Reverse Engineering for the Structural Analysis of Heritage Constructions

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Reverse Engineering Workflows for the Structural Assessment of Historical Buildings

Angelo Massafra[a]*, Davide Prati[b] and Riccardo Gulli[a]

[a]*Department of Architecture (DA), Alma Mater Studiorum University of Bologna, Bologna, Italy;*

[b]*Department of Engineering and Applied Science (DISA), Università degli Studi di Bergamo, Bergamo, Italy*

* Viale del Risorgimento 2, Bologna, Italy, 40136, angelo.massafra2@unibo.it , +39 051 2093155, ORC-ID: https://orcid.org/0000-0002-3642-4660, LinkedIn: https://www.linkedin.com/in/angelo-massafra-727983193/?originalSubdomain=it

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Supported by advancements in 3D scanning and parametric modeling tools within the architecture, engineering, and construction sectors, reverse engineering processes for cultural heritage (CH) have recently gained popularity. While many studies have focused on simple 3D reconstructions to create virtual environments, a specialized subarea of this research field has targeted more specific digitization objectives, including, among many, structural analysis of building components. This emerging field has not yet been systematically developed due to the intrinsic challenges associated with CH. Within this context, this paper proposes and describes a reverse engineering-based method that utilizes terrestrial laser scanning and visual programming (VP) to analyze displacements and deformations that occurred over time in historical masonry buildings and applied it to the timber trusses, masonry facades, and columns of two selected Italian case study buildings. This method allows for comparing the surveyed condition of these components, considered the "deformed state", with their ideal configuration, reconstructed using VP algorithms, considered the "original state". The outcomes of this comparison facilitate the investigation of the components' structural behavior and support joint considerations to assess the overall condition of the investigated building, providing helpful knowledge for guiding structural improvement interventions.

Keywords: reverse engineering, built cultural heritage, terrestrial laser scanning, parametric modeling, generative algorithms, structural analysis

Introduction

Many Italian historical buildings were erected utilizing masonry construction techniques before seismic safety laws were established in the peninsula in the 1970s. As a consequence, the preservation and renovation of these historical buildings today is a complex task involving specific regulatory and performance requirements for protecting both the historical values and structural integrity of this material heritage. Therefore, conservation programs for existing structures should leverage a comprehensive

understanding of the structural, architectural, and technological components of this architectural heritage.

Innovative technologies and multidisciplinary approaches are recently emerging as valuable tools for supporting the conservation and regeneration of CH buildings (Lovell, Davies, and Hunt 2023). In particular, since these buildings necessitate non-invasive or microdestructive diagnostic analyses to be in-depth understood before being modified, digital technologies like 3D scanning and computational modeling have risen, changing how historical structures are researched in the field of CH studies.

Novel methods for studying historic masonry walls have revealed the challenges in accounting for crucial factors such as historical transformations and variations in material strength, which are often neglected in traditional analysis models. This awareness highlights the limitations of the conventional approach in accurately analyzing these structures. Historical buildings adhere more to the principles of 'Building Practice' than nineteenth-century 'Structural Mechanics', which still influence the structural assessment approaches required by regulations. In contrast to the latter approach, reverse engineering has become a thoroughly investigated, non-invasive method for examining the functionality of existing buildings and pinpointing areas for potential enhancement.

This work presents an analysis method for masonry heritage buildings. This method, which stems from years of research already described in previous works (A. Massafra, Prati, and R. Gulli 2024), is systematically described in each technical step for the first time, leveraging the research experience accumulated by the authors in the last decade. The systematized method, which was initially created to assess timber trusses and then extended to other structural elements like walls and columns, can be used to analyze displacements and deformations in typical structural elements of historical masonry buildings over time using techniques like TLS, parametric 3D modeling and VP.

This study has two main objectives. The first is to organize the methodological results gained from prior research to thoroughly structure an integrated assessment strategy, illustrating how academics and professionals can benefit from this methodology. The second consists of applying the method to two case study heritage buildings that are representative of the Italian masonry heritage: the Basilica of San Domenico in Siena, a medieval basilica, and the Teatro Comunale in Bologna, an eighteenth-century theater.

The paper is structured as follows. Section 2 presents the research background and state of the art, detailing the tools, technologies, and methodologies employed. Section 3 provides a conceptual overview of the workflow, exploring each process stage in detail. Section 4 provides the most relevant findings of the workflow application. Section 5 will discuss the advantages and disadvantages of the method in relation to its efficacy and efficiency.

Background

Digital technology for building representation, design, and management has made substantial progress in recent decades. Computer-aided design (CAD) was developed in 1957 by Patrick Hanratty and evolved into the concept of the "Building Information Model" in the early 1990s (van Nederveen and Tolman 1992), when Charles M. Eastman proposed the idea of the "Building Product Model" (Eastman 1999) later termed "Building Information Modeling" (BIM). Since then, BIM has gained growing attention and widespread acceptance (Li et al. 2017), reaching the built CH field as the so-called Heritage BIM (HBIM) in 2009 (Murphy, McGovern, and Pavia 2009).

In recent years, the surge of digital survey research has expanded opportunities in this field. Many studies have concentrated on deploying techniques for obtaining existing buildings' information through 3D scans, developing algorithms that facilitate semantic segmentation and extracting valuable data from point clouds, sometimes through

Artificial Intelligence-based (AI) techniques (Xie, Tian, and Zhu 2020). Due to these technological advancements, there has been a significant increase in research output in new disciplines, including intriguing studies on point cloud-enabled structural assessment (Sánchez-Aparicio et al. 2023).

Terrestrial Laser Scanning

Digitization of building stock has been increasingly popular in recent years, especially for preservation and management purposes (Suchocki et al. 2018). Laser scanner surveying has been a crucial tool for establishing a new way to quickly and accurately gather and depict geometric and dimensional data in the form of three-dimensional point clouds.

These scanners, categorized as active optical sensors since they emit energy in the form of light, can efficiently and methodically capture an object's spatial coordinates or surface shape by emitting a beam, light field, or pattern onto an object and then analyzing the reflected signal. They differ from photogrammetry as the latter does not involve light emission (Remondino 2011) and demonstrate many advantages that have allowed them to become highly effective tools for precisely and efficiently bringing the built heritage in digital format for accurate structural assessment. The laser field gathers angle data, distance measurements, and reflectance details regarding the material qualities of the scanned surface (Vögtle, Shwab, and Landes 2008). Depending on the sensor used, the distance between the device and the object is acquired by measuring either the time of flight (TOF) or the phase shift (PS) of the reflected beam (San José Alonso et al. 2012). They usually record their environment as point clouds, which are sets of points in three dimensions obtained by aligning several scans.

Visual Programming and Parametric 3D modeling

Parametric modeling is another digital technique that has become popular in architecture and construction. It is commonly called "feature-based modeling" because objects are generated through processes or "features" whose attributes are regulated by parameters. This method offers continuous oversight of a model's geometry and the fundamental mathematical principles it is based on. It deviates from conventional CAD methods and has been well-received by numerous professionals for its adaptability and creativity.

