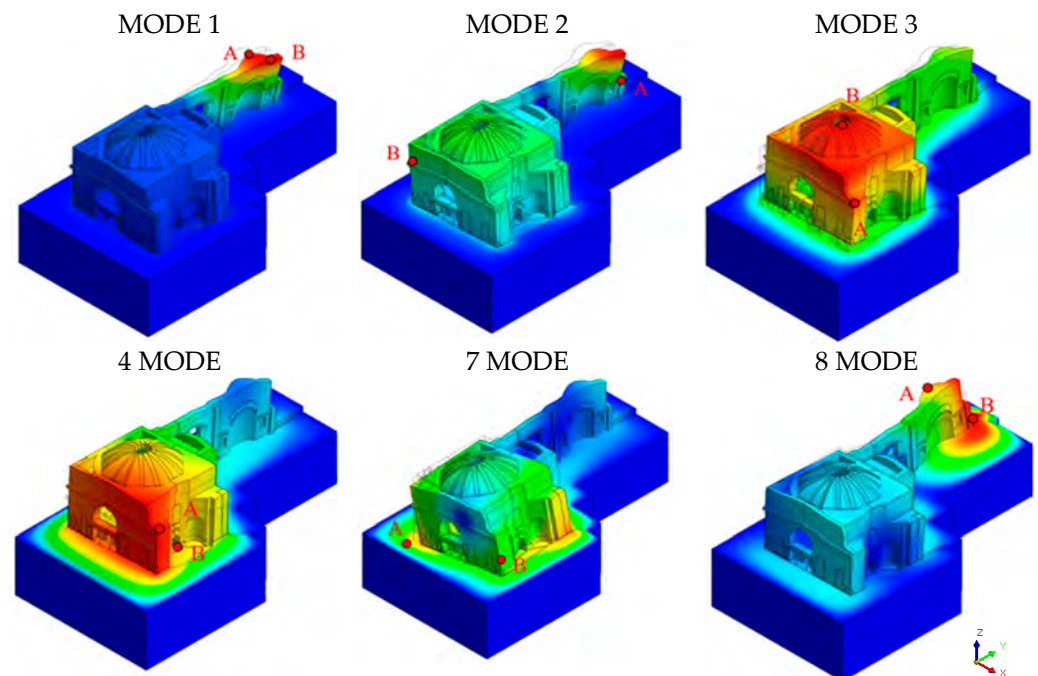
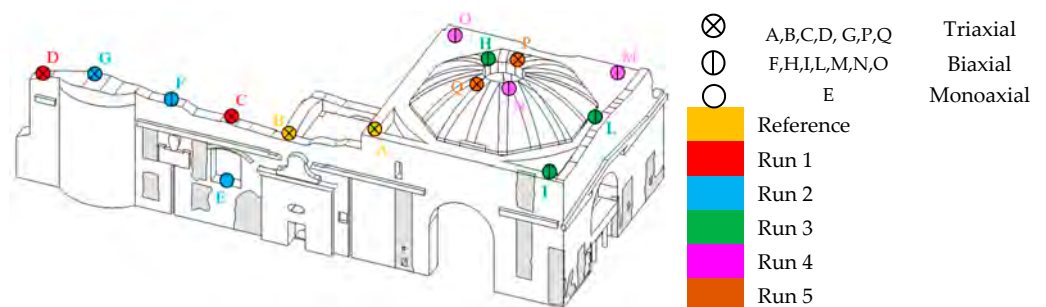
The analysis, with the software Midas Fea NX [16,17], were carried out by calculating eight vibration modes with the Lanczos method. The frequency values of the vibration modes and the corresponding participating masses are listed in Table 2, while the most representative mode shapes are given in Figure 17, where the letters A and B represent the points with the largest displacements.

In order to obtain an optimal configuration of the accelerometers, avoiding nodal points of zero displacements, the maximum and minimum displacements of the nodes in X, Y and Z were considered from the modal analysis [18]. The choice of the modes for the optimum setup, was made by identifying the modes with a greater participant mass.

The obtained configuration for accelerometers (Figure 18) will allow the OMA.

Table 2. Frequency and modal effective mass of the FE model.

