Article

From Digital Restitution to Structural Analysis of a Historical Adobe Building: The Escuela José Mariano Méndez in El Salvador

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Abstract: Nowadays, the research in the fields of conservation and restoration is focusing on recording large amounts of data and information in order to obtain highly accurate surveys that include most details of constructions. Documenting and surveying are fundamental activities in achieving the successful preservation of cultural heritage, but also in implementing efficient strengthening interventions of structures. The applications of methods and techniques that link the disciplines of geometrical surveys and structural analyses are still fragmented, and further research is necessary to fully transfer site information into structural models. In this article, the authors propose a methodology with which to link different restoration fields, with the aim of highlighting the strengths and weaknesses of the interoperability between surveys (carried out through detailed restitution from point clouds), heritage building information modeling (HBIM), and structural analyses to connect three different disciplines. The goal is to find a synthesis model that brings together historical and geometric characteristics, but also physical–mechanical properties, for a structural evaluation through a finite element model (FEM). The case study of the Escuela José Mariano Méndez is analyzed, an extremely damaged historical adobe building in Santa Ana, the second largest city of El Salvador; it is considered fundamental to the national economy, particularly after the "coffee boom" in the late 1800s. The site, located near the historic center, is also known as "Antigua Escuela de Artes y Oficios" and embodies the architectural traditions of the region, being built in adobe and stone. Roma Tre University and the Secretaría de Cultura de la Presidencia (SECULTURA) are partners in this research project to document and restore the historical and cultural value of this site.

Keywords: historical adobe building; HBIM; FEM; laser scanner

1. Introduction

The integration of data in a building information model (BIM) allows for the efficient archiving of the information of constructions, while the seven dimensions of the model (three-dimensional geometry, time, cost, sustainability, and management) enhance several aspects of the architectural engineering construction (AEC) sector. The automatic updating and detection of errors or inaccuracies in the project, as well as the transfer and sharing of the contents within the team, are the main advantages resulting from the use of the BIM working methodology.

The BIM method was initially developed to support the design, construction, and management of new buildings and infrastructures; its application to monuments and existing buildings for assessment and restoration came after, as a consequence of the needs of the industry. This is because the seven dimensions of work mostly refer to standardized elements, typical of new designs. It is more difficult to reproduce damaged, cracked, or collapsed elements, and it is very complicated to design and model strengthening interventions in existing buildings over time. Some techniques still cannot be implemented in so-called digital twins, which are digital representations of existing real entities, provided

by the first international standard UNI EN ISO 19650 [1], adopted and implemented in Italy in the UNI 11337:2017 [2], and divided into ten parts and applied in D.lgs. No. 50/2016 [3].

2. Scope and Methodology

The utilization of open BIM technology, a strategy for cooperation during the design and construction of buildings based on standards and open processes, is the goal of HBIM. This open path is currently a goal to be achieved that still has some restrictions. Despite this, the definition of BIM or HBIM models ready to be exported and used by other software is partially achievable considering some of the collected information. The advantage of a BIM (compared to other methodologies) is its interoperability, which allows the importing of products from other processing platforms for modeling constructions.

In this research, an integrated methodology is proposed to make clear the transition between a laser scanner survey and structural analysis through the creation of a single model. The advantage of this working environment is that it is able to integrate all of the technologies of the AEC industry, as well as the tools of various pieces of software, to define a single model, which can be simultaneously employed by users of different sectors and reduce the uncertainties in the design and implementation phases, as has been presented in a previous work by the authors [4].

In the literature, few works provide useful indications with which to define an interoperable model from a survey to a structural analysis in a BIM environment.

Some criticalities regarding the modeling of historical constructions subject to deterioration and formed by complex geometries are shown in the research by Ursini et al. [5], Want et al. [6], and Pirchio et al. [7], which presents similar methodologies of interoperability and exchange, proposing strategies with which to overcome the difficulties. These works show that it is possible to reconstruct stratigraphic units (SUs) for some types of materials; for example, by processing them for masonry (SUM). This allows modeling that collects elements of damage through the overlapping of multiple wall elements and the simulation of degradation. This provides a useful collection of data applicable for documentation and assessment purposes [8]. In these simulations, the acronym AHBIM is used, which more specifically indicates an architectural heritage BIM.

The transition from a photogrammetric survey to a BIM to a finite element model (FEM) for a structural analysis, often known as scan-to-BIM-to-FEM or point cloud-to-BIM-to-FEM, is one of the key points that still needs to be improved [9]. The first step implies the detection of irregular and damaged geometry of a monument from photogrammetry; the second involves the discretization of the geometry into finite elements, including irregularities, and adding the mechanical properties of materials.

In this work, the authors focus on the limitations and strengths of interoperability between models and technologies. This step is possible through the verification between a correct interpretation of the historical phases, an integrated point-by-point survey (point cloud), and consequent modeling in the BIM environment; in the final stage, the employment of a structural analysis in order to evaluate the dynamic behavior of the construction provides a valuable tool with which to plan the preservation and maintenance activities of built heritage. This need arises from the desire to improve and link the restoration sector with architecture and structural engineering, as well as enhance an approach that ensures productive collaboration for the preservation of historical constructions. This case study is part of an international research project on El Salvador's built heritage, funded by the Italian Agency for Cooperation and Development through the project Fortalecimiento de la Secretaría de Cultura de la Presidencia de El Salvador a través de la valorización del patrimonio cultural, AID 9961.

A historical building, the Escuela José Mariano Mendez, was severely damaged in the past; all of the roofs collapsed, and this caused the fast decay of the materials, especially the adobe blocks that are particularly sensitive to weathering. This project aims to document and record the present condition of the building in order to facilitate the conservation activities for the valorization of the site.

This work focuses on a detailed description of the monument in which geometries were regularized with an accuracy higher than 5 mm and the structural parameters of the materials were estimated according to the available results of the tests. It, therefore, proposes a model that accurately reproduces the monument and allows for the exporting of geometrical and material data for the purpose of structural analyses. Finally, a structural model of the building was obtained and employed in order to define the modal parameters as well as understand the state of preservation of the construction.

This process has allowed for the connection of different disciplines, ensuring collaboration between different experts and providing the means with which to carry out an efficient and coherent restoration from both historical and architectural perspectives.

The research, therefore, addresses the following issues:

- Interoperability of a historical BIM as a basis for information exchange between different disciplines;
- Digital representation of irregular geometries, collapsed elements, deteriorated materials, and degraded surfaces;
- Transition from a geometrical survey to structural modeling through the creation of a unique model that includes the multidimensionality of the BIM working methodology.

These aspects support the evaluation of the structure's safety and facilitate the preservation of its historical value.

3. The Site

The Escuela José Mariano Méndez is a historical building in Santa Ana, the most important city of the homonymous department, and the second largest city of El Salvador.

El Salvador is a state in Central America subject to frequent and intense seismic events. Precisely for this reason, this work aims to combine important operations in view of future restoration or structural rehabilitation operations. The region is seismically active due to its proximity to the "ring of fire", the Circum-Pacific Belt along the Pacific Ocean characterized by active volcanoes and frequent earthquakes; the main earthquakes of the region are reported in Figure 1.
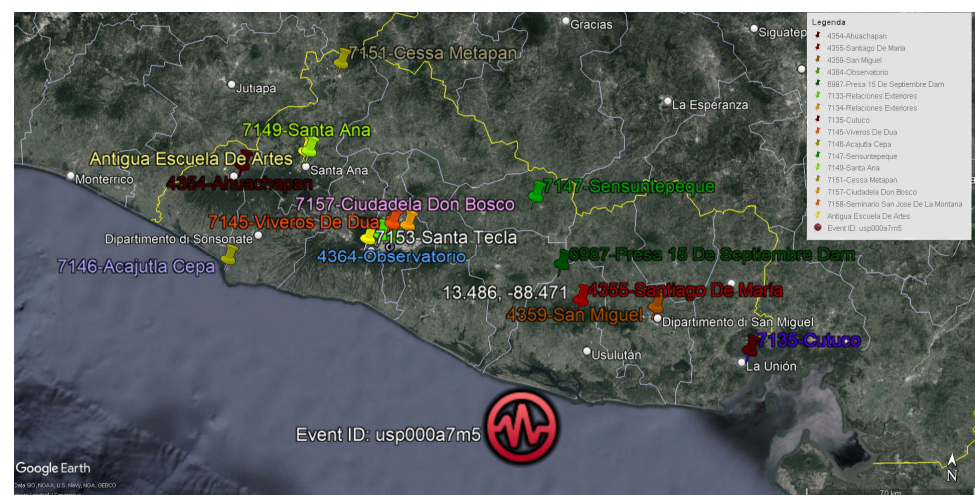
Figure 1. Map of the main seismic events in El Salvador in the 20th century; Santa Ana is marked in the northeast region.