The main methods for parameterizing geometries are geometric constraint solving, textual scripting, and visual or nodal programming (VP). Geometric constraint solving involves creating and linking different model elements through dimensional and geometric constraints (Bettig and M. Hoffmann 2011; Zou et al. 2022). Parametric BIM object families are usually modeled through this technology. Textual scripting, instead, consists of digital modeling by running programs through text-based programming languages such as C# and Python. It offers high versatility and accessibility to computer system resources but demands advanced computer expertise (Chiesa 2020; Ganin et al. 2021). VP, in contrast, uses visual and non-textual elements and does not necessitate programming expertise. This method employs a graphical interface featuring two screens: the node diagram creation and the generated geometries display (Kossakowski 2023; Globa, Ulchitskiy, and Bulatova 2018). VP uses graphs and flowcharts to make parametric modeling easier for non-skilled programmers, so complex features can be constructed by connecting nodes and arrows in a suitable sequence (Collao et al. 2021).

Reverse engineering for improved built heritage structural knowledge

Nowadays, point clouds are essential for defining a building's geometry, but they also have their main limitation. Without post-processing, they only convey spatial information

and lack any extra significance. For this reason, current research on digital surveys is making significant efforts to develop technologies capable of semantically segmenting point clouds (Yang, Hou, and Li 2023; Özkan et al. 2022) and enabling scan-to-BIM processes to generate BIM models from point clouds (Bosché et al. 2015).

Both research routes are crucial for enhancing the understanding of existing buildings but face considerable problems when applied to CH. Historical buildings typically have intricate geometric, structural, and technical features. Timber roofs, for instance, usually feature diverse structural patterns, cutting procedures, metal connections, and members with different cross-sections. Masonry façades, on the other hand, frequently display various architectural elements on their surface, including half pilasters, buttresses, protrusions, and recesses. To accurately represent these elements digitally, sophisticated surveying tools and advanced 3D modeling techniques are required. These tools must be capable of capturing the distinct characteristics of each structural category while following its semantic criteria.

For this reason, digital tools for surveying buildings have become popular among experts for their efficient and precise data collection capabilities at a reasonable price. LIDAR (Laser Imaging Detection and Ranging) and TLS techniques are widely used as the basis for capturing 3D data. Multiple strategies have been studied for creating 3D models in different file formats from scanned point clouds, such as interpolating surveyed points with meshes or constructing 3D models using NURBS surfaces.

Raw survey data can also be used to develop 3D models for analyzing historical buildings' structural behaviour. However, these approaches to structural assessment focus more on research than practical or professional applications. Among the most significant examples in the literature, Bertolini-Cestari et al. (2016) used TLS point cloud data to create a finite element model (FEM) for assessing the roof condition at the Castello del

Valentino. Andriasyan et al. (2020) utilized TLS or Structure From Motion (SFM) data to create information models of elements in historic buildings by reconstructing their geometry through parametric algorithmic modeling techniques. Santos et al. (2022) developed a technique to assess the structural integrity of ancient timber structures with irregular sections. They integrated LIDAR data and non-destructive test data into an HBIM Model for numerical analysis using FEM. Youn, Yoon, and Ryoo (2021) utilized a comparable method to examine the structural characteristics of a Korean historical building pre- and post-restoration. Moyano et al. (2022) utilized TLS methods to get precise geometry data on a medieval portico in Spain. The work involved converting point clouds into 3D models and then using VP algorithms to detect potential structural deformations in the columns. Wang, Wu, and Bai (2022) created an automated technique to generate the axes of masonry columns using TLS survey data. This method converts the data into FEM models for numerical computations.

Material and methods

Methodological approach

The presented method aims to understand, evaluate, and interpret the behavior of heritage building structural components by analyzing the hypothetical deformations that they have undergone over time. The primary assumption is to take advantage of the vast amount of spatial information that can be obtained from a survey conducted using TLS, which allows for the detailed examination of areas of these buildings that are commonly difficult to inspect using traditional survey methods due to their low accessibility, excessive height, or obstruction generated by other elements commonly found in such places.

Figure 1 depicts the main steps of the method: "data collection," "data modeling," "data analysis," and "results interpretation." A fifth phase, "data monitoring," can also be added to these steps.

In the first phase, historical research about the building is conducted. In parallel, a TLS survey of the building is made.

In the second phase, the point cloud is edited and transformed into 3D models: the Basic 3D Model (B3M) and the Ideal 3D Model (I3M). The B3M depicts the surveyed condition of the structural components, whereas the I3M represents their presumed original state. Meanwhile, in-situ inspections are conducted to characterize the main construction attributes of the investigated components.

In the third phase, displacement analysis is conducted. The B3M and I3M are geometrically compared, and their deviations are highlighted to identify the potential displacements the examined elements underwent over time, producing the so-called Displacement 3D Model (D3M). Meanwhile, historical data are cross-referenced with construction data for a more detailed construction characterization.

In the fourth phase, the interpretation of all the acquired and processed information is conducted to figure out the surveyed building components' structural behavior and make joint considerations about the structural influence of the interconnected elements, forming a basis of knowledge to support structural improvement design.

Lastly, the fifth phase involves repeating the whole process - periodically or after unpredictable catastrophic events - to monitor the building elements' displacement trends.

Technical implementation

The analysis method has been refined through years of research experiences conducted by the authors and tested on various case studies. As a result of these research efforts,

some algorithms and tools have been developed to be applied to different kinds of construction elements, including beams, columns, façades, slabs, and more complex systems such as trusses. While previous works have helped assess specific vulnerabilities in the examined buildings (Davide Prati, Massafra, and Guardigli 2023; Angelo Massafra et al. 2021), this study, for the first time, represents the approach comprehensively, demonstrating how the authors took advantage of the previous research efforts to systematize the method by employing the resulting method to investigate some structural elements placed in two selected Italian case studies: the Teatro Comunale in Bologna (Bergamini 1966) (Figure 2) and the Basilica of San Domenico in Siena (Riedl and Seidel 1985) (Figure 3).

Figure 4 depicts the technical workflow we developed with a specific focus on the phases of data collection, data modeling, and data analysis conducted through digital tools. The diagram provides information about the main methodological steps, the inputs and outputs, the models produced and their data format, the types of processes implemented (manual, assisted, or automated), the algorithms developed, and the software used. Below is the detailed technical description of the workflow.

TLS survey

Once the case study is identified, the first step is to conduct an accurate TLS survey of the building under investigation. This procedure involves conducting several on-site scans to detect the building's geometries and a desk post-processing phase necessary to align the scans into a single point cloud. For surveying the whole Basilica of San Domenico and the roof of the Teatro Comunale di Bologna, we employed a FARO CAM2 FOCUS 3D® laser scanner using a targetless approach. For each examined building, the survey resulted in several 3D scans aligned and merged through the FARO SCENE 2019® software using an interactive cloud-to-cloud registration. The outcomes,

shown in Figure 5, were two .XYZ point clouds, one for each invested building. Table 1 reports the technical data of the survey campaign, while Table 2 shows the cloud-to-cloud alignment parameters.

