# Usability and Interoperability of an Accurate HBIM Architectural Model for Structural Analysis

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## Abstract

This contribution proposes a multidisciplinary approach to support AEC professionals, such as architects, restorers and structural engineers, in performing structural assessments of historic masonry buildings from a digital model. By integrating advanced 3D modeling tools with historical knowledge and technical data, HBIM enables a detailed and accurate digital representation of historic buildings. Thus, an accurate HBIM model with complex geometric configuration can be used for structural assessment. Currently, public and private administrations in Italy are requesting seismic assessments and structural consolidation of existing buildings. This type of analysis requires appropriate digital models complete with a critical historical building survey describing the transformations it has undergone over time and the construction techniques adopted. The proposed methodology will be tested on a structural element of an Italian basilica of historical-architectural relevance: a pillar of the nave of San Michele Maggiore in Pavia. This research will describe the processes and methods used to use an accurate HBIM model with construction technique in structural analysis software. Digitization of the historical-critical survey using HBIM methodology for cultural heritage is a valuable knowledge tool useful for future structural analysis and consolidation and improvement interventions.

## 1. Introduction

### 1.1 Background

Studying, preserving, and managing Cultural Heritage (CH) is often much more complex than working on a new building due to historical and cultural aspects involved. Historical heritage information is often limited, fragmented, or characterized by a high degree of uncertainty, which greatly complicates the process of producing accurate documentation of existing structures. It is therefore critical to adopt efficient technologies to process and manage the information associated with a historic building, such as Historic Building Information Modeling (Murphy et al., 2009). HBIM is a widely established methodology that extends traditional Building Information Modeling (BIM) to the preservation, management, and analysis of heritage structures. Over the past decade, HBIM research has focused on three key aspects: (i) data acquisition processes and modeling techniques, (ii) the use of HBIM for building management, and (iii) conducting structural condition analysis within HBIM environments (Lovell et al., 2023). Nowadays, the market offers the possibility of integrating BIM software with special packages designed specifically for finite element analysis (FEA), but the main limitation lies in the reduced ability of these plugins to interpret geometric complexity, usually typical of buildings of historical interest (Barazzetti et al., 2015). Although the scan-to-BIM methodology is increasingly used, problems remain in the parametric three-dimensional modeling of complex architectural elements and, consequently, this complicates its use for structural analysis (Avila et al., 2024).

### 1.2 Research question

Modelling the structures of historic buildings is a complex activity that requires the integration of multidisciplinary knowledge related to the monument, including both the field of engineering and architecture. Despite the results obtained with the application of the HBIM method, challenges remain, particularly in refining data acquisition techniques, refining modeling accuracy, and adapting methodologies to meet the complex demands of historical structures (Penjor et al., 2024). In structural discipline it is essential that the final model is reliable and accurate but simplified enough to avoid unnecessary increases in computational costs (Penjor et al., 2024). This context shows the need to improve the interoperability of models and data, establish standardized protocols and improve structural analysis capabilities. They are essential steps for HBIM to become a universally practical and powerful resource in heritage conservation (Avila et al., 2024).

### 1.3 Related works

From the review of the state of the art on the HBIM methodology, some relevant contributions on the use of an accurate HBIM model for structural analysis have been selected. A first approach to converting BIM models of existing buildings for numerical simulations was tested in 2015. The researchers (Barazzetti et al., 2015) have developed the accurate BIM of a historic building for structural simulation, encountering interoperability problems between the software and making some model correction operations simplifying the complex architectural elements. In another contribution the researchers (Pepe et al., 2020) have identified a workflow to build digital models that can be used in HBIM and FEM environments. Starting from point cloud modelling, the researchers built a model in the Rhinoceros software that can be exported to BIM and calculation software, using ACIS (*.sat) as an export format. Another contribution (Ursini et al., 2022) addressed the interoperability problems of models created in BIM software for calculation software, using parametric models and mesh models, finding problems for complex architectural elements.