On the 18th of July 1912, a violent earthquake of 5.9 on the Richter magnitude scale and VII grade on the modified Mercalli intensity (MMI) scale caused damage in Armenia, Izalco, and Santa Ana [10].

On the 6th of September 1915, a strong earthquake of 7.7 on the Richter magnitude scale caused the collapse of several buildings in the areas of Juayua, Salcoatitan, and in the south of Apaneca. Five deaths were recorded in Santa Ana.

In 1986, one of the most severe earthquakes in San Salvador caused 1500 deaths and 200,000 injured [11]. On the 13th of January 2001, an earthquake of 7.6 on the Richter magnitude scale destroyed 172 of 262 municipalities of the country, including Santa Ana. A month after, at 08:22 (February 13), an earthquake of 6.6 on the Richter magnitude scale struck La Libertad, San Salvador, and Santa Ana [12].

Following the seismic events, in 1994 a national technical standard was proposed with the name of "Norma Técnica para Diseño por Sismo" [13].

Based on the hazard research carried out by Singh et al. [14], the current seismic code of El Salvador establishes the verification of civil structures for events with a minimum return period of 475 years, considering not only the seismicity of a site but also its vulnerability and exposure, as well as the consequent landslides as side effects, typical of the territory [14]. The maps of the level of exposure and vulnerability are provided by the Ministero de Medio Ambiente, and the seismic data as well as risk maps (Figure 2) [15,16] are provided by the Servicio Nacional de Estudios Territoriales (SNET) [17].
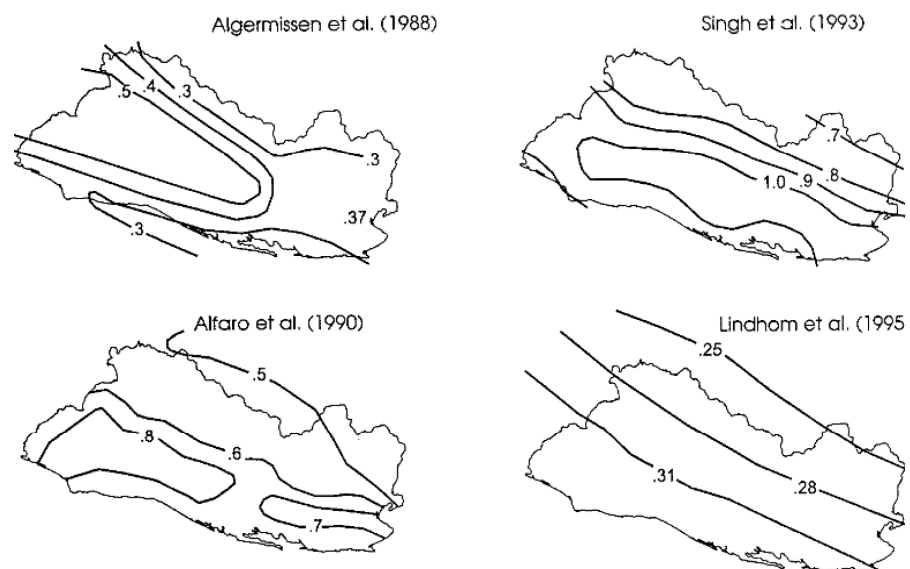
Figure 2. Maps of seismic hazards in El Salvador, reporting the peak ground acceleration (PGA) for 475-year return period events suggested by various studies over the years (1988–1995) [15,16].

4. The Antigua Escuela de Artes y Oficios

This city of Santa Ana is considered fundamental to the national economy, especially after the "coffee boom" that occurred at the end of the 1800s. The school is located near the old town of the city, between the Calle José Mariano Méndez Pte and the 13 Calle Pte, a few blocks away from the Centro Historico (CH), the historical center, as shown in Figure 3.

The Escuela, also known as the "Antigua Escuela de Artes y Oficios", the Ancient School of Arts and Crafts, dates to 1911, as shown in Figure 4a. Nowadays, the building is in critical condition due to a lack of maintenance, the civil war, and natural disasters that have affected the region, as shown in Figure 4b.

The construction presents a central cloister surrounded by the main entrance building with two levels; the two lateral parts and the rear part of the building present a single level (Figure 5a). The building is characterized by several architectural elements in adobe, stone, and brick masonry (walls, arches, and portals), as well as a few reinforced concrete beams (Figure 5b).

The roofs and the central body failed during the various earthquakes that occurred over the years. Nowadays, there are no remains of the original roof nor of the central body, of which only the columns that divide the courtyard are visible. This leaves the structure as an open skeleton.
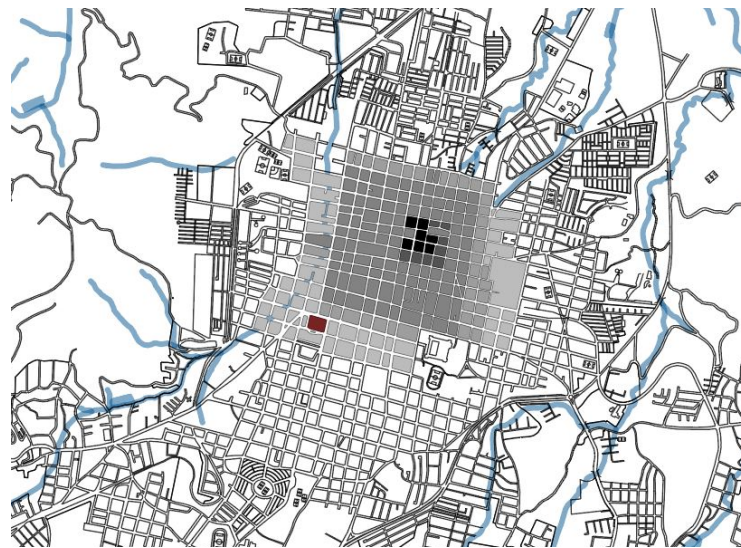
Figure 3. Escuela José Mariano Méndez in red, the historical center from 1532 to 1920 (progressively black to light grey).
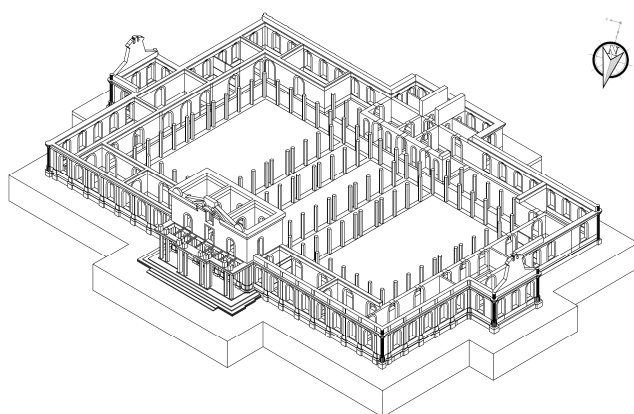

(**a**) (**b**)

Figure 4. The Escuela José Mariano Méndez in 1911 (**a**) and 2019 (**b**).

(**a**) (**b**)

Figure 5. (**a**) Building axonometry and orientation; (**b**) structural materials of the Escuela José Mariano Méndez.