After the survey, manual procedures are employed in the FARO SCENE® software to segment the building point cloud and extract only points referring to the investigated components, constituting a small subset of points from the whole cloud. A bounding clipping box is made for each building component (i.e., a column, a wall, or a truss). Then, the enclosed points are exported in the XYZ format and imported into the Geomagic Studio® software. In this environment, other quick manual editing operations are conducted to clean up the component's point cloud. All the points not belonging to the component under investigation are selected and deleted (like points referring to trees and vegetation in the exteriors and scaffolding, pipes, ducts, and furniture in the interiors). The outcome for each component is the B3M. This point cloud model, exported from Geomagic Studio® in the XYZ format and then imported in Rhino®, represents the geometry of the building components in the surveyed state, which is assumed to be the "deformed state" of the building component. Please refer to the top-right part of Figure 1 to figure out examples of B3Ms for truss, wall, and column elements.

From Basic 3D Model to Ideal 3D Model

Starting from the B3M, the I3M is created through a series of assisted and automated operations that allow reconstructing the hypothetical condition of the building component when it was originally built. The algorithmic modeling part of the I3M generation procedure is conducted in the Rhino® 3D modeling environment with the support of Grasshopper® (GH) as VP software. This procedure includes four main steps: (A) segmentation of the B3M for extracting the points referring to the most significant cross-sections of the structural component; (B) vectorization of the components' cross-sections;

(C) deletion of the hypothetical deformations that occurred on the sections through time;

(D) 3D modeling of the component. These steps vary slightly according to the type of investigated element.

(A) The first step of the I3M modeling stage consists of selecting and extracting from the B3M the only groups of points representing the primary cross-sections of the component. This step is performed manually for the trusses and automatically for the walls and columns. For each beam composing the trusses, the portions of points near the joints and at the beam's centerline are selected manually thanks to the Rhino® polygonal selection feature, for a total of three cross sections for each beam. Instead, a GH point cloud segmentation algorithm is used for walls and columns. This algorithm allows for dividing the B3M into horizontal bands of points representing the cross-section of the elements by setting a predefined distance between the sections. For the Basilica of San Domenico, this distance was set equal to 2 m for the external facades, which are higher than 40 m, and equal to 0.2 m for the masonry columns, being less tall. Example outcomes of this step are displayed in Figure 6a.

(B) The GH "Cross-Section Vectorization Algorithm" (CSVA) is then applied to the segmented point groups to vectorize them as polyline cross-section curves. For each point group, CSVA first recognizes the inclination angle of the cross-section and creates a plane inclined at this angle with its origin at the center of mass of the point group, representing the lying plane of the cross-section. Then, CSVA selects a 5-cm-wide point slice parallel to the lying plane and projects the enclosed points onto the plane. The script interpolates the points through a third-degree vector curve using a local polar coordinate system oriented in the lying plane to arrange the points correctly. The resulting curve is further processed to be transformed into a polyline made of a defined number of segments. This number is chosen according to the complexity of the shape of the section.

Our application set it to 100 for truss, wall, and column sections. The result is a set of vectorized curves representing the most significant cross-sections of the deformed component (Figure 6b).

(C) After the cross-sections are vectorized, other GH algorithms are applied to them to delete the hypothetical deformations that occurred on the curves during the time and translate them into their presumed undeformed original state. The translation operation leverages specific theoretical assumptions on the behavior of heritage components (reported below) that we experienced in situ and formulated through years of research on the topic. These assumptions are differentiated by the different types of components. Consequently, three different workflows are used for truss, wall and column elements to model the I3M starting from the section curves of the B3M, as indicated in Figure 4.

(C.I) Trusses. For deleting the trusses' hypothetical deformations, two algorithms are applied to the trusses' curves: the "Truss Projection Algorithm" (TPA) and the "Truss Rectification Algorithm" (TRA).

TPA recovers the displacements of the cross sections outside the vertical plane of the truss, which is considered the vertical plane passing from the lateral bearings of the truss. This operation is performed by projecting the barycenter of the cross-sections on the truss vertical plane using the GH "Project" node and, then, moving the cross-section to the projected barycenter by executing the "Move" node in GH.

TRA recovers the deformations that occurred in the vertical plane of the truss, applying backward the standard kinematic deformation hypotheses to the previously projected curves in GH. The deformation hypotheses assumed are the following: (i) the lateral bearings of the trusses (joints A and A') remained at their original positions, (ii) the rafters and the posts underwent slight bending deformation, (iii) the joints between

rafters and queen posts (joints B and B') inward lowered and rotated due to roof loads (with consequent rotation of the queen posts), (iv) the ridge joints (joint C) slightly lowered due to roof loads, (v) rigid connection between the rafters and tie-beams was assured by metallic brackets, and (vi) no significant axial deformation happened on the beams.

Based on these assumptions, TRA gradually recovers the curves' in-plane deformations by: deleting the vertical translation of the joints B, B', and C; straightening the rafters by canceling the rotation of joints A, A', B and B'; rectifying the posts by deleting the rotation of joints B and B'; and canceling the bending deformations of al the beams by projecting each beam's centerline section on the straight line that joins the centroids of the two end sections of the beam. The application of TPA and TRA on a truss element is depicted in Figure 6b.

(C.II) Walls. For deleting the walls' hypothetical deformation and getting the ideal curves of the wall component, the "Wall Curve Interpolation Algorithm" (WCIA) is run in GH. WCIA takes as input the horizontal cross-sections of the wall, vectorized in the previous step, and then selects the portion of the curves that best represents the planar condition of the façade, removing pilasters, buttresses, protrusions, and other similar obstacles. The cleaned curves are divided into a certain number of points located at equal distances (100 points were considered for the facades of San Domenico) and, for each group of points, the script computes the "linear regression line" thanks to the "Interpolate (IntCrv)" GH node (Figure 6b). This line is the one-degree polynomial curve that, for each section, best interpolates the points in the XY plane and represents the cross-section as an ideal undeformed line. If the wall has several planes, i.e., composed of parts with different thicknesses or shapes, the WCIA is applied only to the lowest part of the wall connected to the ground.

The theoretical assumption behind this modeling step is to evaluate masonry buildings' out-of-plane mechanisms (first mode) by breaking down their structure into macro-elements for executing linear kinematic analysis. This type of assessment is considered the most relevant for such structures since Italian earthquake-damaged structures in the last years demonstrated that the independent structural response of the macro-elements – caused by disconnections between them which can be exacerbated by earthquake activity – rather than the whole structure, characterizes the buildings' seismic behavior. Moreover, out-of-plane mechanisms are the most dangerous since they often cause macro-element collapses with intense earthquakes.

(C.III) Columns. The deletion of the hypothetical deformations that occurred on masonry columns is made instead through the "Column Projection Algorithm" (CPA). CPA allows for automatically deleting the transversal deformation hypothetically undergone by the column's sections through time by considering the ideal column as a perfectly vertical column. This GH script takes the vectorized cross sections of the column as input, and then, for each section, it identifies the centroid. The centroids are projected onto the vertical axis, passing through the centroid of the column's base section (the section nearest to the ground), and, finally, the curves are translated to the new centroids. The outcome is the set of cross-section curves in their ideal position (Figure 6b). The central theoretical assumption is that the base of the column remained in its original position and that the column underwent only transversal deformations (e.g., due to the thrust of arches and vaults), disregarding axial deformations due to compression.