MODE	MODAL EFFECTIVE MASS			FREQUENCY
	X [%]	Y [%]	Z [%]	f [Hz]
1	6.93	0.17	0.01	1.22
2	9.24	1.92	0.01	1.32
3	3.37	41.03	0.36	1.50
4	0.41	6.12	38.72	1.83
5	0.08	1.04	2.84	1.84
6	1.63	7.59	13.94	2.01
7	28.05	4.21	0.02	2.03
8	0.00	0.04	3.55	2.40

**Figure 17.** The optimal points for each vibration mode of the Octagonal Hall.**Figure 18.** Positioning of the PCB accelerometers for the environmental vibration analysis (OMA).

The OMA is a method that aims at identifying the modal properties (frequencies, damping ratios and mode shapes) of a structure under ambient vibration. This means that it is sufficient to analyze the response of the structure to unknown random vibration (output-only modal identification) to extract the modal parameters of the building. Frequently, the

total number of accelerometers available is not sufficient to assess the overall behavior of the building; for this reason, it is necessary to use the Multi-Run Operational Modal Analysis Method.

This method post-processes the OMA of each run relative to the main parts of the construction. The modes of each run are later combined and scaled based on the most appropriate and complete run (target modes). With the use of the Multi-Run technique, it is important to evaluate the position of the reference at a point with important dynamic displacements, always avoiding nodal points, to adequately scale the data obtained from the other accelerometers. It is usually advisable to have at least two triaxial references [18]. In case at hand, it has been chosen to use five different runs with two fixed references (Node A and Node B) subsequently joined through the Multi-Run technique.

6.2. Pushover Analysis and NDT Setup

The non-linear static analysis was carried out in Midas FEA NX, applying two types of lateral forces:

- the first proportional to the masses defined as a uniform load (Mass Push);
- the second proportional to the second vibration mode in X and to the third in Y (Modal Push).

Both push loads were applied independently along the x and y axes. The analysis was carried out by applying them to the initial condition of the structure (vertical loads) as a horizontal increasing load. The vertical load was applied in 3 steps and the horizontal loads in 40 steps, using a convergence criterion. The push proportional to the masses of the structure and the push relative to the vibration mode was applied, automatically by the software, in concentrated forces to each node. The value of the force calculated from the response spectrum, was further amplified by a double factor, to make the effect of material plasticization more visible. The push obtained from the spectral analysis has been calculated using the seismic spectrum proposed by the NTC2018 [19].

The non-linear behavior of Roman masonry has been modeled using the theoretical curves implemented in the software Midas Fea NX. To describe the behavior in the plastic compression field, a compression curve was used, proposed by Feenstra [20]. For the tension curve, the one proposed by Hordijk, Cornelissen & Reinhardt [21] and Hordijk & Reinhardt [22] was used. Both of these curves were correlated with the experimental curves proposed by Samuelli Ferretti [10] and Brune & Perrucchio [11].

The theoretical curve is based on a Smeared Crack Model [23,24] and is given in terms of stress vs. strain. The experimental values obtained by Brune & Perrucchio were then converted into a σ - ϵ relationship, assuming a constant strain distribution over the crack, justified for a mesh element with a lower order and for particular cases of symmetry, as in this case [25]. The correlation between the experimental and numerical curves has been illustrated Figure 19. As for the case of elastic analysis, due to the different states of degradation, it was considered a variation equal to 20%.

The soil has been modelled with springs with a stiffness estimated based on the available geotechnical data, assuming that the modulus of the subgrade reaction is equal to $k_s = 36,000 \text{ kN/m}^3$ (Silty medium dense sand). The results of the analyses are in Figure 20, in which the cracks opening in the last step of each push-over analysis is plotted.

