HBIM STRUCTURAL MODEL TO EVALUATE BUILDING EVOLUTION AND CONSTRUCTION HYPOTHESES: PRELIMINARY RESULTS

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ABSTRACT:

Historic Building Information Modelling (HBIM) is a technology that has proven to be very effective for the management, preservation, and maintenance of heritage buildings. HBIM allows a digital replica of the building, in which information can be stored, designs can be made, and future actions can be planned. To do this, it is obviously necessary to have a thorough knowledge of the building and its historical evolution. The HBIM model can therefore become the ideal place in which to develop and model construction hypotheses of building portions that no longer exist, or even record its development over time using different phases of work. Based on this context, the aim of this article is to use the HBIM approach for modelling different construction hypotheses and use the model to study the behaviour of different configurations with structural analysis. To do this, the case study of the church of San Michele Maggiore in Pavia was chosen, which in the 15th century underwent major restorations due to structural failures of the vaults of the central nave, which were replaced with the current cross vaults. In the literature there are different constructive hypotheses of the ancient vaults, which have been modelled in HBIM precisely to evaluate the different structural behaviours following the method presented. This article presents the historical analyses and geometric surveys that led to the HBIM modelling and the model itself. In the future, after careful selection of the most appropriate software, structural calculations will be made to study the structural behaviour of the building.

1. INTRODUCTION

Protect, enhance, conserve are key words contained in the Italian Code of Cultural Heritage and Landscape Legislative Decree No. 42/2004 on the subject of Italian historical heritage. From this legislation, it was understood the need to adopt a strategy to conduct a planned management of the existing building, the so-called planned conservation. Together with conservation there is also knowledge, which is necessary to preserve the historical value. The research conducted on San Michele Maggiore in Pavia was developed based on that premise. The most recent studies and restorations carried out on the building date back to the nineteenth and sixties, mainly of a historical nature. The need to deepen structural and architectural knowledge of the church was achieved by employing the Historic Building Information Modelling (HBIM) methodology (Murphy et al, 2009), a valuable tool for the built environment (Scala et al., 2022). Although the BIM process has reached a considerable level of maturity, several aspects related to the application of the method to existing structures through the scan-to-BIM process require further research; the need to find appropriate approaches to integrate, manage and store thematic information (Ferro et al., 2023). In addition to the design phase for conservation and restoration, the preliminary knowledge phase is also of paramount importance for structural restoration. The combination of critical survey (including geometric survey, study of materials and construction techniques, and cataloguing of the buckling and cracking model), stratigraphic analysis, and study of the building typology is optimal. In addition, in the context of the structural rehabilitation of historic buildings it is essential to have as in-depth knowledge as possible of the construction phases, the building techniques, the materials, the transformations, and the differences in height of the elements (Matteuzzi, 2017). Historical-critical analysis is of paramount importance in the broader context of structural safety assessment.

Given the mentioned context, it also becomes important to the knowledge of the building to have an adequate understanding of its evolutionary stages that brought it to its present form. Historical sources, previous geometric surveys, and expert opinions allow us to identify various building hypotheses, which can be modelled and later analysed through structural analyses. The purpose of this paper is to use the HBIM environment to define and model various building hypotheses for a portion of the church of San Michele Maggiore. The modeled hypotheses will then be used for structural analyses. The research work is currently underway, so preliminary results are presented here.

The article is organized as follows: Section 2 presents related works dealing with the modelling of stratigraphic units and constructive hypotheses in HBIM environment; Section 3 describes the workflow of the presented research; Section 4 presents the preliminary results and Section 5 discusses the conclusions and future developments of the research.

2. RELATED WORKS

In the literature, there are several studies that have addressed the issue of maintenance, restoration of historic buildings. In recent contributions, researchers have sought to simplify the procedures of designers and technicians, using the well-known Building Information Modeling systems for assessing building conditions to investigate the state of conservation and facilitate decision-making choices for maintenance (Yang et al., 2020).
From a state-of-the-art review of the HBIM methodology, more specific HBIM contributions for the archaeology of the built

environment and HBIM models aimed at structural analysis were selected. HBIM for archaeology are models that integrate stratigraphic and material knowledge, the various historical and evolutionary phases of the building. One of the first examples of the application of stratigraphic analysis to BIM in the architectural field is the Church of S. Maria di Scarica in Valle d'Intelvi (Brumana et al., 2013). The BIM model allows the representation of the "volumetric stratigraphy" by grouping the elements according to recognized or hypothesized construction phases. In the case of the HBIM of Castel Masegra, (Brumana et al., 2015), the model had the objective of representing the "volumetric stratigraphies" (the three-dimensional element contains stratigraphic data, diagnostic analyses and historical information) identified through the subdivision of the elements constituting the model according to the different construction phases.