(D) After getting the ideal vectorized cross-sections of the structural component, 3D modeling algorithms are applied in GH to the vector curves to produce the I3M. As in the previous step, this procedure is differentiated for trusses, walls, and columns.

(D.I) Trusses. The 3D modeling step for timber trusses uses two VP algorithms: the "Curve Loft Algorithm" (CLA) and the "Truss Joint Modeling Algorithm" (TJMA).

CLA is iterated over each beam of the truss. It allows for the creation of an open polysurface enclosing the central part of the beam (from one end section to the other, passing from the centerline section), relying on the "Loft" node of GH, which, for each beam, takes as input its three cross-section curves.

TJMA, in contrast, performs the 3D modeling of the outer parts of the truss beams, i.e., the joints. First, this algorithm identifies the "projection planes" of the truss. These are the truss vertical plane, the beams axial planes, the vertical planes passing through the lateral bearings, and the horizontal plane passing from the ridge. Subsequently, for each end section of each beam, TJMA identifies the nearest projection plane. Then, it projects the centroid of the section to the identified plane and moves the section to the projected centroid. Finally, it applies a loft operation from the joint section curve to the moved section curve and, for each beam, merges the resulting polysurfaces with the polysurfaces created by CLA (Figure 6c). The merged polysurface is closed thanks to the "Cap Holes Ex" node in GH. The outcome is a set of closed 3D BRep objects (one for each beam composing the truss), considered the I3M of the whole truss.

(D.II) Walls. The I3M modeling procedure for walls involves the employment of the "Plane Interpolation Algorithm" (PIA). PIA allows for creating the so-called "average vertical plane" of the façade, which is, in other words, the plane that, according to our assumption, represents the ideal condition of a perfectly vertical and flat façade, excluding the out-of-plane deformations that presumably occurred over time.

PIA takes the interpolated section lines realized in the modeling step C.II as input to generate the average vertical plane of the wall. Following an interpolation approach similar to that used for extracting the ideal curves from the B3M, this algorithm calculates

the "vertical linear regression plane" that best interpolates the ideal curves. Then, it forces this plane to be perfectly vertical. The result is a "Plane" object in GH (Figure 6c), converted into a surface element thanks to the "Rectangle" node to be ready for export in other modeling environments.

(D.III) Columns. The 3D modeling of column elements employs the same approach for the truss beams. First, CLA is applied to the set of the column's ideal curves, obtained in step C.III. This script performs a loft operation between the curves and produces a polysurface enclosed between the base and top sections of the column. Then, a polysurface capping algorithm is run on the polysurface to produce a closed 3D BRep object (Figure 6c), which coincides with the I3M of the column.

From Ideal 3D Model to Displacement 3D Model

Once the I3M is generated in GH, it is saved in Rhino thanks to the "Bake" command and exported into the IGS format. The IGS file is then imported into Geomagic Studio® to generate the D3M. This last model consists of a 3D model that takes the geometries of the I3M and colors them according to the deviations between the I3M and the B3M.

The B3M-I3M comparison, in particular, is conducted using Geomagic Control®. This tool allows for the evaluation of the deviations between the outer faces of the I3M and the points of the B3M and the highlighting of the differences between each "ideal" component and its "basic" counterpart. Thanks to the software features, minimum and maximum deviation thresholds are manually set to indicate on a chromatic scale the entity of the hypothetical movements between the surveyed configuration and the ideal one, as shown in the examples in Figure 6d. Then, the deviation values are saved on the geometries of the D3M so that it is possible to select any point of the D3M and extract numerical data about the distance of this point and the nearest point in the B3M and its subdivision along the x, y, and z axes. The comparisons can be made both in the 3D space

or in user-selected 2D planes significant for the analysis, such as in the vertical plane of the truss, in the planes perpendicular to the ideal plane of the wall, and in the vertical plane passing from the column axis. The extracted data are exported in CSV format for each component and organized in synthetic tables for analysis.

Results

Timber truss displacements

The workflow applied on the timber trusses of the Teatro Comunale yielded excellent insights into the condition of the building's roof system. Comparing the I3M and B3M enables the formulation of comprehensive assessments of the present deformation conditions of the roof trusses. By synthesizing and integrating data from 3D models and comparing point clouds, intriguing inferences were made about the displacement and behavior of the entire roof system of the building. Each truss displacement was found to be interconnected with the others, both within and outside the trusses' vertical planes (see Figure 7).

Based on the findings, each truss exhibits a slight asymmetry in its plane in relation to the lowering of the post-rafter joints. Specifically, a slight decrease of approximately 3 cm is observed in the right post-strut joint, while the sagging values in both the left post-rafter and ridge joint are insignificant. The right queen post rotates clockwise, and the left one rotates counterclockwise. The queen post on the right side shows a more significant rotation than the one on the left. The imbalance is evident in the king post, where a slight clockwise rotation is observed. Rotation values are directly linked to joint displacement values: the higher the lowering, the more pronounced the joint's rotation. The truss span of approximately 25 meters had minimal distortion,

indicating that the covering system is in acceptable shape. Similarly, the tie beam exhibits minor bending displacements.

In-Plane Displacements

The side triangular fields of all the trusses showed a similarly asymmetrical behavior in their vertical plane, unbalanced toward the east side of the building. A careful visual analysis of the orthophotos and some measurements deriving from the point cloud highlighted that the eastern bearings of the tie-beams were about 10 cm lower than those on the western side. In general, the static behavior can be summarized as follows:

- Unbalanced tie-beam inflection towards the east side of the building.
- Counterclockwise rotation of node B (bottom rafters-western queen post-straining beam), resulting in rotation of the western queen-post.
- Node C (ridge node) rotates clockwise and lower than node B, causing the king posts to follow suit.
- The clockwise rotation of node B' (straining beam-eastern queen post-bottom rafter) is more extensive than the rotation of node B, resulting in a rotation of the eastern queen-post in the same direction.
- Almost no lowering of B nodes.
- Almost no lowering of C nodes.
- Lowering the B' nodes by 1-4 cm.
- Lowering of node A' (eastern lateral bearing) as expected.
- Rotation of the straining beam clockwise to match the movements of nodes B and B'.

The results may be ascribed to two distinct sources. The height difference between the eastern and western bearings appeared negligible compared to the extensive length of

the trusses. This was likely due to tolerance errors during construction in the 18th century and can be attributed to the general static behavior of the original masonry structures of the entire building. A significant sinking phenomenon on the eastern side of the historic building is highly probable. The historical investigation revealed details about an ancient water route near this location that may have caused ground shifts. Confirming this information requires a detailed analysis of the crack pattern on the theater's walls.

Out-of-Plane Displacements

All evidence about displacements outside the trusses' vertical plane supported the theory of a combined roof shift. The trusses pivoted about their side bearings towards the theater stage (to the north). The western rafters have rotated towards the theater proscenium, except for the second truss, with a maximum displacement of 5 cm. Conversely, the eastern ones have experienced a rotation in the other direction, as shown in Figure 8.