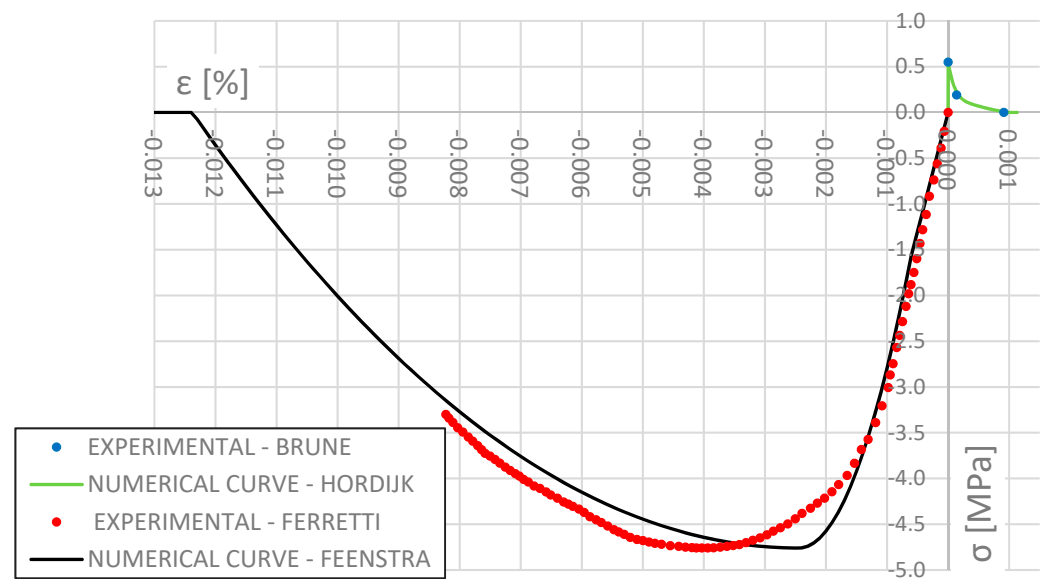


Figure 19. Correlation between the experimental and theoretical curves (compression and tension).

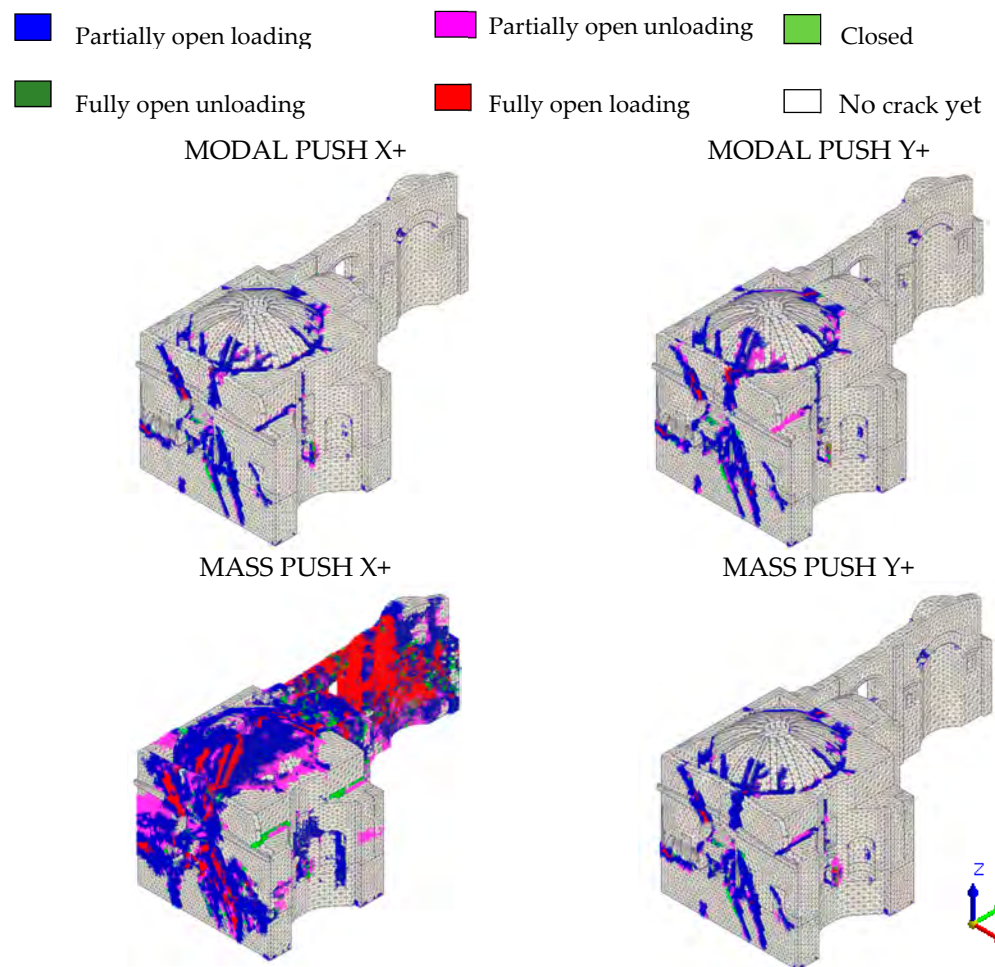


Figure 20. Southeast view: cracking in the different push-over analyses.

As a final result, it is possible to highlight areas where greater damage can be expected and predict critical areas to be tested (Figure 21).