The original roof was made of wood and is partly visible from the structures that stand out at the entrance where there are remains.

The typological elements are summarized in the following categories:

1. Adobe masonry (unit dimensions of 42 × 28 (or 22) × 16 cm), used mainly for single-level walls.
2. Brick masonry (unit dimensions of 28 × 14 × 7 cm) with mud mortar, used mainly for double-level walls.
3. Stone masonry with lime mortar for the lower portions and foundations.
4. Brick jambs and arches around window and door openings, embedded in the masonry.
5. Brick masonry columns.

5. On-Site Recording and Documentation

The acquisition of the factual data of the Antigua Escuela de Santa Ana structures occurred through various stages: in 2015, data were acquired through laser scanning and drone photogrammetry; in 2016, representations were created in plan and elevation, including detailed sections; and in 2021, three-dimensional models were produced, useful for the development of a BIM for a structural analysis. The work was carried out by different groups (both Salvadorian and Italian) in Santa Ana, El Salvador, and in Rome, at the RILTEC laboratory of the Department of Rome Three.

The process for the creation of the HBIM model consisted of a series of procedures that, starting from data acquisition through to the integration of surveying via drone photogrammetry and laser scanning, allowed for the definition of 3D elements for structural modeling within a BIM working methodology.

The integration of laser scanning and drone photogrammetry surveying is an advanced technique for acquiring geospatial data, which requires a certain level of accuracy. In this technique, a drone is used to acquire high-resolution images of areas of interest from 30 to 120 m of altitude, while a laser scanning survey is used to acquire high-precision data at reachable heights. This results in a digital model of the building, both its exterior parts, including roofs and elevated sections, and its interior parts, including individual rooms, thus accurately determining dimensions, elevations, and thicknesses, particularly useful for structural evaluations. The congruence and alignment of the two models were ensured by a topographic survey and spherical markers.

On the other hand, laser scanning and photogrammetry present specific issues that can compromise the quality and accuracy of the results. In the case of laser scanning, the main issue concerns the reconstruction of complex and irregular surfaces of historical architecture. In fact, a laser scanner uses a laser beam to scan the environment and reconstruct a three-dimensional model of the object in question; however, if the surfaces of a building are significantly irregular, the laser is not able to correctly record the data, causing uncertainty in the reconstruction. Photogrammetry is based on the processing of two-dimensional images to create a 3D model of a building; however, the quality of the results also depends on the quality of the images and the lighting conditions of the environment. Furthermore, the reconstruction process can be very long and requires the use of powerful computing tools as well as specific software (Figure 6).

The images acquired by the drone were processed using digital photogrammetry software (Photoscan) [18]; the procedures normally adopted (the alignment of photos as well as the generation of a sparse cloud, a dense cloud, and a mesh adapted to the cloud and textured) are reported in Figure 7. The final model consists of a dense cloud of approximately 13,620,000 points, a mesh model of 12,000,000 triangles, equipped with the actual color, and an ortho mosaic of 8500 px. × 6900 px., with a GSD (ground sample distance: the distance between two pixels on the ground) of 2 cm./px, located according to the geographical reference system WGS 84 (EPSG:4326).

The usual procedures for processing and recording 3D laser scanner data (cloud alignment, inconsistent data filtering, and orientation) are carried out in the first phase via the use of Faro Scene software and in a second phase via the use of Autodesk Recap software [19] to finalize the data in order to achieve a structured point cloud, i.e., containing the various clouds obtained from the individual scans, registered with each other, for a

total of approximately 1.585 million points, equipped with the actual color and with an average resolution of 1 cm./px.
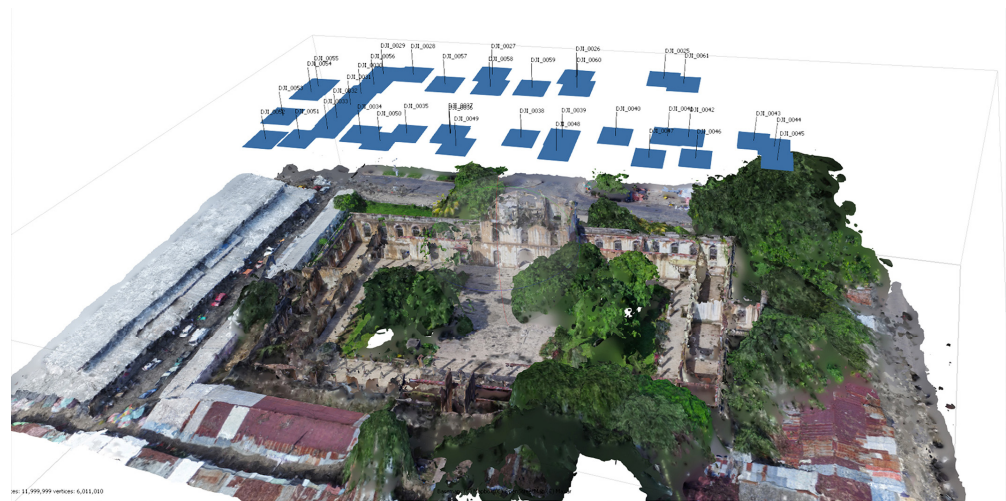
**Figure 6.** Positioning of photographic vantage points on the complex.
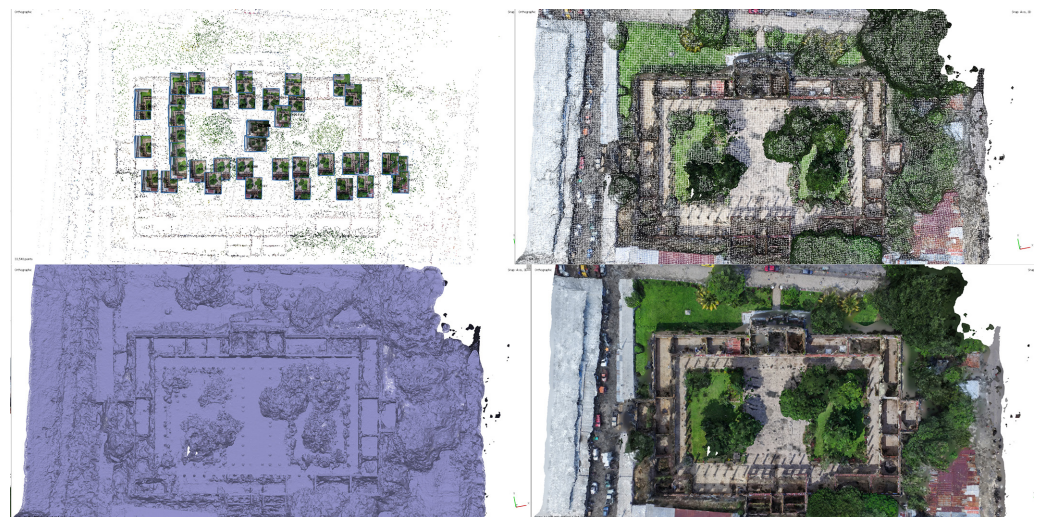
Figure 7. Progressive steps in the model generation: sparse cloud and photo alignment, dense cloud, triangulated mesh, and mesh with texture application.

The two clouds were aligned and integrated with each other, filtering out the incorrectly calculated data and converted into a single point cloud at a scale of 1:1, which represents the essential three-dimensional data from which the metric dimensional information, useful for subsequent processing, was extracted (Figure 8).

The line drawings were produced by a second working group using a point cloud or mesh model, derived from the survey. Plans and sections were created according to the corresponding planes and views of the survey model. These drawings, which include, in addition to the planimetry at a scale of 1:100, three elevations and five sections (scale of 1:100), four sections (scale of 1:50), and an explicative detail of a wall (scale of 1:25), with an indication of the out-of-plumpness of the wall, are aimed primarily at documenting the construction, its state of conservation, and the deformation aspects of the architectural elements (Figures 9–11).