The trusses were restricted in their movement towards the proscenium on the eastern side of the central trusses, likely because of the metal walkway in that area. The platform has worked as a bracing element attached to the central tie-beams and the floor, enabling the central trusses to impede movement.

When analyzing these consequences, the significance of combining historical research with data from the new technology utilized by the workflow becomes explicit. Knowing what interventions the structure has had over its life cycle makes it easier to identify the problems currently affecting the historic building. Archival documents indicated that the proscenium area has consistently exhibited structural issues at the roof level since the theater was built. Since 1980, the timber trusses have endured the forces exerted by the wooden vault, which has been linked to the trusses using metal tie-rods (Pozzati, Diotallevi, and Zarri 1982). The vault shifted towards the proscenium area, a

known structural vulnerability of the theater. Hence, the metal tie-rods pulled the joints of the trusses in a uniform direction.

Façade displacements

The survey campaign faced challenges due to the Basilica's considerable height, reaching 42.85 meters in the transept and 48.25 meters in the bell tower. Difficulties also arose in obtaining accurate data about the upper part of the inner transept and conducting surveys on the steep slopes of the hillside. Figure 3 displays the survey results, featuring labeled images of the façades. The workflow was applied to analyze the transept's façades to understand its behavior and any potential issues. In particular, Façade A, Façade B, Façade C, and the bell tower were inspected.

Façade A

At the bottom section of Façade A (Figure 9), there was a 9 cm vertical offset between its base and top, causing the top to extend outward from the building in the positive y-direction. The top section of the façade rotated in relation to its average xy-plane, with the side next to the bell tower extending outward from the structure. The investigation revealed that the façade and bell tower displacements were compatible. Additionally, the bell tower exhibited a relative displacement between its base and top in the same direction. The analysis of Façade A and the bell tower displacements indicated that Façade A tilted slightly and interfered with the bell tower's motions. When looking at the opposite side of the bell tower aligned with the y-axis, a more noticeable difference of 19 cm between the top and the base was measured. This data supported the assumption that the bell tower is tilting outward from the building in that direction. Observing the cracking pattern on Façade A, where a vertical lesion is visible at the border with the bell tower, indicates a detachment between the two macro-elements.

Façade B

Facade B (Figure 10), located across from Facade A on the transept, revealed its lower section, with the upper right corner slightly protruding outward from the structure, creating a vertical overhang of approximately 10 cm. A horizontal rotation with a 5 cm divergence between the downward side and its symmetrical counterpart was found on this section of the façade. The top of the façade followed the same pattern as the bottom section, causing rotation in the xy-plane with the side next to Façade C extending outward from the building. The analysis of both sections of the façade, the lower and upper parts, indicates a combined tilting of the façade that hinders Façade C's movements. The theory was supported by the vertical lesion found on the downstream side of the transept, near the cloister side facade, displaying detachment and overturning in the upper section.

Façade C

Façade C (Figure 11) had lateral zones that extended beyond the mean plane of the facade outward and central zones that extended inward, with a maximum deviation of 18 cm between the lateral and central components. The shift from blue areas at the edges to yellow areas at the center happened along deformation isolines inclined at approximately 45°. This data confirmed the theory of triggering a kinematic chain involving simultaneous overturning on both sides of the transept, affecting the deformations of facades A and B.

The thorough examination of the movement of all the facades, viewed as a whole structural system, led to the interpretation presented in Figure 12.

Column displacements

A careful examination of the church focused on analyzing the behavior of the columns in the crypt and transept. The results from the crypt were significant because of the

combination of displacement analysis and crack pattern analysis. Historical study and on-site inspections enhanced the understanding of the columns' behavior, resulting in consistent findings. This diverse method provided valuable insights regarding the behavior of the vaults in the Basilica's crypt.

Figure 13 shows that the two central columns have fundamentally symmetrical displacements. The right center column showed more significant quantitative deviations than the left central column, with a relative offset of approximately 7 cm within a length of 580 cm. The displacements of the columns in the crypt were principally caused by the thrusts from the central vault overhead, which were more considerable than those from the sides. The deformation mechanism is demonstrated clearly by a significant crack at the center of the vault, highlighted in red in the picture. The analysis suggests additional interventions are necessary to address this issue and prevent potential structural collapses. For example, placing metal chains can help counteract the vault's forces on the column heads, offering structural reinforcement.

Discussion

This research developed a method allowing the use of parametric 3D modeling to analyze heritage buildings from a qualitative and structural standpoint. The method described was used in multiple case studies to show its effectiveness in evaluating and understanding the deformation conditions of various construction components frequently found in traditional Italian historical architecture, such as columns, timber trusses, and masonry facades. The study highlighted the importance of incorporating digital technology like TLS tools and VP algorithms into historical building analysis and regeneration processes. It offered a way to examine historical buildings when data was hard to collect using traditional methods like manual or direct surveys.

The proposed method deviates from the conventional manual generation of a FEM model and involves more than merely vectorizing the geometry of elements in historic buildings. Many workflows that use data from LiDAR, SfM, and TLS surveys to automatically or semi-automatically convert them into information models utilizing parametric methods are available. Usually, the resulting models are the main and only focus of the research. The discussed holistic methodology allows for several assessments and can be applied to a broad range of building components.

We know this study highly relies on geometric reconstruction and analysis of the structures in the geometry domain. Material type and condition estimation, as well as archival research on the construction phases, can deepen the level and the accuracy of the analyses. Nonetheless, one of the research goals was to highlight the effects (displacements, deformations, rotations) before investigating the causes (material quality, loads estimation, conservation conditions). Given the age of these structural elements, we preferred observing before calculating or, in other words, using an inductive strategy rather than a deductive one. Deductive reasoning is reasoning in which the premises (if true) guarantee the truth of the conclusion. Inductive reasoning is reasoning with premises that make it probable that the conclusion is true but do not absolutely guarantee its truth. It was deemed that the definition of a new knowledge path should be based on the second approach.

In light of the benefits highlighted for applying the method to similar structures throughout the text, it is essential to thoroughly evaluate both its limitations and the potential future directions of research. This evaluation is especially crucial within the broader context of contemporary research, which frames the study's scope and relevance. For this reason, the presented process is evaluated according to the following criteria: (1)

degree of automation, (2) required input, (3) resources and time, (4) computational complexity, and (5) extensibility to new applications.

(1) Regarding the level of automation of the workflow, the achieved automation is only partial. The process of generating the I3M models from point clouds (i.e., the B3M models) is fully automated through VP algorithms in Grasshopper. However, manual operations are required to preprocess the B3M models inputted into Grasshopper. These procedures include scan registration, scan alignment, point cloud editing for cleaning, and segmentation of points referring to the survey elements, which constitute a small subset of points from the whole cloud. Furthermore, all comparisons between B3M and I3M results from these models are facilitated by software (specifically, Geomagic Control). However, they require manual procedures for data extraction and formatting into tables and graphs for analysis. Integrating the proposed method with automatic point cloud segmentation methods (see the review by Xie, Tian, and Zhu (2020)) would significantly enhance the workflow's automation.