Some contributions studying the geometric and material composition of the elements of a historic building through the HBIM model were also selected. A significant contribution is the HBIM of the church of Collemaggio in L'Aquila (Brumana et al., 2018). Through the diagnostic investigation conducted,


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the researchers obtained the exact geometry of a column, modelling the individual stones, but it was not possible to investigate its core. The thickness of the column has been assumed. Other contributions present an HBIM workflow to support the conservation and maintenance activities of historic buildings, with a focus on the simulation of building construction systems (Maiezza, 2019) (Martinelli et al., 2022). A preliminary study on the digital model of the pillar of San Michele Maggiore was carried out in a master thesis, through the Scan-to-BIM process, modelling the pillar in a simplified way, only the external surface (Degasperi, 2015).

In this contribution, the authors will investigate the interoperability of a digital model created in a BIM environment, accurate at a historical, informative and geometric level whose geometry can be suitable for finite element analysis.

The following paper is organized as follows: Section 2 describes the proposed methodology, case study and analysis of the construction technique of the pillar hypothesized by scientific literature; Section 3 “Results” describes the results obtained: the structural HBIM model implemented; the interoperability of the model in the Midas calculation software, the finite element model and the linear static analysis conducted to test the model. Section 4 “Conclusions” discusses the results obtained and future developments of the research.

## 2. Main body

### 2.1 Methodology

In this paper we aim to test a workflow for developing an accurate and informationally and geometrically efficient HBIM model that can be used directly in computational software, working on interoperability for structural analysis. The composite pillar with a larger section was chosen as a case study (Fig.1) for the following reasons: i) it is of fundamental importance in the statics of the building for the structural function it performs; ii) currently, there are no studies on the construction techniques and stratigraphy of which it is composed; (iii) we want to test the analysis on three-dimensional elements with different modeled materials.

Figure 1. View from south aisle of central nave pillars. In the foreground the pillar under study. San Michele Maggiore, Pavia, Italy.

The proposed methodology is divided into three phases (Fig.2):

- Knowledge phase. It deals with the integrated survey, performed using laser scanning, drone photogrammetry and a topographic network. The construction technique of the pilar is investigated through the existing literature.
- Development phase. It deals with the integration of the survey and historical sources for the creation of the structural HBIM model with Scan-to-BIM process The model will be exported and imported into a calculation software to test interoperability.
- Analysis phase. The structural HBIM model will be tested with structural analysis.

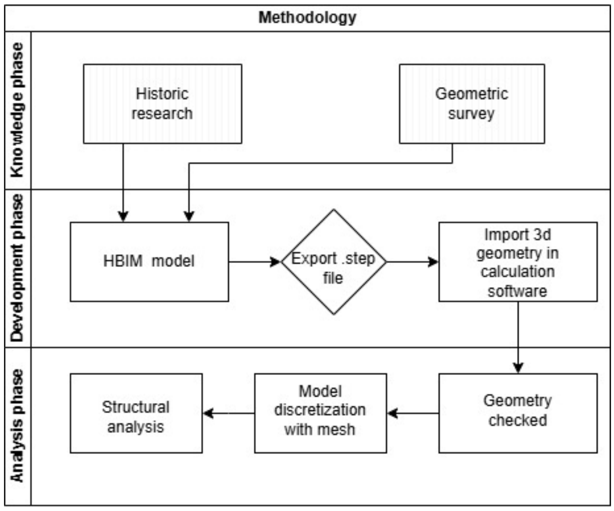


Figure 2. Proposed methodology workflow.

### 2.2 Case study

The basilica of San Michele Maggiore in Pavia, located in Lombardy, Italy, was chosen as a case study. It is one of the main basilicas in the city of Pavia and it is considered one of the oldest. The structural element chosen to test the proposed methodology is a Romanesque composite pillar of the central nave. The central nave is composed of eight pillars: four major sections, and four of minor section (Fig. 3).
The exact date of construction is not certain, but many scholars lean towards the period between the eleventh and twelfth centuries (de Dartein, 1865-82). The Basilica of San Michele Maggiore was built in the Lombard Romanesque style (Peroni, 1967). It diverges from other medieval churches in the city by the extensive use of sandstone for exteriors and decorations. In the fifteenth century it underwent important structural changes. According to existing scientific literature, the central nave had two cross vaults, which were later replaced with four cross vaults due to structural problems. Additional pillars were then added that were integrated into the existing structure (Peroni, 1967). Over the centuries, the basilica underwent numerous and remarkable interventions.