In this paper the authors (Brusaporci et al., 2018) proposed BIM on the basis of the archaeological analysis of the buildings of the San Vittorino complex near L'Aquila. In particular, the study focused on the wall of the ancient church of San Michele Arcangelo to verify some building construction hypotheses. In this article the authors (Trizio et al., 2019) have created an HBIM for the church of S. Francesco in Rocca Calascio, near L'Aquila. Of particular importance was the modelling of the stratigraphic units. These were two methods for parametric modeling of stratigraphic units. In both cases, the parametric data of each entity was customized and updated with the data from the stratigraphic analysis. Another research group (Diara et al., 2020) published a study on the implementation of HBIM for archaeology of buildings through open-source software, such as FreeCAD, which combines CAD and BIM programs. The program was implemented on multiple levels: libraries, material database, and IFC classification. Several studies show early attempts to move construction archaeology into BIM.
According to the research conducted for the Tuscan Temple of Uni in Marzabotto (Garagnani et al., 2016), the authors state that the HBIM procedure has proven useful for the historical reconstruction of what no longer exists. The only known elements were excavation investigations of the surviving foundation structure of the temple and historical literature relating to the building tradition of the Etruscan Templars. The authors of this paper believe that the ArchaeoBIM information cataloguing process is a versatile and profitable approach for the documentation of archaeological heritage, as a complete knowledge management system, useful both for the consultation of the materials contained and for the more analytical study of the places. The research group (Pepe et al., 2020) proposes a workflow for the creation of 3D models for HBIM and structural analysis starting from an accurate point cloud survey, integrating the use of different software and plug-ins.

As far as structural models and analysis are concerned, the following scientific contributions are reported. In this research, the authors (Barazzetti et al., 2015) converted the HBIM model of Castel Masegra into a model for structural finite element simulation (BIM-to-FEM). Lastly, the authors in this contribution (Aita et al., 2023), through existing fragments of stone tiles from a temple at Tholos in Delphi, used two-dimensional calculation and structural analysis methods to hypothesize the structural typology of the roof that no longer exists, creating a support for the verification of the hypothetical reconstructions deduced by archaeologists.

3. METHODOLOGY

The purpose of the research presented in this paper is to develop and test a HBIM-based workflow to visualize, store, and assess different construction hypotheses for portions of the building that no longer exist to date. The chosen case study is the church of San Michele Maggiore in Pavia, so some steps of the method will be closely related to the chosen case study, but are intended to be generally replicable in other contexts as well.

The proposed method (summarised in Figure 1) involves an initial phase of knowledge of the building and its historical construction phases. To do this, an analysis of historical archives and all historical sources is necessary in order to define and understand the building's history. In addition to historical sources, interpretations and construction hypotheses proposed over time by scholars of recognised importance are also helpful for this purpose. In parallel with the historical analyses, it is necessary to develop a geometric survey, to be able to better define the current state of the building and to be able to compare it with what has been identified in the historical sources.

On the basis of the historical analyses and the geometric survey it is then possible to define construction hypotheses for parts of the building for which the evolution over time is uncertain. These construction hypotheses are developed in the HBIM environment, using as a basis the point clouds obtained from the survey and the data and drawings identified from the historical analyses. The HBIM model, modelled with the appropriate simplifications typical of a structural BIM model, then becomes the starting point for carrying out structural analyses. Structural analyses make it possible to study the behaviour and loads transmitted to the structures in the various changes that the building has undergone over time.

The method presented is part of an ongoing research, which will deal with the implementation of a historical BIM system for the church of San Michele Maggiore in Pavia, aimed at its knowledge, maintenance and conservation. At present, the different construction hypotheses have been modelled in HBIM, but the structural analyses have not yet been developed. Preliminary results will therefore be presented in the next section.

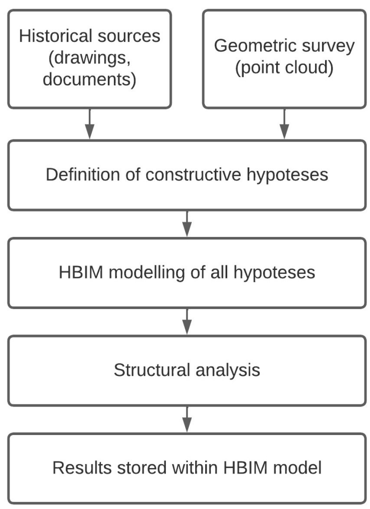

Figure 1. The method proposed to model and asses the various constructive hypothesis using a HBIM-oriented workflow.