(2) Regarding the required inputs for conducting the investigation, the only input needed for the data modeling procedures is the TLS point cloud of the structural elements analyzed (together with exhaustive knowledge of the building's history, which is always recommended and required in renovation processes). This aspect can be seen as either an advantage or a disadvantage. For instance, considering that the proposed method does not necessitate executing destructive tests on materials, this is undoubtedly a significant advantage, particularly given the imperative to preserve the historical buildings' integrity. Conversely, depending on the object's size and complexity, the surveying process may entail additional time and costs compared to traditional analysis methods.

(3) The necessity for specific and sometimes costly instrumentation, such as TLS, as well as the requirement for time, resources, and specialized skills for applying the

method, is an aspect that could potentially limit its professional use. However, it is worth noting that these limitations can be easily overcome thanks to the digital evolution of the sector that started in recent years. The costs of survey tools are quickly decreasing. New low-cost techniques for obtaining highly detailed point clouds more rapidly are also emerging (such as mobile TLS). Furthermore, the availability of advanced digital skills in the sector is growing since, with the ongoing digitization of the AECO sector, these competencies have become a focal point in the curriculum of higher education institutions.

The cost of using digital techniques and methods also lies in the time required for the different steps of the process. Concerning the workflow described, acquiring point clouds does not require extra time. It is, therefore, sufficient to plan a standard survey campaign which, in the cases addressed, varied from 8 hours for the rooftop of the Municipal Theatre to 3 days for the acquisition of the entire San Domenico complex. On the other hand, the back office post-processing took relatively little time, 1/2 working days to complete the scan alignment. With the new on-the-fly techniques, the alignment procedures can be further streamlined. The usually time-consuming editing phase was limited to merely selecting the point clusters needed to digitize the model's cross-sections. Therefore, the most time-consuming part remains the comparison between B3M and I3M, where the analysis of deviations is still partially manual (especially when applied to wooden trusses).

(4) Regarding computational complexity, the use of VP tools makes the application of the method accessible even to non-expert users who lack specific skills in computer programming. This aspect is likely one of the key factors contributing to the widespread adoption of VP in the AECO and CH sectors, as highlighted in the review paper by Collao et al. (2021). Accessibility could be further enhanced in the future

through the development of software systematized with user graphical interfaces. Furthermore, the approach presented is highly (a) extensible with the analysis of other elements and (b) complementary with other applications.

(a) Regarding the first aspect, the method's flexibility with various construction types has already been demonstrated in the article. Indeed, applying the method to various element types has contributed to the reliability of the process, which was initially developed only for timber trusses (D. Prati et al. 2019). The analyses conducted in this study have allowed for testing different workflows and clarifying definitions using a consistent methodological approach, which helps make typological comparisons between similar construction systems and understand many other elements within a building more globally and comprehensively.

(b) Concerning the second point, based on a semantic representation of constructions, the method presented can complement applications with similar or different informative purposes. The complementarity of the method with HBIM modeling tools has already been verified in (Angelo Massafra et al. 2020), where B3Ms were used for the semi-automatic generation of BIM models of timber trusses. These processes are crucial for the information modeling of the built heritage. Indeed, although point clouds are valuable tools for describing the geometries of a building, one limitation is that they only contain geometric data. Because CH buildings contain a variety of construction elements or structures that are difficult to model, it is essential to pursue paths that could handle both automatic segmentation and semantic enrichment of scanned data with the goal not only to semantically segment point clouds but also to enable scan-to-BIM processes that would generate BIM models from them. Additionally, the parametric models developed could be used for finite- and discrete-element analyses, for example, similarly to what was done by Santos et al. (2022). Finally, other complementary studies

could involve the experimental assessment of the dynamic behavior of timber trusses, as done by Castellaro, Prati, and Guardigli (2022).

(5) Future research developments will concern the monitoring of case studies already analyzed through a new application of the method and the extension to other construction typologies, such as vaults and ceilings, both regarding the structural analysis workflow and the automated generation of HBIM models. In this paper, the displacement analysis of the two case study buildings – the Basilica of San Domenico in Siena and the Teatro Comunale in Bologna – has proven to be a valid interpretation method for understanding the structural behavior of the investigated elements, as well as providing insight into the overall behavior of the buildings. Although the detected movements do not currently threaten the case study buildings, they highlighted the need for long-term monitoring. The results of the analyses also helped identify anomalies in the behavior of certain elements, such as the cracked masonry vaults in San Domenico's crypt. They can become the starting point for future research and potential intervention strategies on these historical buildings.

Declaration of interest statement

The authors report there are no competing interests to declare.

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Figures

Figure 1. Diagram representing the articulation of the proposed method.

Figure 2. The Municipal Theater. On the top, pictures of the main façade and the great hall. At the center, plan of the roof and static schemes. On the bottom, configurations of truss n.3 over time. (a) Original configuration. (b) Addition of girders. (c) Connection with the vault. (d) Installation of new technological systems.

Figure 3. The Basilica of San Domenico in Siena. On the top, evolution of the Basilica over time from 1300 to present. On the bottom, pictures and drawings of the Basilica (2022).

Figure 4. The reverse engineering process for the analysis of heritage building components showing the methodological steps followed for modeling and analyzing, as well as the tools and algorithms used.

Table 1. TLS survey campaign overall data.

Case study	Number of Scans	Number of Points	Working hours	Average Scan Resolution	Scan Quality filter
Basilica of San Domenico (Facades)	85	1.129.302.838	24	7.67 mm/10	4x
Basilica of San Domenico (Crypt)	45	870.697.162	8	7.67 mm/10	3x
Teatro Comunale di Bologna (roof)	60	1.014.651.419	8	7.67 mm/10	3x

Table 2. Cloud-to-cloud registration parameters.

Case study	Average Standard Deviation (mm)	Average Overlapping Between Scans (%)	Subsampling average distance (cm)	Searching Radius (m)
Basilica of San Domenico (Facades)	2.2	16.1	2 cm	0.5 m
Basilica of San Domenico (Crypt)	1.3	8.2	1.5 cm	0.1 m
Teatro Comunale di Bologna (roof)	1.5 mm	36.0 %	3 cm	0.2 m

(a) Teatro Comunale di Bologna

(b) Basilica di San Domenico in Siena

Figure 5. TLS point cloud of the Teatro Comunale of Bologna (a) and the Basilica of San Domenico in Siena (b).

(a) B3M segmentation and extraction of the cross-section points

(b) Cross section vectorization and deletion of the hypothetical deformations

(c) 3D modeling of the ideal structural component

(d) Comparison between the I3M and B3M

Figure 6. Modeling steps followed for creating the I3Ms starting from the B3Ms for truss, wall, and column components.

Figure 7. Displacement analysis of a timber truss in the Teatro Comunale of Bologna, Italy. On the top, I3M and B3M comparison. Green points lie on the I3M, representing null deviations. Red points deviate from the I3M outside and blue ones inside. On the bottom, graphs represent the displacements of the trusses in their vertical planes (different scale values). (a) Struts. (b) Tie-beams. (c) Rotation of the posts.

Figure 8. Movements of the rafters outside their vertical plane. (a) Section representing the western rafters. (b) The plan for the roof is extracted from the point cloud.