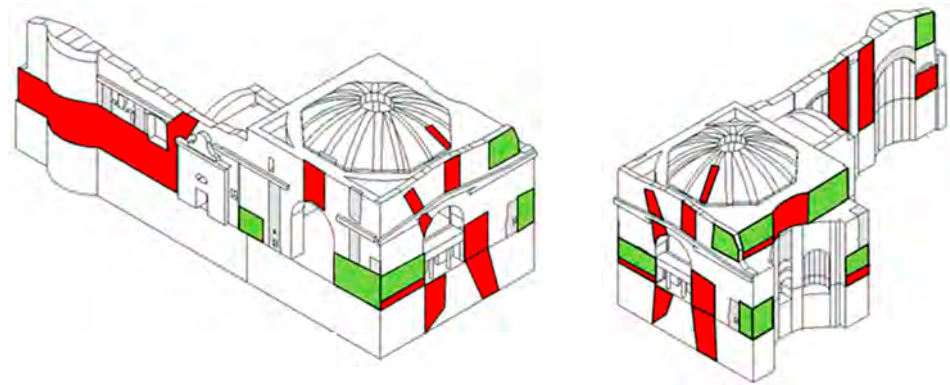


Figure 21. Areas where greater damage can be expected (red) and safe areas (green).

7. Conclusions

The research work integrates different sources and techniques such as historical research, material data, geo-technical data, visual inspection, drone inspection, geometric modeling and HBIM modeling to obtain a finite element structural modeling of the historical buildings. Obviously, the goodness of the obtained structural model is sensitive to an expert judgment that allows for the development of an overall structural assessment that is preliminary to a rigorous modeling. The visual inspection is fundamental, which should be the first approach to the structure, allowing for the identification of the different materials used, the areas where there is any degradation and any reconstruction carried out during the building life.

In particular, the HBIM technique allows for the continuous updating of the building database, including the addition of layers from monitoring data, and therefore it could be useful for managing maintenance interventions over time. Given a performed HBIM, as a 3D reference model, it will be easier to monitor and individuate cracks, degradation and any other source of modification.

The paper demonstrates the possibility of establishing a methodological path to design a set of non-destructive measures, such as tomography and endoscopy, and ambient vibration tests, optimized in both number and type. In the specific case of the Diocletian Baths, the proposed methodology allowed for an optimal planning of the tests in progress, which will make it possible to update the FE model for a more accurate design of any future intervention.

A crucial aspect is the collection of all the information useful to describe the structure under evaluation: documents and geometric data, plans, elevations and sections, and historical background including the different historical phases that have taken place in the past, which may have modified the original structure.

Today, help is given using photogrammetry techniques that, through the use of drones, aim at obtaining information on the geometric characteristics and sometimes to identify degradation sources. More difficult is the characterization of material properties in absence of mechanical tests.

Unfortunately, the research highlighted the lack of sufficient data to characterize the mechanical parameters of the Roman masonry of the Imperial Age, despite being well known from the historical and archaeological point of view. The scheduled experimental campaign will provide a valuable contribution to the knowledge of the mechanical properties of the opus caementicium. More generally, a systematic application of the proposed approach to the heritage assets, would help the institutions responsible for their conservation and restoration.