4. PRELIMINARY RESULTS

4.1 Case study

The Basilica of San Michele Maggiore is one of the main churches in Pavia, considered the oldest in the city. Some historical and political facts are reported as proof of the significant importance of this monument. A first basilica dedicated to San Michele, which no longer exists, was built for the first time in Pavia during the Lombard period (probably in the sixth century). Historical documents attest that during the Frankish period many monarchs of the Italian kingdom were crowned in this church: Berengar I in 888, Hugh of Arles in 926, Berengar II together with his son Adalbert II in 950, Arduin of Ivrea in 1002, Henry II (later Holy Roman Emperor) in 1004. In this year a great fire devastated the city of Pavia, and this first ancient structure of San Michele was destroyed or heavily damaged. A historical event of great importance was the coronation of Frederick Barbarossa, which took place in the present church in 1155. In fact, the current church dates back to the end of the 11th and the beginning of the 12th century and was consecrated in 1132. The Basilica of San Michele was built in Romanesque style, and is unanimously considered one of the masterpieces of Lombard architecture of the period (Peroni, 1967). In the nineteenth century it was the subject of an important stylistic restoration, conducted by Carlo dall'Acqua, and of a series of graphic surveys elaborated by important foreign intellectuals such as historians and architects. The surveys produced in this period were mostly carried out by foreign researchers, due to how the interest of San Michele Maggiore crossed the Italian borders.

4.2 Hystorical analysis – Constructive hypothesis

The area of the church identified for the tests presented here is the ceiling of central nave. It was selected as a good case study for the following reasons: it underwent important transformations and it was the subject of numerous reliefs.
The most important work, as far as the ceiling of the nave is concerned, was the reconstruction of the vaults between 1488 and 1491 Following very serious damages, especially in the central vaults that become unsafe, the board of priests who manage the church decided to restore it. According to several historical studies the existing vaults were modified due to a structural problem. The current scheme includes four cross vaults with the addition of four additional columns, at the level of the matroneum, with two new arches through the main central nave for the imposition of the new cross vaults and additional external buttresses. The work was entrusted to Jacopo da Candia in 1488, an expert master builder, then passed on to his son Agostino. In August 1491 the works were definitively finished because the pictorial decorations were completed. According to the documents, a radical renovation was carried out only for the vaults of the main nave (Peroni, 1967). However, the previous state of the replaced vaults is not documented.

Numerous documents and especially graphic panels of the church date back to the nineteenth century and are still preserved and accessible today. Jean Baptiste Louis Georges Seroux d'Agincourt (1730-1814), French art historian, and Giovanni Voghera, Italian architect, represented in some panels the longitudinal section of the San Michele Maggiore with the four cross-vaulted bays of the central nave, the wooden framework of the attic and the connecting bridge of the matroneum, which no longer exists. Further surveys of the church of San Michele were subsequently drawn up by Fernand De Dartein dating back to 1840. He was a French engineer, university professor and scholar of medieval architecture. In his book *Étude sur l'architecture lombarde et sur les origines de l'architecture romano-bizantine* there are numerous graphic restitutions of some buildings in northern Italy, including San Michele Maggiore. Plan, sections, elevations and views represent the church from several points of view. Of fundamental importance is the plan of the church, the last surviving relief also used for the restorations carried out in the nineteenth century. In the longitudinal section of the basilica (Figure 2), De Dartein represents a reconstruction hypothesis of the ancient vaults of the central nave. In fact, he tries to graphically reconstruct the previous structure starting from the relief made from life at the time. It is clear that on the part of the French scholar there is an extreme precision and understanding in the drawings made (De Dartein, 1865-82).

In the 1960s, the Municipality of Pavia commissioned Professor Piero Sanpaolesi to restore the basilica, which carried out a chemical consolidation of the exteriors due to the state of decay of the sandstone constituting the church (Lombardini, 2020). In a published paper (Sanpaolesi, 1967), Sanpaolesi describes the primitive hypothesis of a domed roof of the central nave. He visited the attics of the basilica and saw the remains of the previous vaults, which the Da Candia demolished and replaced with the four crosses vaults. He saw the stumps of the ancient structures which, in his opinion, when viewing the brick equipment, he hypothesized were the remains of the pendentives on which the hypothetical domed vaults rested (Figure 3). The current vaults were so low as to blind all the side windows of the nave, windows that are now filled in and visible only from the outside and from the attic.