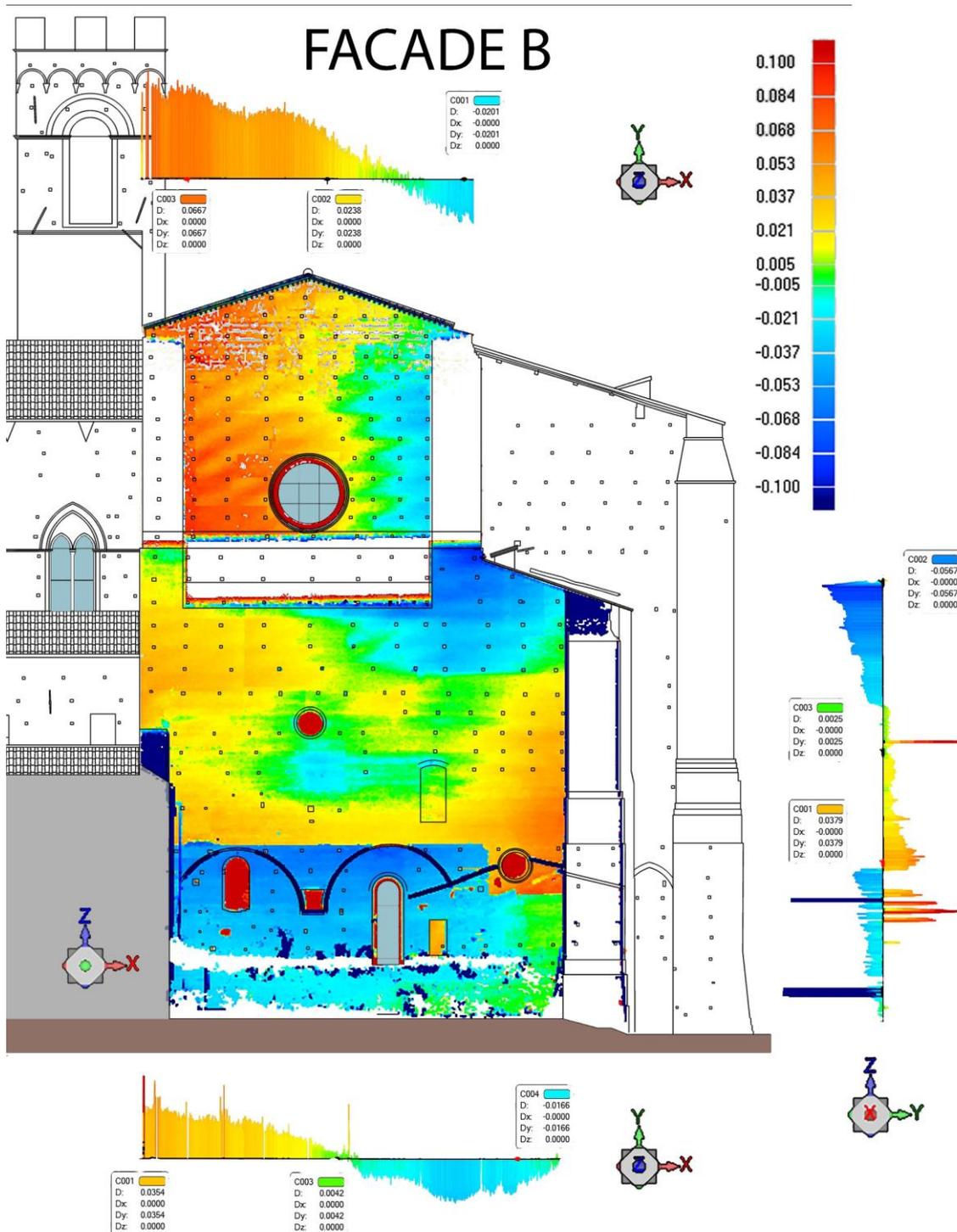Figure 9. Displacement analysis of the façade A and Bell Tower. The green points lie on the mean plane of the façade. Red points deviate from the mean plane in the positive y-direction towards the outside of the building, blue ones in the negative y-direction towards the inside of the building. The deviation values are represented on a scale 100 times larger to allow greater readability in the sections.
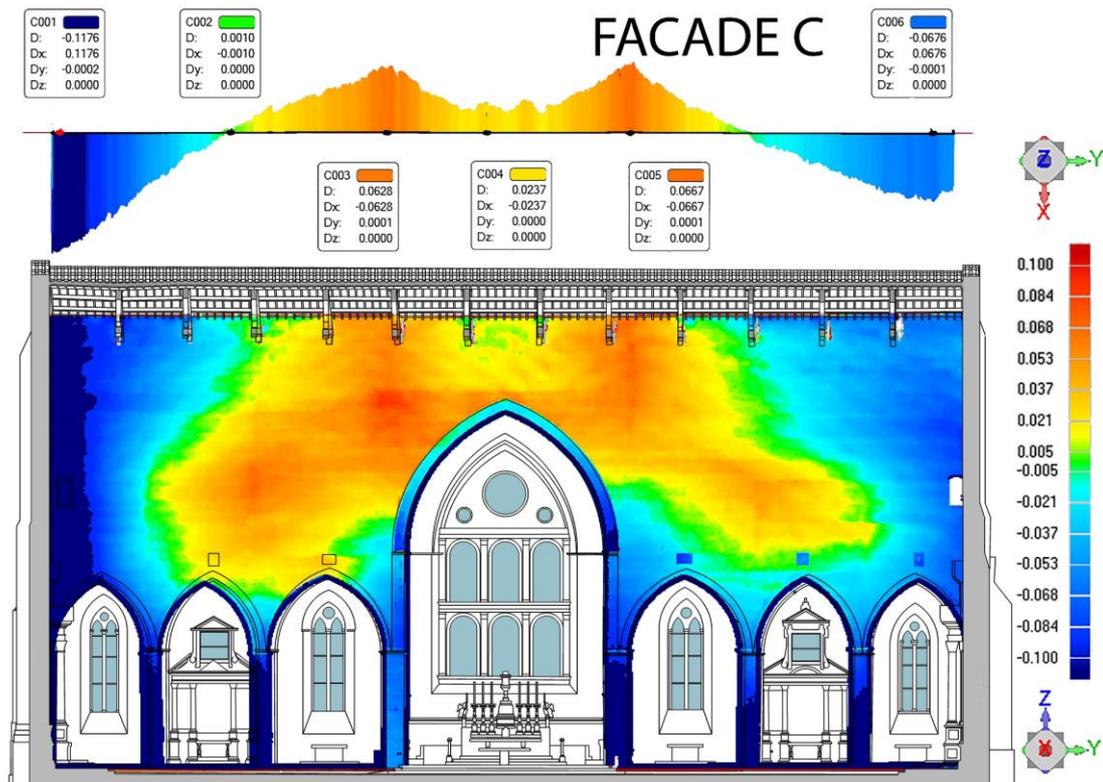
Figure 10. Displacement analysis of façade B. Red points deviate from the mean plane in the positive y-direction towards the inside of the building, blue points in the negative y-direction towards the outside of the building. The deviation values are represented on a scale 100 times larger to allow greater readability in the sections.