Figure 8. Overall view of the structured point cloud, considering the alignment of the laser scanner point cloud and the drone point cloud.
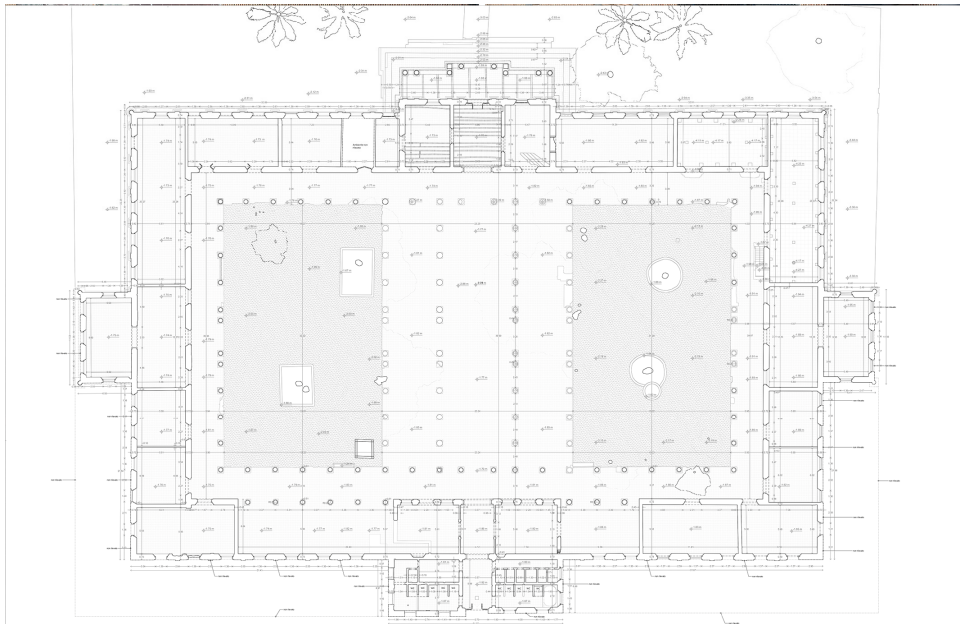
Figure 9. Overall plan.
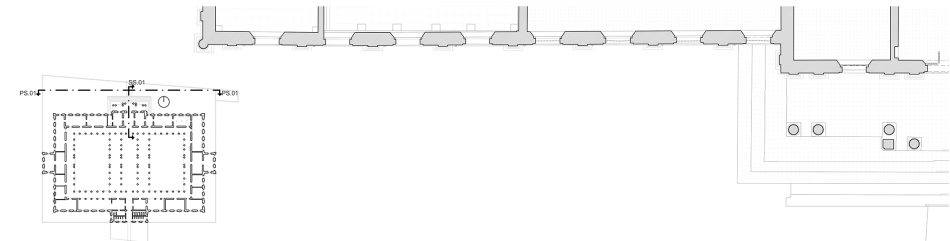
Figure 10. North half-elevation.

Figure 11. (**a**) West section and (**b**) east section.

In the third phase, carried out in 2021 by a third team, considering the survey methodologies applied to the structural analysis and the classification of architectural elements through HBIM systems [20], an integrated procedure was developed, dedicated to the systematization of data into a univocal reference system, the segmentation of the cloud and the simplification of mesh geometries, through the optimizer and retopology procedures, and to the geometric modeling of 3D elements formed by closed and defined geometries.

The optimizer process, a procedure within the 3D modeling software 3Dstudio Max [21], allows the number of points to be reduced by a percentage while maintaining the edges, corners, and surface as normal; the retopology procedure performs three types of model simplification: one by Reform, one by Quadflow, and one by Instant mesh (an open source program) [22], in which the geometry is redefined according to the chosen number of quadrangles.

Through the process of optimization, the mesh geometry was changed from approximately 3,000,000 triangles to one of 500,000 triangles, and the resulting mesh was subsequently modified by redefining the topology, converting the triangle geometry (500,000) into a quadrangle geometry (120,000), without losing the original detail definition in the process.

The procedure involves the use of the link between the survey scan files and the modeling files through Autodesk Recap 2021 and Autodesk Autocad 2021 [23]. This makes it possible to navigate within the model in real view and capture 3D snapshots of the point cloud to define geometric models that correspond more closely to real measures.

Among the issues identified, the fact that ancient architecture, such as the Antica Escuela, has several elements that modify the simple geometric element (out-of-plumb fractures, deficiencies, etc.) makes it difficult to create a geometric schematization as the basis of the BIM working methodology. Therefore, an intermediate 3D model was used in this phase; based on the segmented cloud of the survey, the model is a simplified mesh of each analyzed element, on which the theoretical geometric model is reconstructed.

As illustrative cases, two rooms of the Antigua Escuela were analyzed: the first was located in the north wing, in which, as previously mentioned, certain elements of structural relevance are highlighted, such as the perimeter walls, composed of adobe (raw soil) blocks, arranged in rows of alternating diatons (bricks parallel and perpendicular to the wall), the pilasters of the external façades and the door as well as window openings, made of bricks, set into the adobe masonry, and the covering of the masonry, consisting of a thick layer of plaster and a colored paint finishing (Figure 12).

The second is in the central body of the south wing, with some particularly critical elements with regard to the cracking and deformation picture, such as walls with arched compartments with various lesions, as well as elements close to the keystone and prone to collapse (Figure 13).

(**a**) (**b**)
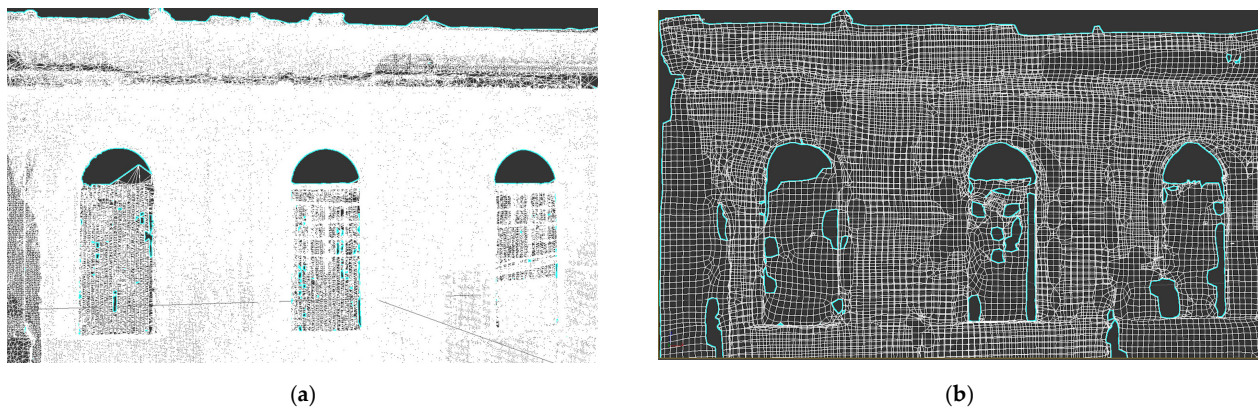
Figure 12. Geometrically simplified model of a wall: the first (**a**) is based on a triangulated mesh and the second (**b**) is based on a quadrangulated mesh.

(**a**) (**b**) (**c**)

Figure 13. (**a**) Geometrical model of the wall simplified into geometry: from a triangulated mesh to a quadrangulated mesh with a window inserted; (**b**) real-view image in recap software of a damaged wall; and (**c**) a simplified model of the same damaged wall.

6. Heritage Building Information Modeling

The complete HBIM of the entire monumental complex is fundamental for data sharing, aimed at the rational and accurate organization of the activities included.