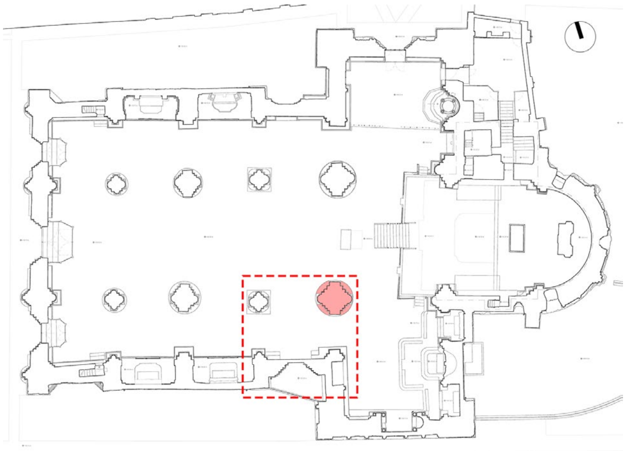

Figure 3. Ground floor plan of basilica San Michele Maggiore in Pavia. In red the pillar under study. The hatched box indicates the bay of HBIM model (Fig.6).

### 2.3 Analysis of construction techniques

Due to the unavailability of diagnostic surveys on the basilica of San Michele Maggiore, significant texts and contributions on the basilica were consulted for the study of Romanesque building techniques. For the study of Romanesque construction techniques, architectural treatises and books concerning San Michele Maggiore have been consulted. Treatises from the medieval period, treatises from subsequent periods and contributions from those who assisted or carried out the main restoration work of the basilica of San Michele were checked out.

Firstly, an important contribution on the construction methods of the Medieval era, the notebook of Villard de Honnecourt, was consulted. Graphic plate no. 63 (Erlande-Brandenburgn, 1987) documents construction details of pillars and stones cutting for the cathedral of Reims (Figure 4). Villard graphically indicates what the joints of the pillars should look like. Note the horizontal section of a pillar: stone ashlars assembled and joined by joints. The author Trogu Rohrich (Trogu Rohrich, 2003) collects in her book “Le tecniche costruttive nei trattati di architettura” the different construction techniques in architectural treatises. In the paragraph of the book, "Columns and pillars", she cites some of the greatest Italian treatise writers who have documented the methods of construction of columns, reported below. Leon Battista Alberti, describing the technique of the ancients, says that "the columns were fixed to the bases with iron pins, secured with lead, which were inserted into the cavity made at the base of the column. For this work, stones were used that were still rough, of which only the ends had been modeled". Vincenzo Scamozzi, about stone columns, describes the composition in ashlars arranged longitudinally and transversely, rounded and well adhering to each other and with the base and top of the element. Sebastiano Serlio highlights the importance of the connection with the masonry through a ligament to be made with stones common to the two structures.

Another fundamental contribution to the knowledge of the basilica of San Michele Maggiore was made by Fernand de Dartein, a French scholar. In his treatise (de Dartein, 1865-82) he describes the basilica with numerous graphic plates made on site during his trip to Italy. He was a spectator of the great restorations carried out in the nineteenth century by the engineer Carlo Dell'Acqua (Dell’Acqua, 1875). He describes the structure of the masonry of San Michele Maggiore: "the walls of the building consist of an internal core in sack casting and stone (sandstone) or brick cladding. The wall of the bag is made up of large, rounded stones, firmly bound together by a very hard hydraulic mortar. The most accurate masonry of the walls is done in the manner of the lining and, judging by the structure revealed by the recent drilling of a door in the north transept, it must be bound to the sack wall only by the adhesion of the mortar*”*.