Figure 11. Displacement analysis of façade C. Red points deviate from the mean plane in the negative x-direction towards the inside of the building, blue points in the positive x-direction towards the outside of the building. The deviation values are represented on a scale 100 times larger to allow greater readability in the sections.
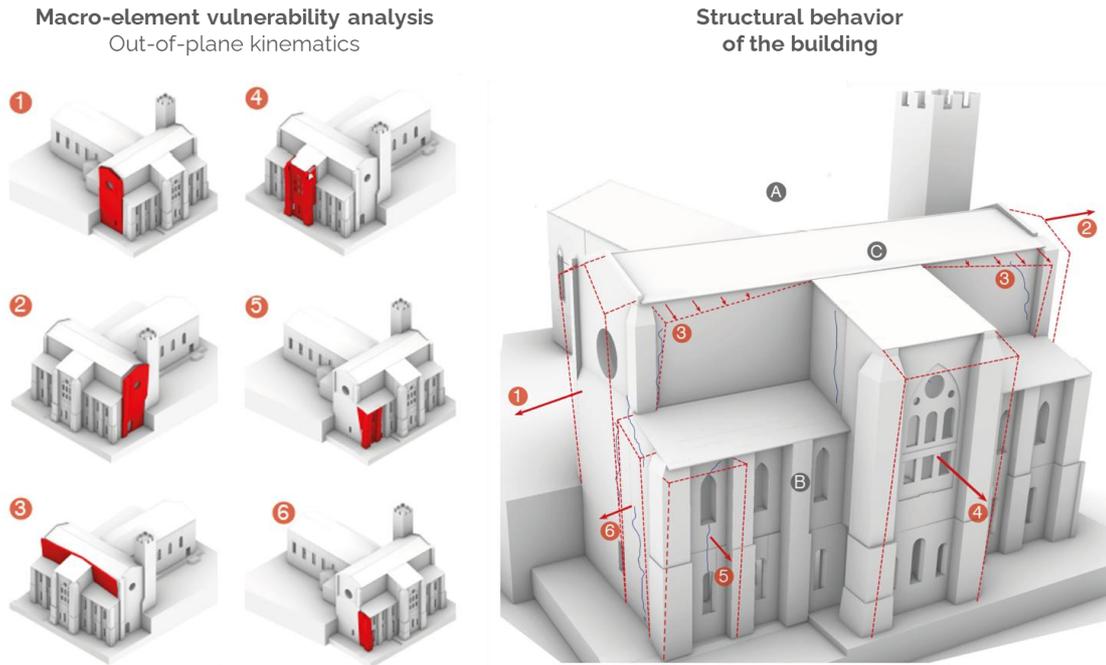
Figure 12. On the top, TLS point cloud of the Basilica of San Domenico in Siena: identification of the investigated masonry walls and the reference system. On the bottom, an analysis of macro-elements and an interpretation of the structural behavior of the transept of the Basilica of San Domenico in Siena.
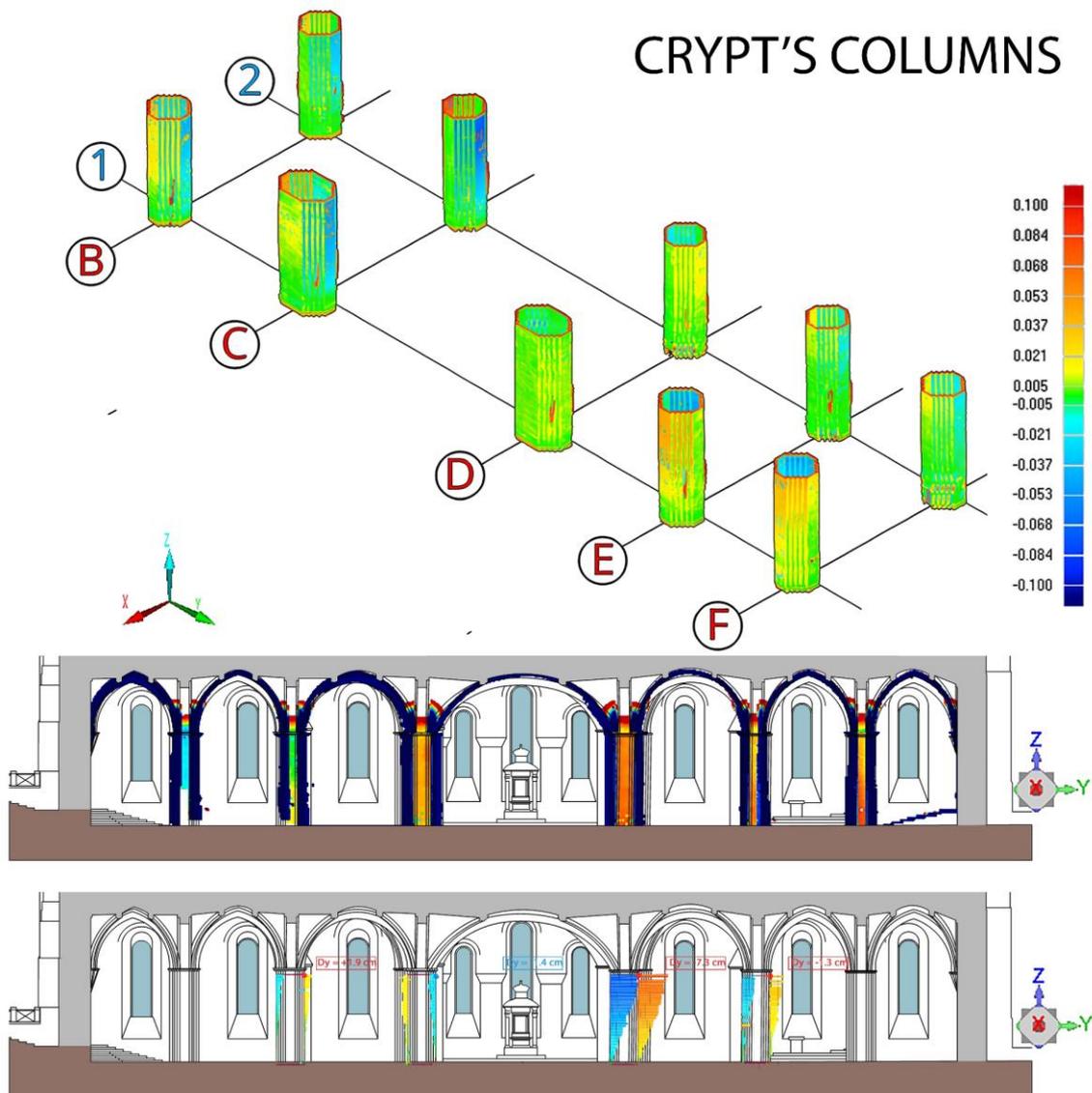
Figure 13. On the top, a 3D representation of the displacements of the crypt's columns. On the bottom, the displacement analysis of some of San Domenico's crypt columns. Green points lie on the I3M, representing null deviations. Red points deviate from the I3M outside, while blue ones are inside. The deviation values are magnified by 100 for improved readability in the sections.