In the light of what is documented in the literature, these will be the configurations that will be taken into account in the HBIM modeling and in the subsequent structural analysis:

1. **Hypothesis 1**: construction system of two cross vaults in two bays of the main nave, hypothetical configuration prior to 1488., hypothesized by Fernand De Dartein (Figure 2).
2. **Hypothesis 2**: construction system of two domed vaults on pendentives in two bays of the central nave, hypothetical configuration prior to 1488, hypothesized by Piero Sanpaolesi (Figure 3).
3. **Current configuration**: four-span cross vaulted construction system with two arches and four additional pillars, configuration built between 1488-1491 by the Da Candia masters and currently existing (Figure 4).

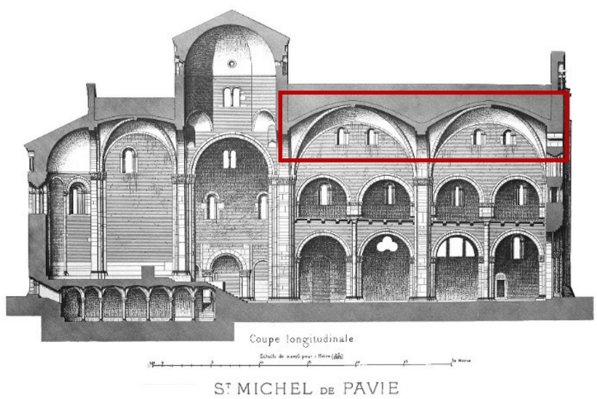

Figure 2. Construction hypothesis of the ancient vaults of the central nave made by Fernand de Dartein, 1865-82

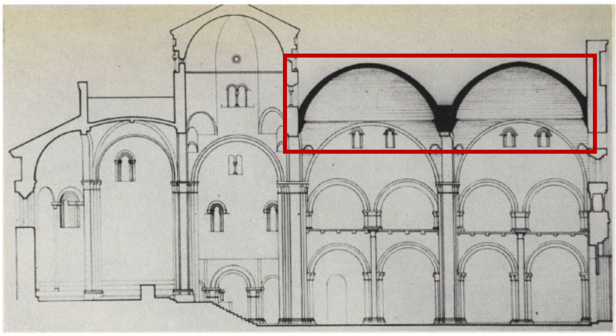

Figure 3. Construction hypothesis of the ancient vaults of the central nave made by Piero Sanpaolesi, 1967

4.3 Geometric survey

For the Basilica of San Michele in Pavia, an accurate geometric survey was carried out. The acquisition techniques used were laser scanners and photogrammetry both from the ground and from Unmanned Aerial System (UAS), with topographic support network. The survey involved internal and external surfaces, to document the actual state of the monument.

To support the integrated survey, a topographic frame network was created using a Total Station (Leica TS30). The topographic network was used for the acquisition of the detail points for the georeferencing of the TLS and photogrammetric data with Drone. These measurements were made for polar coordinates (directions and inclined distances) and their uncertainties are compatible with those of the framing network for the survey at the nominal scale 1:50.

The Leica RTC360 high-precision laser scanner was used to define the three-dimensional geometry of the Basilica. The set of laser scanner acquisitions suitably registered allowed the creation of a single 3D Geodatabase, from which all the information needed to generate traditional conventional two-dimensional representations was extracted. The set of appropriately registered TLS acquisitions constitutes a base from which all the necessary information was extracted to generate the HBIM structural model of the constructive hypoteses in Autodesk Revit. A total of 130 scans were made for interior, resulting in a total of 3,058 billion points.

For the top portions of the vaults, a photogrammetric survey was carried out using data acquired from the ground with a high-resolution camera. For the internal façades of the Basilica, in addition, the integration of photographic acquisition was made using the DJI Mavic 3 Cine UAS drone, in particular for the dome and transept. Starting from the photogrammetric model acquired, high-resolution digital orthophotos were obtained, compatible with the scale of 1:50 (pixel size on the object equal to 5mm).

Starting from the survey data acquired with the laser scanner and photogrammetry techniques, as described above, the vectorized two-dimensional drawings of the fundamental sections of the basilica were made (Figure 4): plans of the crypt and of the ground floor and of the apse area, plans of the vaults, longitudinal and transversal sections. All the section profiles have been integrated into the external parts by the TLS acquired data for the side parts and by drone for the upper parts of the roofs.