The complexity of performing this task is due to the intrinsic nature of modeling in a BIM environment, where commands and input data have been designed in order to create equal and regular elements in series. Irregularities, damage, and surface erosion cannot be easily represented, and damage information has been partly considered in the mechanical characteristics of the materials. As a modal analysis is an elastic analysis, the authors accounted for the damaged state of the building by underestimating the average modulus of elasticity on the masonry (adobe, brick, and stone masonry). The cracks and discontinuities have not been implemented in the structural model because they require a detailed characterization of the element and material's constitutive relationship, which was not considered in this preliminary stage of the analysis. The controls for the creation of objects and families often have constraints that do not respect surface imperfections and historical structures. On the other hand, the need to protect historical, artistic, and architectural assets should also be considered, as suggested by UNESCO in the 1960s and 1970s [24]. For this reason, in recent years innovations have been made in integrating three-dimensional modeling with new technologies and virtual construction environments, which provide a workflow for superior implemented modeling.

With the interoperability between programs, it is possible to use only one shared file to which all of the information can be added, from a 2D survey to a point cloud, but also the construction phases, the chronogram, the metric, and the estimation structural information with analyses and verifications. These implementations and this connection

make it possible to create directly achievable executive projects working at various scales, both locally and globally simultaneously with a parametric design [25].

Despite the work that is being carried out, this process still requires many improvements, given not only the irregular geometry of built heritage but also the difficulty of working on burdensome point clouds that do not offer a direct transition to a model.

Modeling is often associated with the creation of a digital twin. These models can have different purposes, from the study of energy efficiency to structural analyses [26,27].

Nowadays, the first step, consisting of the scan-to-HBIM process, is quite consolidated, while the process from HBIM to FEM modeling requires more effort and is still limited to simple cases with respect to the case at hand [28].

The steps to be performed to obtain a structural model from a point cloud include the following: the collection of data (geometric, historical, physical, and mechanical); point cloud processing, which involves the creation of a cloud; the setting of a geometric model in an HBIM environment that contains information up to seven dimensions; and the transition to a structural model for the analysis (Figure 14).
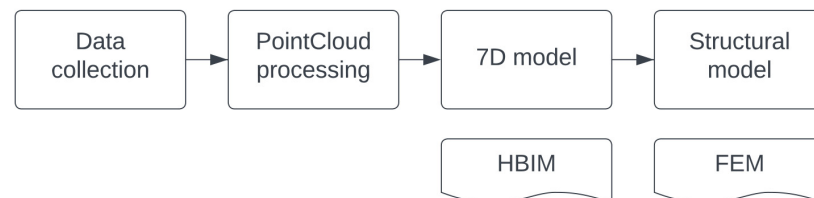
Figure 14. Workflow diagram.

According to standards, UNI 11337 part 4, the level of detail (LOD) defines the quantity and quality of the informative contents in a BIM. The innovation of working in a BIM environment allows the model to contain geometric aspects (three dimensions), but can also contain aspects of another nature (up to seven dimensions). The information concerns the geometric (2D and 3D) and non-geometric features, and it might be extended to time (4D), cost (5D), sustainability (6D), and management (7D). The structural dimensions fall mainly in the geometric field, because the mechanical and physical properties are added in this step and the geometrics are made with the third dimension.

Study Case

The HBIM of the Escuela (Figure 15) is LOD B for the architectural elements and LOD C for the structural elements.

The modeling steps are as follows:

- Setting of the reference grid in plan and levels in elevation along the structural elements (Figure 16a).
- Importing the point cloud derived from the survey along with the available line drawings (Figure 16b).
- Modeling of the structural elements as general BIM masses through the in-place components (Figure 16c) in order to facilitate the importing into the finite element mesh generator.

Finally, the model was georeferenced and oriented by setting the latitude and longitude of three reference points; with this operation, the real cardinal point and the coherence of the model are preserved. The consolidated point cloud was divided into two groups of data to enhance the modeling functionalities and reduce the dimensions of the file.
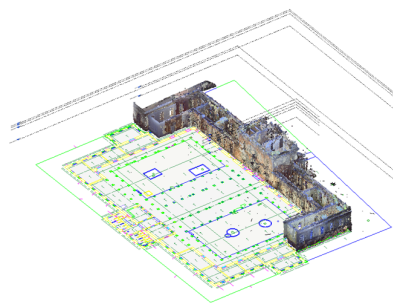
HBIM is convenient in the estimation of quantities through the automatized generation of tables. In this case, the surface and volume of the internal spaces were automatically calculated together with the volumes of the structural materials (Figure 17).
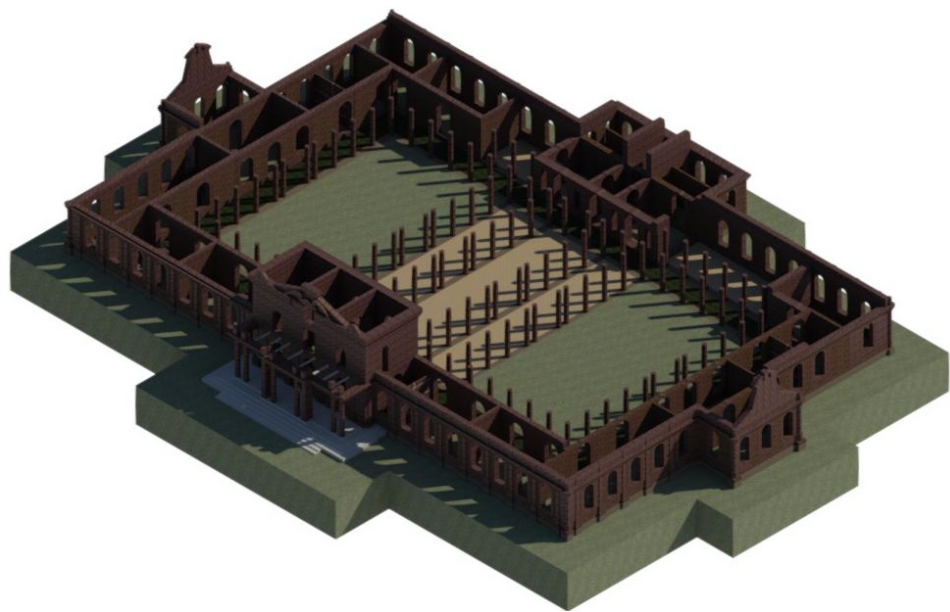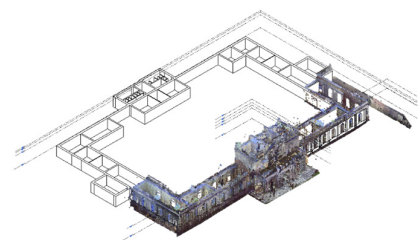
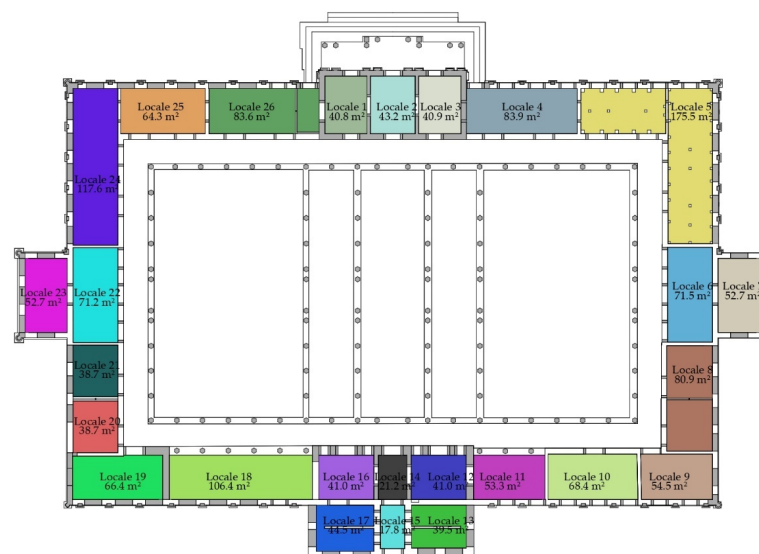**Figure 15.** HBIM of the Escuela José Mariano Méndez.
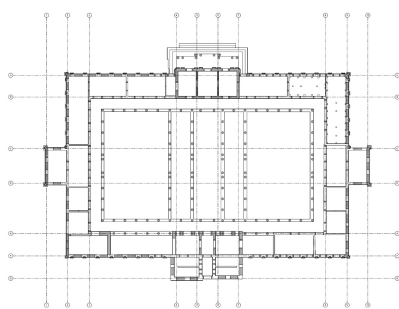
(**a**)   (**b**)   (**c**)

Figure 16. Modeling steps in HBIM: (**a**) plan of structure with the grid; (**b**) point cloud addition; and (**c**) BIM modeling with a point cloud.