Lastly, Paolo Piva in his book “Le cattedrali lombarde" describes two churches that no longer exist in Pavia, contemporary with San Michele Maggiore, the churches of S. Stefano and S. Maria (Piva, 1990). They were built according to the same architectural style, of which some parts have survived today (Figure 4). In particular, the surviving lower part of a pillar of the church of S. Maria is noteworthy. It is composed of stone ashlars externally and internally a core filled with mortar and bricks.

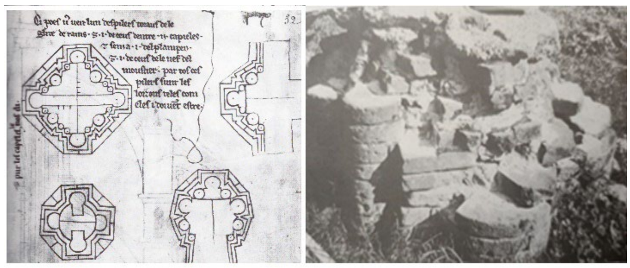

Figure 4. A portion of the graphic plate by V. de Honnecourt, pillar of Reims Cathedral, left side; surviving lower part of a pillar of the Romanesque church of S. Maria in Pavia. Source P. Piva “Le cattedrali lombarde”, right side.

### 2.4 Geometric survey

In view of a complete 360° knowledge of cultural heritage, it is necessary, as a preliminary step, to understand the spaces, volumes, geometries and details of the artefact. To achieve this, today's technology offers extremely satisfactory survey techniques: laser scanner surveying and photogrammetry. These techniques are widely used in the restitution of existing buildings. Mainly for the creation of a three-dimensional model, digital data, called point cloud, is first generated by laser-scanner or photogrammetry methodology.
For the Basilica of San Michele Maggiore in Pavia, an accurate geometric survey was carried out. The acquisition techniques used were laser scanner (TLS) and photogrammetry both from the ground and from the Unmanned Aerial System (UAS), with topographic support network. The survey involved internal and external surfaces, to document the current state of the monument. 130 scans were obtained for the interior, for a total of 3.058 billion points. The survey data obtained allow the graphic rendering of the building at the nominal scale of detail 1:50. The set of appropriately recorded laser scanner acquisitions allowed the creation of a single 3D Geodatabase, from which all the information necessary to generate traditional conventional two- dimensional representations was extracted. The set of properly recorded TLS captures provides a basis from which all the information needed to generate the HBIM model with Autodesk Revit software has been extracted. (Fazion et al., 2024).

### 2.5 Scan-to-BIM process: HBIM model

From what has been investigated in the existing scientific literature, two possible configurations of the construction


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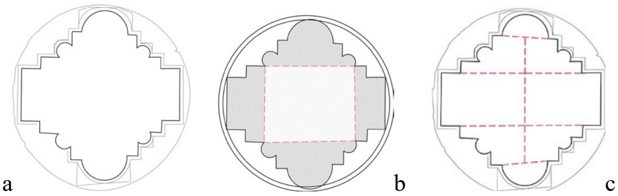
system of the pillar have been evaluated: i) the construction technique represented by Villard de Honnecourt, stone ashlars cut, shaped and hooked, ii) sandstone ashlars with a filling core inside consisting in brick and mortar (Figure 5).
In this contribution we will test the configuration of type (b).



a b c

Figure 5. Geometric study of the pillar. Configuration a): survey of the current state; second configuration b): hypothesis with external stone ashlars and internal brick core; third configuration c): hypothesis with hooked stone blocks.