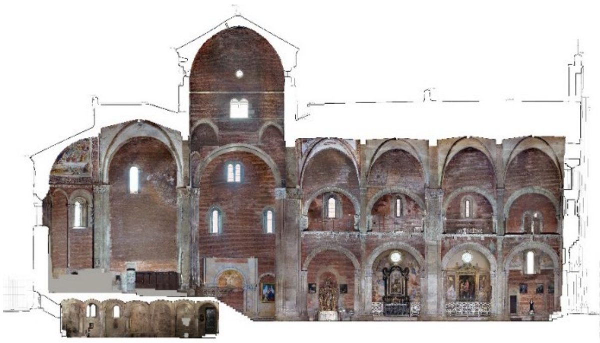

Figure 4. Longitudinal section vector restitution of the current state with orthophoto, made by Mantova Research Lab, 2023

4.4 Scan-to-BIM process

The data collected, both historical and geometric, make it possible to create a digital model aimed both at managing the multiple information and documentation present (historical, material, etc.) and at interpreting and representing what is still unknown and under investigation (technologies and stratifications of the different phases of intervention that led to the current layout of the church). Through the SCAN-to-BIM process (Brumana et al., 2017) it was possible to model the central nave of the church in the actual condition. Into the same HBIM model it was possible to model the different phases corresponding to the various historical evolutions of the building's construction.
This is certainly the most delicate and complex phase. With Autodesk Revit software, the point cloud obtained from the survey was imported and the HBIM model was created. The vaulted systems were generated through NURBS modeling (Banfi, 2019). Since these are elements with complex geometries and significant deformations, the 2D profiles of each vault were obtained and then interpolated to create the surfaces necessary to create accurate geometric models (Figure 5).

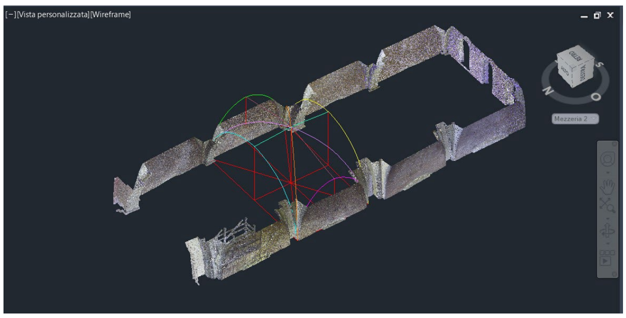

Figure 5. Extraction of the profiles from the point cloud of one of the four existing vaults, made by Da Candia masters.

Only the structural elements have been modelled, omitting the decorative elements, entablatures, frames and capitals, which are not essential for the purposes of structural analysis. Each element has been identified in Revit with the “structural” property (Figure 6).

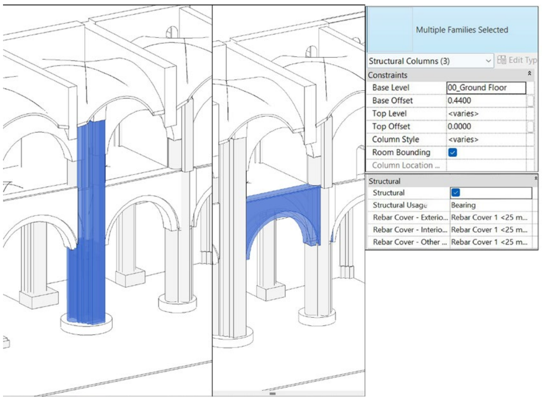

Figure 6. Elements modeled according to the "structural" property in Revit.

For the reconstruction of the hypothesized vaults existing in the literature, the known drawings of the two scholars have been recovered: the sections written by Fernand De Dartein and the sections reproduced by Piero Sanpaolesi. Through an overlapping and proportion of the existing reliefs with the vectorized two-dimensional drawings processed by our survey, the profiles of the hypothesized vaults were obtained and reconstructed, obtaining thicknesses and dimensions with the Autodesk AutoCAD software (Figure 7 and Figure 8). Using as a basis the reliefs of the two bays of the central nave and the six existing pillars on which the ancient vaults were developed, the skeleton of the geometry of the vaults was reconstructed and the three-dimensional model was created. The resulting models were then imported into Revit and the parametric vaults were created with the software's system families.
As far as the attic is concerned, no surveys and inspections have been carried out. The thickness of the current existing vaults, built by the Da Candia masters in the 15th century, have been deduced from a scientific article (Zamperini, 2014) dealing with the attic of the church of San Michele Maggiore and the wooden trusses.