Figure 17. HBIM plan view: automatized definition of the interior room (locale) surfaces.

The model was constructed with in-place massing (which is an object specific to the current project context, not related to others), considering the properties of walls, columns, and floors, to facilitate the structural interpretation of the construction. Structural modeling requires the idealization of the construction after the interpretation of structural behavior; this iterative process necessitates assumptions and the recurrent validation of the results of the analysis. The HBIM working methodology allows for a wider range of data retrieved from different disciplines that foster the interpretation of structural behavior. The fundamental aspect to keep in mind is the selection of the appropriate method of analysis with which to model the structure; each method presents its assumptions and limitations. For cultural heritage, the investigating techniques are limited to non-destructive methods, and the results are often not sufficient to fully characterize the construction. Structural modeling is based on assumptions of structural behavior; expert and experienced users are more sensitive to identifying relevant structural aspects; and it is also common that the assumptions need to be reviewed and updated. In this process, the structural model benefits from associating multidisciplinary information, as in HBIM. Therefore, if the main field of application of a BIM is structural, it is necessary to understand the design modalities in advance, especially for complex structures, such as historical ones [5].

7. Structural Analysis

A structural analysis is the last step of the proposed methodology with which to conduct the final safety assessment of the monument in its present state and highlight the significant damage that requires intervention by keeping in mind that the final goal is the reopening of the monument and investing it with new life.

HBIM consists of a single model interoperable with other platforms and software; in this case, only the structural elements were exported in a .sat format and imported into FEM software, Midas FEA NX, for mesh generation [29]. Structural elements are modeled with the local component of Revit [30]. The interoperability is guaranteed by a specific software link for Midas or by exporting .IFC (an open source database that is the acronym of Industry Foundation Classes) or other formats for other structural software.

To create an FE model, it was necessary to simplify the structure by discretizing all of the circular elements and removing all of the geometric elements with very small dimensions in order to facilitate the process of creating the mesh. The mesh elements thus created were subsequently checked in order to assess the perfect connection between the element nodes.

The modal analysis was carried out on the structural model; five different types of materials have been identified in the construction. Their mechanical properties have been defined according to a literature review [31], and the available experimental unit compression tests are reported in Table 1 [31].

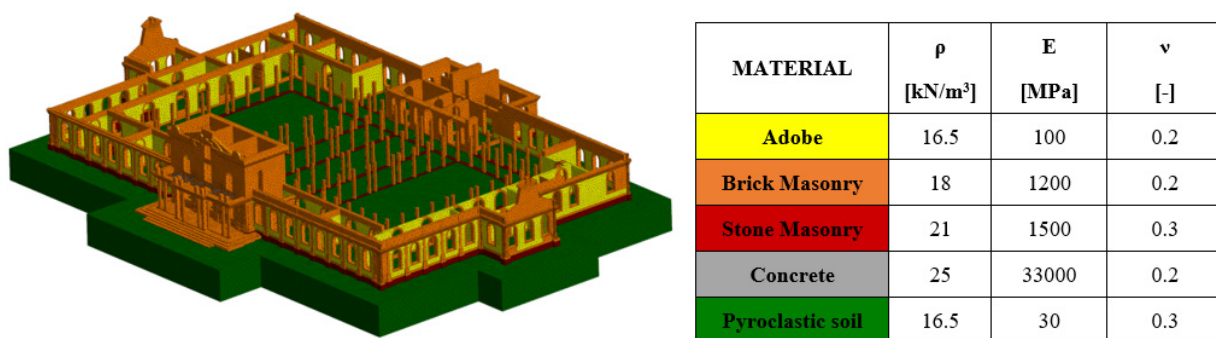**Table 1.** Compression tests were carried out on different adobe and mud brick specimens.

		Mud Brick Sample			Adobe Sample				
		1	2	3	1	2	3	4	5
Max load	[kN]	13,750	12,200	12,000	3510	3460	3850	3150	3340
Compressive strength	[MPa]	7.20	6.31	6.12	1.44	1.41	1.55	1.27	1.34
Average	[MPa]		6.54				1.40		

The soil type was defined with reference to the lithological maps of the site [32,33], illustrated in Figure 18, which shows the lithological map of El Salvador and the relative geographic position of the Escuela located in an area with a predominance of pyroclastites. The soil characterization was assumed from the average values of similar soils in the scientific literature.
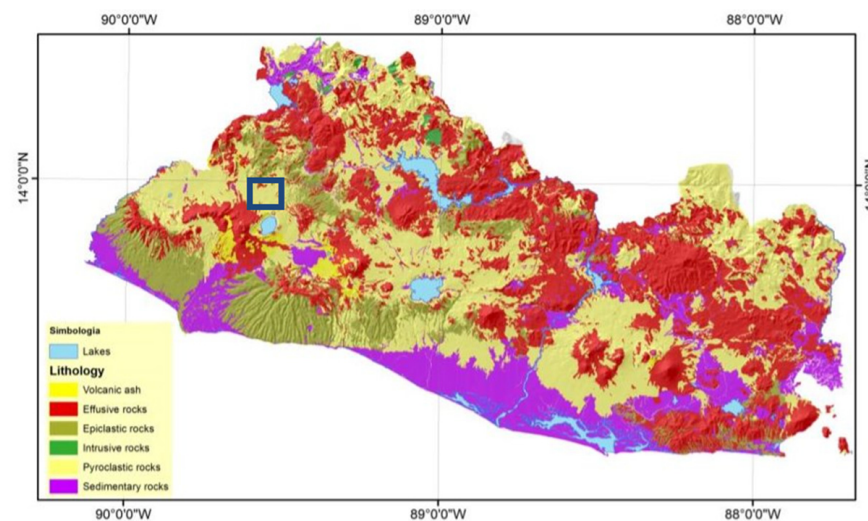
Figure 18. Lithological map of El Salvador with a geographical indication of the Antica Escuela de Arte.

Figure 19 shows the FEM of the Escuela, considering the differentiation of materials based on a visual inspection, photographs, and available point clouds.

MATERIAL	ρ [kN/m³]	E [MPa]	ν [-]
Adobe	16.5	100	0.2
Brick Masonry	18	1200	0.2
Stone Masonry	21	1500	0.3
Concrete	25	33000	0.2
Pyroclastic soil	16.5	30	0.3