The geometric survey, conducted using laser scanning and photogrammetric techniques, enabled the generation of a detailed point cloud of the building.
The hypothesis of the building technique investigated was modeled in the BIM environment. The geometric survey, conducted by laser scanning and photogrammetric techniques, allowed the generation of a detailed point cloud of the building. The collected data, both historical and geometric, allow for the creation of a digital model aimed both at the management of the multiple information and documentation present (historical, materials, etc.) and at the interpretation and representation of what is still unknown and under investigation. Through the Scan-to-BIM process (Brumana et al., 2018) the south bay of the basilica was modeled (Fig.6). The basilica has a total length of about 55 m, a maximum width of 39 m and in the naves of about 29 m, and a nave height of 18.40 m. The pillar object of study has a height of about 13.50 meters with a cross section of 3.23x3.42 meters. The outer stone face, inner core and capitals were modeled separately through the Revit program families under the pillar category. The inner core and stone face were modeled as a parametric family (Figure 4), capable of changing geometric parameters as needed and being able to accommodate the nonstandard configuration typical of the existing historic heritage. Various simplifications were adopted for the non-structural elements. The decorative profiles of the pillar present at the base were simplified and regularized, stone wear, ashlar displacements and inclinations of the pillar with respect to a vertical axis were not considered. The decorative part of the capital was not modeled.
To verify the accuracy of the geometry modeled with the point cloud, we used the Autodesk Point Layout plug-in within Revit. Through the Cloud Analysis tool, it is possible to select the cloud and the surfaces of the model, generating a colour image with a metric scale that highlights the distances between the cloud and the geometry (Fig.7).

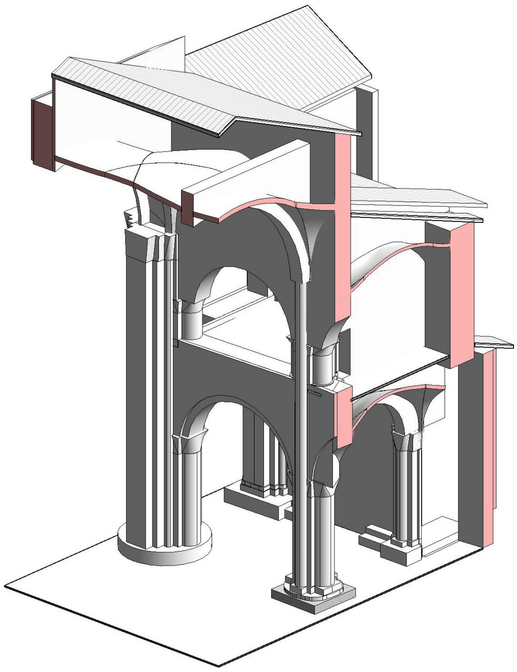


Figure 6. HBIM model of the south bay. Axonometric view from the nave with the pillar object of study.

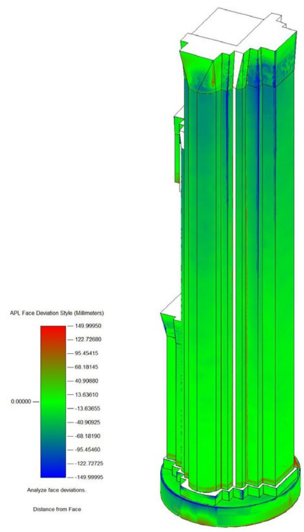


Figure 7. Model validation through the plug-in in Autodesk Revit Point Layout. The red and blue areas correspond to the approximations made in the modelling, degraded material at the base and off-axis tilt of the pillar.

### 2.6 Data storage

This phase of work involves the informative implementation of architectural elements. Once the modeling is completed, each modeled element contains geometric information about the materials. Parameters such as: length, width, height, volume and surface area are associated with each element. The exact material and actual texture composing the object is applied. The ashlars and inner core have been classified as “*SMM_material*”, where “*SMM”* means San Michele Maggiore. In “material” the type of material of the modeled element is included, e.g., sandstone, brick, cobblestone, and mixed mortar. This information, digitized within the model, is accessible and shared with the different professionals in the AEC (Architecture, Engineering and Construction) sector. The mechanical parameters of the materials have been taken from Italian regulation NTC2018.

## 2.7 Interoperability

To test the interoperability of the HBIM model, we decided to perform the structural analysis on a pillar of the nave with the structural calculation software Midas Fea and Midas Gen.
It is known from literature how the interoperability of a BIM model of a historic building is a problem and a challenge. The IFC format does not meet the complexity of an HBIM model, and in addition, the use of some plug-ins such as “Link Revit-Midas” create challenges in exporting complex geometries.