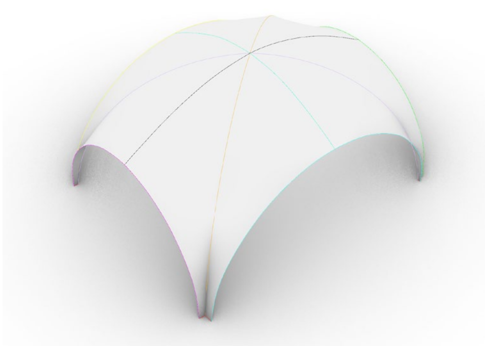

Figure 7. Extraction of the profiles and creation of the surface of the vault hypothesized by F. De Dartein

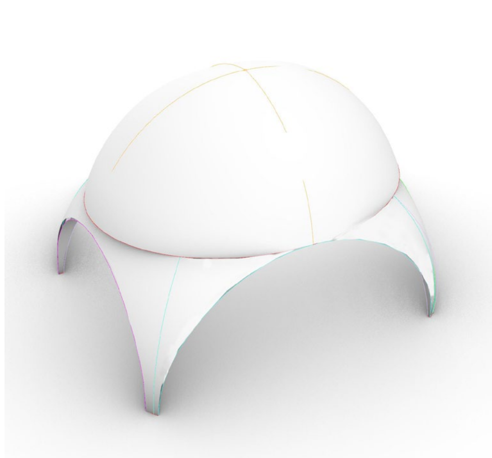

Figure 8. Extraction of the profiles and creation of the surfaces of the domed vault hypothesized by P. Sanpaolesi.

4.5 Creation of construction phases

Through the “phases” option of Revit, the different construction periods of the building known so far of the central nave of the basilica have been developed, useful for the purpose of maintenance and future interventions.
Before the 15th century structural restoration, the central nave of the basilica presumably consisted of two vaults. There is no certain information on their exact configuration and hypotheses exist in the literature at the moment. The work file, in this initial phase, has been set up with four construction phases currently known according to the research conducted: Original state 11th-12th century, De Dartein hypothesis pre 15th century, Sanpaolesi hypothesis pre 15th century, Costruzioni Da Candia 15th century (Figure 9). The construction assumptions were modeled according to the creation and demolition phases present in Revit. They appear as elements removed, in the phase of creation of the vaulted systems operated by the Da Candia masters (Figure 10). In the HBIM model they are therefore documented as elements that no longer exist, but through the different phases set in chronological order it is possible to visualize the different configurations over time of the vaulted ceiling of the central nave (Figure 11 and Figure 12). Therefore, according to the historical research carried out so far, each element is inserted in the corresponding temporal construction phase. The construction phases of the basilica will be implemented later by dating the rest of the complex through the historical research still in progress.

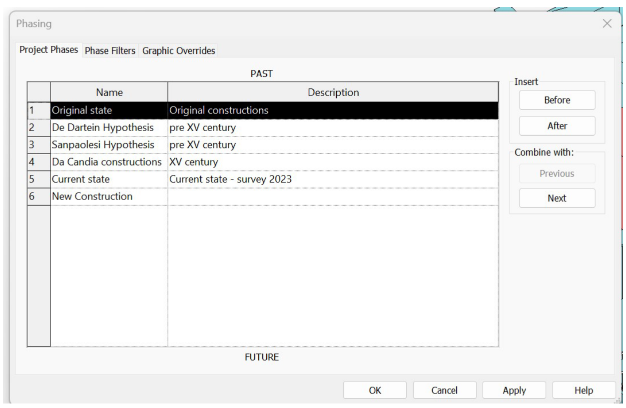

Figure 9. Creating “Phases” in Revit for the Center Nave.

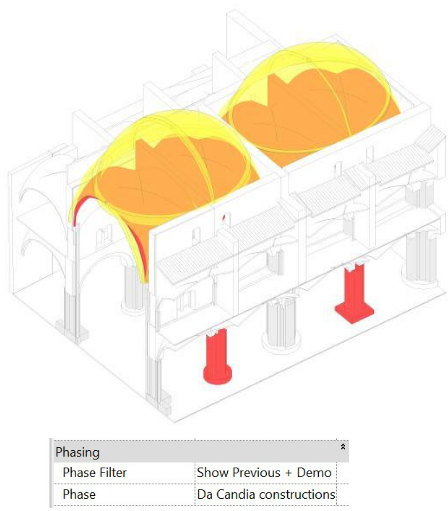

Figure 10. Comparative Phase: vaults hypothesized by Sanpaolesi highlighted as demolished and current vaults of the Da Candia highlighted as new construction.