Figure 19. FE model of the Antica Escuela de Arte with the five materials.
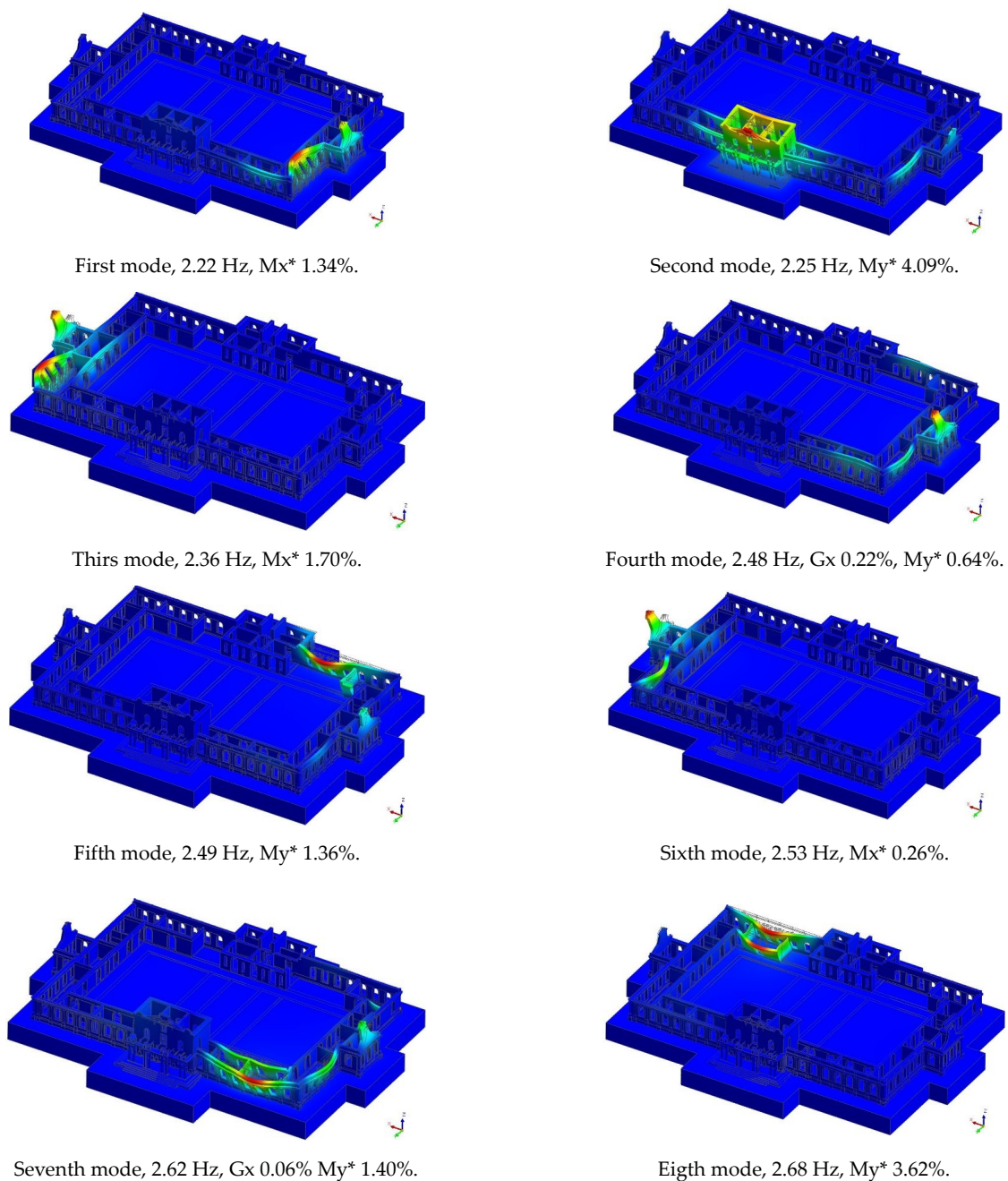
The structure has been three-dimensionally constrained at the base of the soil, and horizontally constrained on the soil lateral faces. The model was created with 2,004,341 tetrahedral elements and 80,017,364 nodes.

The results of the modal analysis are reported in Figure 20, where Mx* and My* are modal parameters (modal effective mass, initially written as GAMMA* from Greek, and the modal mass participation percentage, or G*, in the x and y directions).

It is evident that the structure does not exhibit homogeneous dynamic behavior, probably due to the absence of the upper floors. The main modes involve the walls adjacent to the central blocks as well as the central blocks themselves of the front and side entrances of the structure. After the collapse of the slabs/roofs and the transverse stiffening walls, the connectivity of the structural elements is not guaranteed.

7.1. Results

The working methodology defined in the work and applied to the Antica Escuela de Artes resulted in a preliminary structural characterization of the construction. A basic elastic analysis (modal analysis) of the FEM highlighted a crucial aspect of the construction: the overall lack of integrity of the structure. This simple consideration provides scientific support for the planning of localized and efficient investigations.

First mode, 2.22 Hz, Mx* 1.34%.

Second mode, 2.25 Hz, My* 4.09%.

Thirs mode, 2.36 Hz, Mx* 1.70%.

Fourth mode, 2.48 Hz, Gx 0.22%, My* 0.64%.

Fifth mode, 2.49 Hz, My* 1.36%.

Sixth mode, 2.53 Hz, Mx* 0.26%.

Seventh mode, 2.62 Hz, Gx 0.06% My* 1.40%.

Eigth mode, 2.68 Hz, My* 3.62%.

Figure 20. The first eight vibration modes of the vibration of the finite element model of the Antica Escuela de Artes.

7.2. Discussion

The link between surveying, architectural modeling, and structural analyses is therefore considered effective following the proposed methodology. The results of the analysis vary according to the case study chosen and the purpose for which the analysis is obviously carried out. Further implementations can be performed by conducting non-linear analyses and modeling different intervention proposals considering multidisciplinary information. The refinement of the models with an interactive process of the modification of the elements based on the updated collected information fosters the definition of comprehensive models able to represent the overall condition of the facility.

8. Conclusions

This research aimed to propose a multidisciplinary methodology with the goal of overcoming several interoperability problems that are currently felt in the BIM working methodology. It thus proposed a step-by-step scan-to-HBIM-to-FEM approach where, from a photographic survey and the creation of a point cloud, it obtained the geometry of a complex structure formed by arches and tympana of different materials. The representation of the historical monument included the missing portions due to subsidence, collapses, and structural damage. The transition to the FEM environment, through the interoperability of HBIM, mainly considers geometric and material data; due to the difficulties that this step involves, however, the overall collected information was considered in the interpretation of the structural system.

Research in this subject is currently limited due to the lack of collaboration between experts in various fields, the overcoming of which would lead to greater improvements in this field. This proposed methodology aims to emphasize the importance of interoperability between software through the creation of a single model with all of the necessary information, but also through synergic collaboration among those with different research expertise. Cloud-to-BIM-to-FEM modeling is still adverse, as it is not possible to implement direct links between software and a significant contribution of interpretation of the construction is required; however, it is possible, through a larger series of steps, to develop complex models (both geometric and structural) with multiple avenues of internal information that can be useful to different users.

Starting from a historical masonry case study in Central America in a seismic zone, HBIM was developed from a point cloud survey, after which, from archival research, the building materials, the soil, and past seismic events, it was possible to reconstruct the history of the building construction. Geometric modeling in the HBIM environment is always characterized by some difficulties that can be overcome through BIM local mass modeling objects that allow greater flexibility. The accuracy of the geometric model was possible thanks to the laser scanner survey obtained with the point cloud that allowed it to have all of the necessary geometric information in three dimensions (3D). Once the transition to solids for finite element modeling had taken place, including the information dataset within the multiparameter HBIM, structural analyses were performed.

These types of steps represent a methodology that is becoming part of the current architecture–engineering interaction. For this reason, the research proposes an approach that can unify the cloud-to-BIM-to-FEM steps and provide a specific procedural process that allows for the maintenance, restoration, and safety of historical heritage assets. The aim is to ensure the preservation of architectural heritage and original structural techniques, also ensuring the safety of users and passing on to future generations historical knowledge of the past.

These steps are only possible by encouraging collaboration and ensuring dialogue between various experts and various disciplines, favored by the creation of a common base model that leads to the formulation of a single language.