Author Contributions: V.S. and C.S. have contributed to the methodology, survey, modeling and analysis. Finally, C.B. and S.S. are the scientific directors of the work. They have made the conceptualization of the research and have made the critical revision of the paper, contributing to the analysis and discussion of the results. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by the PRiSma Laboratory of the Department of Architecture of Roma Tre University, Rome, Italy.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: A sincere thanks also goes to Museo Nazionale Romano, Rome, Italy.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Westoby, M.J.; Brasington, J.; Glasser, N.F.; Hambrey, M.J.; Reynolds, J.M. Structure-from-Motion photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology* **2012**, *179*, 300–314. [CrossRef]
- Özyeşil, O.; Voroninski, V.; Basri, R.; Singer, A. A survey of structure from motion. *Acta Numer.* **2017**, *26*, 305–364. [CrossRef]
- Banfi, F. The integration of a scan-to-HBIM process in BIM application: The development of an add-in to guide users in autodesk revit. *ISPRS Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *XLII-2/W11*, 141–148. [CrossRef]
- Da Gai, E. Il Centro Annonario Pontificio alle Terme di Diocleziano. In *Le Terme di Diocleziano—La Certosa di Santa Maria degli Angeli*; Friggeri, R., Magnani Cianetti, M., Eds.; Milano Electa: Milano, Italy, 2014; pp. 314–331.
- Paulin, E. Les Thermes de Dioclétien. Restaurations des Monuments Antiques par les Architectes Pensionnaires de L’Accadémie de France a Rome, Firmin—Didot et cie, Paris. 1890. Available online: <http://digi.ub.uni-heidelberg.de/diglit/paulin1890/007> (accessed on 23 August 2021).
- Albisinni, P.; Carlevaris, L.; Micucci, A. *Storie del Cielo su Cielo—Le Vicende dell’Aula Ottagonale alle Terme di Diocleziano—Disegnare il Tempo e l’Armonia—Il Disegno di Architettura Osservatorio nell’Universo*; Alinea Editrice: Firenze, Italy, 2009; p. 19.
- Metashape Professional—Software per Fotogrammetria v.1.5.2*; Agisoft LLC: St. Petersburg, Russia, 2020.
- Magnani Cianetti, M.; Ines, A. Riflessioni sulla struttura voltata dell’Aula Ottagonale delle terme di Diocleziano. *Palladio Riv. Stor. Archit. Restauro* **2011**, *47*, 55–78.
- Giovannoni, G. *La Tecnica delle Costruzioni Presso i Romani*; Società Editrice d’Arte Illustrata: Rome, Italy, 1925.
- 3 Elevations and 1 Section—Complesso Monumentale delle Terme di Diocleziano—Soprintendenza Archeologica di Roma*; Soprintendenza Archeologica di Roma: Roma, Italy, 1978.
- Revit—Software per il Building Information Modeling*; 19.0.1.1 (x64); Autodesk: San Rafael, CA, USA, 2019.
- Samuelli Ferretti, A.; Giavarini, C.; Santarelli, M.L. Mechanical characteristics of Roman “Opus Caementicium”. In *Fracture and Failure of Natural Building Stones—Applications in the Restoration of Ancient Monuments*; Springer: Dordrecht, The Netherlands, 2006.
- Brune, P.F.; Perruccio, R. The Mechanics of Imperial Roman Concrete and the Structural Design of Vaulted Monuments. Ph.D. Thesis, University of Rochester, Rochester, NY, USA, 2010.
- Ventriglia, U. *Geologia del Territorio del Comune di Roma*; Amministrazione Provinciale di Roma: Rome, Italy, 2002.
- Sistema Informatico Geografico—WEBSIT. Città Metropolitane di Roma Capitale. Available online: <http://websit.cittametropolitanaroma.it/> (accessed on 23 August 2021).
- Midas FEA NX—2021 (v.1.1)*; CSPFEA—Engineering Solutions: Este, Italy, 2021.
- Analysis and Algorithm—Midas FEA—Advanced Nonlinear and Detail Analysis Program. 2020. Available online: <https://pdfcoffee.com/midas-fea-analysis-algorithm-pdf-free.html> (accessed on 23 August 2021).
- Brincker, R.; Ventura, C. *Introduction to Operational Modal Analysis*; Wiley: Chichester, UK, 2015.
- NTC 2018—Aggiornamento delle Norme Tecniche per le Costruzioni. *Gazz. Uff. Italy* **2018**, *8*, 42–50.
- Feenstra, P.H. *Computational Aspects of Biaxial Stress in Plain and Reinforced Concrete*; Delft University Press: Delft, The Netherlands, 1993.
- Reinhardt, H.W.; Hordijk, D.A.; Cornelissen, H.A.W. Experimental determination of crack softening characteristics of normal-weight and lightweight concrete. *Heron* **1986**, *31*, 45–56.
- Hordijk, D.A.; Reinhardt, H.W. Local Approach to Fatigue of Concrete. Ph.D. Thesis, Delft University of Technology, Delft, The Netherlands, 1991; 216p.
- Petrangeli, M.; Ožbolt, J. Smeared Crack Approaches—Material Modeling. *J. Eng. Mech.* **1996**, *122*, 545–554. [CrossRef]

-
24. Vecchio, F.; Collins, M. The modified Compression—Field Theory for Reinforced Concrete Elements Subjected to Shear. *ACI J.* **1986**, *83*, 219–231.
 25. Rots, J.G.; Blaauwendraad, J. Crack models for concrete: Discrete or Smeared? Fixed, Multi-directional or Rotating? *Heron* **1989**, *34*, 6–59.