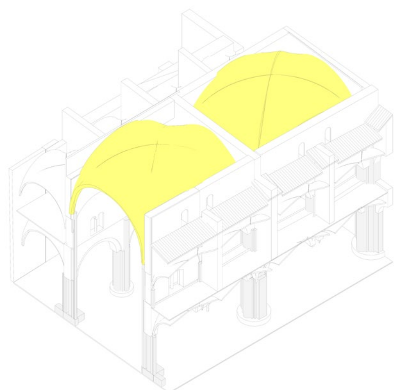

Figure 11. Hypothesis De Dartein phase: vaults hypothesized by De Dartein highlighted as demolished.

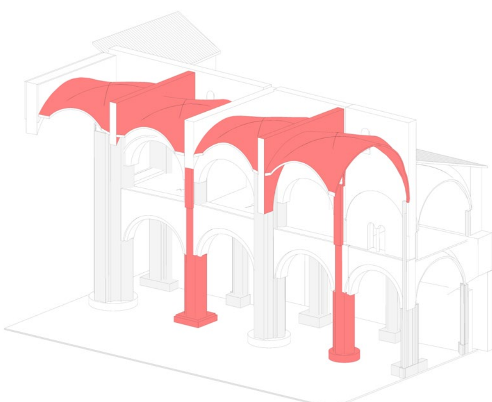

Figure 12. Axonometric cutaway of the construction phase Da Candia: existing vaults.

4.6 Structural analysis

This phase of work will be implemented at a later date. The method that will be followed through the support of an expert structural engineer is outlined below.

The research objective will be to use the HBIM model in a calculation software that will allow to obtain a structural analysis of the loads and forces acting on the vault-masonry-column system. This analysis will be applied to the central vault in the three construction configurations:
1- the four-cross vault system of the current state;
2- the hypothesis of the two cross vaults hypothesized by Fernand de Dartein;
3- the hypothesis of the two domes hypothesized by Piero Sanpaolesi.

Through the creation of specific parameters related to the different geometric configurations, the model will be implemented with additional information obtained from the structural analyses conducted.
In addition, we will try to study the structure as a whole and by macroelements through the decomposition into sub-models. Specific evaluations will be made for the vaults of the central nave and the vaults of the side aisles and women's galleries that show significant deformations. Further evaluations will be made on the behaviour of the hypothesized vaults, prior to the existing ones, demolished at the time due to structural failures.

5. DISCUSSIONS AND CONCLUSIONS

This article describes a method for obtaining an HBIM model that is functional to structural analysis. The results obtained show how the HBIM approach is useful for keeping track of all the construction phases of a historic building. In addition, by creating phases in Revit, it is also possible to document different construction configurations related to the building. In the HBIM model it is possible to represent the evolution of the building construction over time and through specific parameters this data is documented in the model. In addition to what is currently existing in view of architectural and structural restoration projects, it is useful to keep track of and document the ancient systems demolished and replaced, through a reconstruction that is based on the recovery of historical sources and documents in literature. The work done so far shows that the use of the HBIM model proves to be appropriate for documenting even hypothesized configurations, according to different historical phases, also keeping track of those that no longer exist. An HBIM model based on an accurate survey is a starting point for the definition of models for structural analysis. The next phase of this research will identify the most suitable way to be able to import the entire model, with all the specific complexities of the structure, into the most suitable calculation software according to the interoperability with the Autodesk Revit software in order to study the global and local structural behaviour.

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REFERENCES

Aita D., Beatini V., Garavaglia E., Paris V., Pizzigoni A., Sgambi L., The stone roof of the tholos of Athena Pronaia in

Delphi: structural hypotheses starting from fragments of marble tiles, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-M-2-2023 29th CIPA Symposium, 25–30 June 2023, Florence, Italy

Banfi F., HBIM generation: extending geometric primitives and BIM modelling tools for heritage structures and complex vaulted systems, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-2/W15, 2019 27th CIPA International Symposium "Documenting the past for a better future", 1–5 September 2019, Ávila, Spain

Barazzetti L., Brumana R., Banfi F., Lostaffa F., Piraino F., Previtali M., Oreni D., Roncoroni F., Villa L., BHIMM e Augmented Information: il rilievo per la conoscenza e la valorizzazione di Castel Masegra, Atti Asita, 2015

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, Simulation Modelling Practice and TheoryVolume 57, September 2015, Pages 71-87,https://doi.org/10.1016/j.simpat.2015.06.004

Brumana R., Della Torre S., Oreni O., Previtali M., Cantini L., Barazzetti L., Franchi A., Banfi F., HBIM challenge among the paradigm of complexity, tools and preservation: the Basilica di Collemaggio 8 years after the earthquake (L'Aquila), 26th International CIPA Symposium 2017, 28 August-01 September 2017, Ottawa, Canada