One option is 3D export files such as .step, .igs, .sat, and .stl files. These are standard formats for exchanging computer-aided design (CAD) data between different systems and applications and allow the transfer of 2D and 3D graphical information, such as wireframes, solid models. STEP files are compatible with many CAD tools and software, so they can be shared and modified easily. They are accurate and use a mathematical representation of curves, known as NURBS, to store data accurately. They can read and save complete 3D models. A STEP file can be exported directly from Autodesk Revit without having to export a .dxf and convert it to a format recognizable by calculation software.

To test the proposed methodology, we used Midas Fea software, which allows importing some types of three-dimensional files from other software, including the STEP format. When exporting a STEP file (.step or .stp), the unit of measurement of the model (e.g., in meters) is not recognized correctly. The STEP format supports units, but not all software interprets them correctly or respects them when importing. In Autodesk Revit it is possible to choose the export unit of measure for STEP files, while Midas Fea does not automatically interpret or convert units, expecting input consistent with its working unit. Even if the model is set in meters, STEP file often exports geometries in millimeters, without clearly specifying file’s unit. Midas Fea interprets the numbers in the STEP file as being in millimeters, without verifying the units specified in the file. To overcome this problem, the model was saved from Revit in STEP format with units in millimeters. It was then imported into Midas Fea by selecting the import unit of measure in mm, maintaining the consistency of the measurement unit.

## 2.8 FEM model

Midas Fea software allows import of the three-dimensional model and discretization of the geometry. Having successfully imported the geometry into the Midas Fea software, the geometry is checked. Through Boolean operations the surfaces in contact with each other are connected. For the FEM model to be functional, there must be a perfect fit between the surfaces. Once the geometry has been verified, we proceed to assign the material to the different three-dimensional elements, distinguishing the core from the outer facades, and discretize the geometry. To be correct, a mesh must all be connected to each other. Small variations in thickness in the geometry can create singularity points in the mesh, and numerical analysis would fail. A 10 cm tetrahedral mesh was created, and each node matched the other without further modification or adjustment of the mesh.

## 2.9 Linear static analysis

Once the model was discretized and the meshing checked, the model was imported into Midas Gen to solve a linear static analysis (NTC2018). Figures 8-9 represent the geometrical model and the finite element discretization adopted to analyse the structural behaviour of the masonry pillar. It consists of 88,049 nodes and 470,369 four-nodes tetrahedral elements. Linear elastic analyses have been performed. The top section is loaded by a parameterized uniform pressure distribution of 1.0MPa, representing the load transmitted to the pillar by the masonry arches supported by this element. All nodes belonging to the base section are fully restrained. The different colours represent the different solid element forming the pillar: the external portion made by regular stone (with modulus of elasticity equal to 2,000MPa) and the interior core (grey colour) made by normal brick, characterized by a lower modulus of elasticity (1,000MPa).

Figure 10a represents the distribution of the normal vertical component of the stress tensor, along a section taken at about 2.5m from the base section. It can be clearly observed that there is a stress concentration at the left part of the section for two reasons: i) the stiffer material of the external stone layer “attracts” a higher stress; ii) the geometrical configuration of the pillar is such that the constant normal pressure distribution, applied at the top section, causes an additional bending moment into the pillar with an increasing compressive stress in that portion (Figure 10b).

A precise finite element discretization of the pillar, able to distinguish among the different portions and the corresponding materials properties, allowed a rigorous evaluation of the stress state occurring into the material due to the applied load. In particular, the analysis evidenced a stress migration toward the external part of the pillar characterized by a stiffer material.