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References

1. *ISO 19650*; Organization of Information about Construction Works—Information Management Using Building Information Modelling—Part 1: Concepts and Principles. ISO: Geneva, Switzerland, 2018.
2. *UNI 11337-1:2017*; Edilizia e Opere di Ingegneria Civile—Gestione Digitale dei Processi Informativi Delle Costruzioni—Parte 1: Modelli, Elaborati e Oggetti Informativi per Prodotti e Processi. UNI: Milano, Italy, 2017.
3. D.lgs. No. 50/2016—Codice dei Contratti Pubblici. 16G00062. Available online: https://www.normattiva.it/uri-res/N2Ls?urn:nir:stato:decreto.legislativo:2016;50 (accessed on 5 January 2023).
4. Santini, S.; Borghese, V.; Micheli, M.; Orellana Paz, E. Sustainable Recovery of Architectural Heritage: The Experience of a Worksite School in San Salvador. *Sustainability* **2022**, *14*, 608. [CrossRef]
5. Ursini, A.; Grazzini, A.; Matrone, F.; Zerbinatti, M. From scan-to-BIM to a structural finite elements model of built heritage for dynamic simulation. *Autom. Constr.* **2022**, *142*, 104518. [CrossRef]
6. Wang, X.; Wu, C.; Bai, C. Generating the Regular Axis from Irregular Column Grids through Genetic Algorithm. *Appl. Sci.* **2022**, *12*, 2109. [CrossRef]
7. Pirchio, D.; Walsh, K.Q.; Kerr, E.; Giongo, I.; Giaretton, M.; Weldon, B.D.; Ciocci, L.; Sorrentino, L. Integrated framework to structurally model unreinforced masonry Italian medieval churches from photogrammetry to finite element model analysis through heritage building information modeling. *Eng. Struct.* **2021**, *241*, 112439. [CrossRef]
8. Brusaporci, S.; Trizio, I.; Ruggeri, G.; Maiezza, P.; Tata, A.; Giannangeli, A. AHBIM per l'analisi stratigrafica dell'architettura storica. *Restauro Archeol.* **2018**, *26*, 112–131. [CrossRef]
9. Barazzetti, L.; Banfi, F.; Brumana, R.; Gusmeroli, G.; Previtali, M.; Schiantarelli, G. Cloud-to-BIM-to-FEM: Structural simulation with accurate historic BIM from laser scans. *Simul. Model. Pract. Theory* **2015**, *57*, 71–87. [CrossRef]
10. Concultura, Inventario de Bienes Culturales Inmuebles—FIcha de Inventario de Inmuebles con Valor Cultural n. 1 y 2019. 2001. Available online: https://s3-aws-semana.s3.amazonaws.com/semana/upload/documents/Documento_426743_20150507.pdf (accessed on 5 January 2023).
11. Anderson, T. Politics of Central America. 1988. Available online: https://books.google.com.hk/books/about/Politics_in_Central_America.html?id=uar_iWVhSaIC&redir_esc=y (accessed on 5 January 2023).
12. Canas-Dinarte, C. El Salvador: Cronologia de una Tierra Danzarina. Available online: https://webserver2.ineter.gob.ni//geofisica/sis/com/Salvador2001/El_Diario_de_Hoy_de_EL_SALVADOR.htm (accessed on 5 January 2023).
13. Norma Técnica para Diseño por Sismo. El Salvador. 1994. Available online: https://www.eird.org/cd/acs/Espanol/EvalCodi/HablaEsp/Sismos/SALVecs.pdf (accessed on 5 January 2023).
14. Singh, S.K.; Gutierrez, C.; Arboleda, J. Peligro Sísmico en El Salvador Universidad Nacional Autónoma de México, Mexico. 1993. Available online: https://portafolio.snet.gob.sv/digitalizacion/pdf/spa/doc00016/doc00016.htm (accessed on 5 January 2023).
15. Bommer, J.; McQueen, C.; Salazar, W.; Scott, S.; Woo, G. A Case Study of the Spatial Distribution of Seismic Hazard (El Salvador). *Nat. Hazards* **1998**, *18*, 145–166. [CrossRef]
16. Bommer, J.J.; Udías, A.; Cepeda, J.M.; Hasbun, J.C.; Salazar, W.M.; Suárez, A.; Ambraseys, N.N.; Buforn, E.; Cortina, J.; Madariaga, R.; et al. A new digital accelerograph network for El Salvador. *Seismol. Res. Lett.* **1997**, *68*, 426–437. [CrossRef]
17. Ministero de Medio Ambiente. Dirección General de Observatorio de Amenazas y Recursos Naturales. Available online: https://snet.gob.sv/ver/sismologia/ (accessed on 5 January 2023).
18. *Photoscan*; Version 2021; Agisoft: St. Petersburg, Russia, 2021. Available online: https://www.agisoft.com/ (accessed on 9 December 2021).
19. *Recap*; Version 2021; Autodesk: San Rafael, CA, USA, 2021. Available online: www.autodesk.com (accessed on 9 December 2021).
20. Centofanti, M.; Brusaporci, S.; Maiezza, P. Tra "HistoricalBIM" ed "HeritageBIM": Building Information Modeling per la Documentazione dei beni Architettonici, in Parrinello S., Besana D., ReUSO—Contributi per la Documentazione, Conservazione e Recupero del Patrimonio Architettonico e per la Tutela Paesaggistica 2016. Available online: https://www.academia.edu/29499135/TRA_HISTORICAL_BIM_ED_HERITAGE_BIM_BUILDING_INFORMATION_MODELING_PER_LA_DOCUMENTAZIONE_DEI_BENI_ARCHITETTONICI (accessed on 5 January 2023).
21. *3Dstudio Max*; Version 2021; Autodesk: San Rafael, CA, USA, 2021. Available online: www.autodesk.com (accessed on 9 December 2021).
22. *Instant Meshes*; Version 2021; Institute of Visual Computing of ETH: Zurich, Switzerland. Available online: http://igl.ethz.ch/projects/instant-meshes/ (accessed on 9 December 2021).
23. *Autocad*; Version 2021; Autodesk: San Rafael, CA, USA, 2021. Available online: www.autodesk.com (accessed on 9 December 2021).
24. Vecco, V. A definition of cultural heritage: From the tangible to the intangible. *J. Cult. Herit.* **2010**, *11*, 321–324. [CrossRef]
25. Nieto-Julián, J.E.; Farratell, J.; Bouzas Cavada, M.; Moyano, J. Collaborative Workflow in an HBIM Project for the Restoration and Conservation of Cultural Heritage. *Int. J. Archit. Herit.* **2022**. [CrossRef]

26. Murphy, M.; McGovern, E.; Pavia, S. Historic Building Information Modeling—Adding Intelligence to Laser and Image based Surveys. In Proceedings of the 4th ISPRS International Workshop, Trento, Italy, 2–4 March 2011; Volume 38, p. 5.

27. Moyano, J.; Carreño, E.; Nieto-Julián, J.E.; Gil-Arizón, I.; Bruno, S. Systematic approach to generate Historical Building Information Modelling (HBIM) in architectural restoration project. *Autom. Constr.* **2022**, *143*, 104551. [CrossRef]

28. Macher, H.; Boudhaim, M.; Grussenmeyer, P.; Siroux, M.; Landes, T. Combination of thermal and geometric information for bim enrichment. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *42*, 719–725. [CrossRef]

29. Midas FEA NX. MIDAS Information Technology Co. 2021. Available online: www.midasstructure.com (accessed on 9 December 2021).

30. *Revit*; Version 2021; Autodesk: San Rafael, CA, USA, 2021. Available online: www.autodesk.com (accessed on 9 December 2021).

31. Lourenço, P.B.; Pereira, J.M. *Seismic Retrofitting Project: Recommendations for Advanced Modeling of Historic Earthen Sites*; Getty Conservation Institute: Los Angeles, CA, USA; TecMinho–University of Minho: Guimarães, Portugal, 2018.

32. Ministero de Medio Ambiente. Fases y Metodología para la Realizacion de Zonificación Ambiental (marn.gob.sv). Available online: http://rcc.marn.gob.sv/bitstream/handle/123456789/128/Acu%C3%ADferos%20de%20Santa%20Ana%2C%20Zapotit%C3%A1n%20y%20San%20Miguel%202015.pdf?sequence=1&isAllowed=y (accessed on 5 January 2023).

33. Ministero de Medio Ambiente. Mapa Geológico General de El Salvador. Available online: www.snet.gob.sv/Geologia/Sismologia/3mapageo.htm (accessed on 5 January 2023).