Brumana R., Oreni D., Raimondi A., Georgopoulos A., Bregianni A., From survey to HBIM for documentation and management of built heritage: The case study of St. Maria in Scaria d'Intelvi, Digital Heritage International Congress 2013, Marseille, France, October 2013

Bruno N., Roncella R., A restoration oriented HBIM system for cultural heritage documentation: the case study of Parma Cathedral, ISPRS TC II Mid.term Symposium Riva del Garda, Italy, June 2018

Brusaporci S., Ruggeri G., Maiezza P., Tata A., Trizio I., Giannangeli A., AHBIM per l'analisi stratigrafica dell'architettura storica, Restauro Archeologico, 26(1), 112–131, July 2018

Code of Cultural Heritage and Landscape (Legislative Decree 42/2004). Available online: https://www.gazzettaufficiale.it/anteprima/codici/beniCulturali

De Dartein F., Étude sur l'architecture lombarde et sur les origines de l'architecture romano-bizantine. Dunod, Parigi, 1865-82 – graphic tables

Diara F., Rinaudo F., Building archaeology documentation and analysis through open source HBIM solutions via NURBS modelling, XXIV ISPRS Congress 2020

Ferro A., Lo Brutto M., Ventimiglia G. M., A Scan-to-BIM process for the monitoring and conservation of the architectural heritage: integration of thematic information in a HBIM model, CIPA Florence, June 2023

Garagnani S., Gaucci A., Govi E., ArchaeoBIM: dallo scavo al Building Information Modeling di una struttura sepolta. Il caso del tempio tuscanico di Uni a Marzabotto, vol. Archeologia e Calcolatori 27, pp. 251-270, 2016

Garagnani S., Govi E., Gaucci A., Archaeobim: Dallo scavo al building information modeling di una struttura sepolta. Il caso del tempio tuscanico di Uni a Marzabotto, January 2016

Garcia-Valldecabres J., Galliano-Garrigos A., Cortes Meseguer L., Lopez Gonzales M. C., HBIM work methodology applied to preventive maintenance: a state-of-the-art review, WIT Transactions on The Built Environment, vol.205 157-169, 2022

Lombardini N., Il restauro della facciata della basilica di San Michele Maggiore a Pavia e l'opera di Pietro Sanpaolesi. Aracne editrice, Canterano (RM), 2020

Matteuzzi E., San Biagio di Cerbara in Città di Castello – miglioramento sismico e restauro strutturale, Master Thesis 29th May 2017.

Murphy, M.; McGovern, E.; Pavia, S. Historic Building Information Modeling (HBIM). Struct. Surv. 2009

Pepe M., Costantino D., Garofalo A. R., An Efficient Pipeline to Obtain 3D Model for HBIM and Structural Analysis Purposes from 3D Point Clouds, February 2020, Applied Sciences 10(4):1235, DOI: 10.3390/app10041235

Peroni A., San Michele di Pavia. Cariplo, Milano, 1967

Sanpaolesi P., L'antica struttura del S. Michele Maggiore di Pavia, Source: Arte Lombarda, Second Semester 1967, Vol12, N. 2, pp. 11-22, published by: Vita e Pensiero – Pubblicazioni dell'università Cattolica del Sacro Cuore.

Scala B., Fazion B., Fregonese L., Gualerzi G., Geomatics and conservations: parameterization of unique and repeat elementes, Intrecci, International Journal of Architectural Conservation and Restoration, Sira ed., year I (2022) n.2

Seroux d'Agincourt J.B.L.G., Histoire de l'art par les monumens depuis sa décadence au IV ᵉsiècle jusqu'à son renouvellement au XVIe, vol. 1. Treuttel e Würtz, Parigi, 1823 - graphic tables

Trizio I., Salvini F., Giannangeli A., Boccabella R., Petrucci G., The archaeological analysis of masonry for the restoration project in HBIM, ISPRS Congress 2019, Bergamo, February 2019

Voghera G., Antichità pavesi pubblicate dall'architetto Giovanni Voghera. Bizzoni, Pavia, 1825-28 – graphic tables

Yang X., Grussenmeyer P., Joehl M., Macher H., Murtiyoso A., Landes T., Review of built heritage modelling: Integration of HBIM and other information techniques, Journal of cultural Heritage 2020, May 2020

Zamperini E., The timber roof of the central nave in the Basilica of San Michele in Pavia, SAH2014 9th International Conference on Structural Analysis of Historical Constructions, Mexico City, 14-17 October 2014