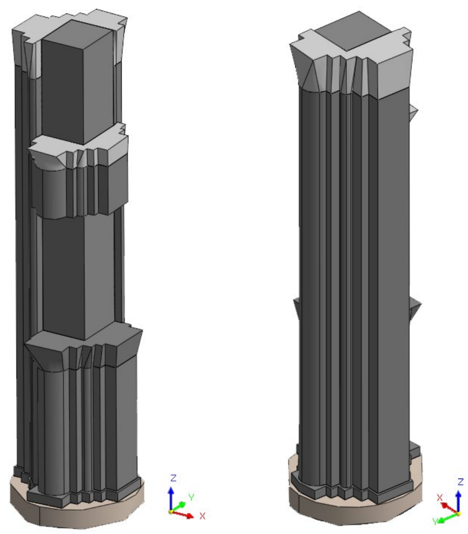


Figure 8. Geometrical model in software Midas Fea

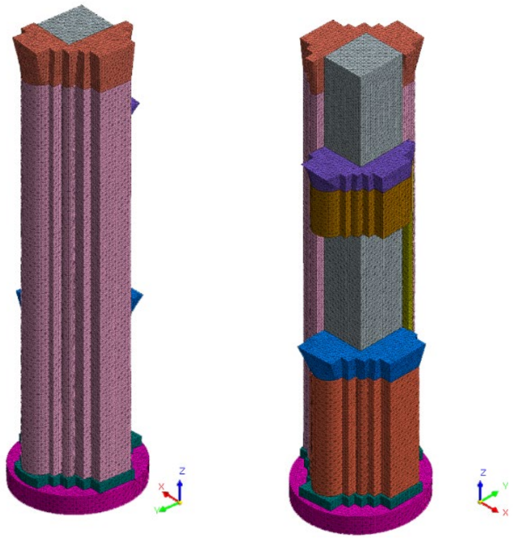


Figure 9. Finite element discretization of the masonry pillar.

a)

b)

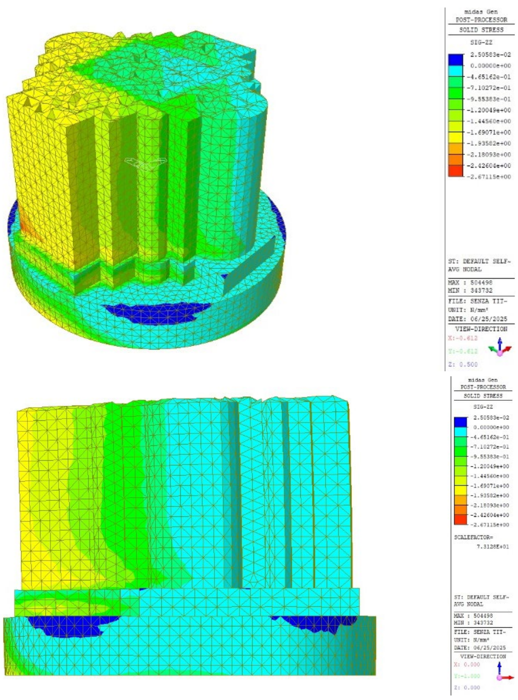


Figure 10. Normal vertical stress (SZZ) distribution: (a) 3D view; (b) elevation view.

## 3. Conclusions

The research carried out in this paper describes a multidisciplinary method that starts from the cognitive investigation of historical structures, through digitization using HBIM methodology, reaching a structural simulation of the model itself. For possible future developments in the knowledge of pillar stratigraphy, this model is optimal, as it will be possible to update it according to new discoveries and investigations, thanks to the modeled parametric elements.

The results obtained from the structural analysis highlight the importance of an accurate geometric and material survey of the structural element under consideration. This proposed workflow is configured as a fundamental path to carry out targeted projects of consolidation and structural improvement, respecting the uniqueness of the historic building.

This methodology lends itself to be a valuable support for AEC professionals. Architects, restorers and structural engineers can investigate all construction phases within a digital model. They can visualize the stratigraphic components of an architectural and structural element and obtain technical information about the materials. Specifically, structural engineers can find support in adopting an HBIM model with construction techniques to design targeted consolidation and structural improvement interventions.

### 3.1 Future works

The method presented is part of an ongoing research that will involve the study and digitization of the basilica San Michele Maggiore. In the future, the method will be tested on a bay and section of the basilica, investigating the iteration between complex structures such as vaults-arches-pillars-walls.
We will use the mechanical and physical parameters of the sandstone of San Michele Maggiore found in archival documents to conduct further structural analysis.
Finally, further tests will be conducted with the different configurations researched in the literature and hypothesized.

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