Reverse Engineering for the Structural Analysis of Heritage Constructions

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Abstract. Reverse engineering is a process in which an existing object is studied to understand how it works and potentially improve it. In the Cultural Heritage (CH) sector, 3D scanning and parametric modeling tools have made reverse engineering a viable approach for studying and understanding historical buildings. This paper presents a method for studying the displacements and deformations in historical masonry buildings over time using reverse engineering techniques, such as Terrestrial Laser Scanning (TLS) and parametric 3D modeling. The proposed workflow is divided into three phases. First, a digital survey is conducted to create a 3D point cloud that accurately represents the current condition of the building's structural elements. This point cloud is called the Basic 3D Model (B3M). Next, the point cloud is reconstructed as a 3D NURBS topological model, and specific visual programming algorithms are used to cancel out the hypothetical deformations that have occurred over time. This model is called the Ideal 3D Model (I3M) because it represents the theoretical, undeformed configuration of the structures. Finally, the I3M is compared to the B3M to identify the deviation between the deformed and undeformed configurations. This comparison allows for determining the structural behaviour of the building's parts and evaluating the overall condition of the building to guide interventions for structural improvement. The method has been applied to several case studies in Italy, including masonry columns, façades, and timber trusses.

Keywords: Reverse engineering · Cultural Heritage (CH) · Terrestrial Laser Scanning (TLS) · Parametric modeling · generative algorithms · Structural analysis

1 Introduction

Preserving masonry heritage is crucial as many historical buildings were constructed using this technique worldwide. To ensure these structures' longevity, effective conservation methods must be developed based on an understanding of their structural systems. When working on protected buildings, minimally invasive approaches are needed, as they

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allow for improving buildings' knowledge without causing damage. In the Cultural Heritage (CH) field, digital technologies, such as 3D scanning and computational modeling, have transformed the practice of researching and comprehending historical structures. In particular, reverse engineering has risen as a non-invasive approach for analyzing how existing buildings work and identifying areas where they could be improved.

Using reverse engineering techniques, such as Terrestrial Laser Scanning (TLS) and parametric 3D modeling, this paper outlines a process for studying displacements and deformations that occur in some structural elements typical of historical masonry buildings throughout their life cycle. This strategy, originally developed for analyzing timber trusses, has been implemented for several types of structural elements belonging to various case study buildings in Italy, such as masonry columns and masonry facades. In this study, findings from previous research are organized to structure the method comprehensively, demonstrating how researchers and professionals could take advantage of this approach. In particular, in the following sections, the application of the assessing method is described on two case study heritage buildings: the Basilica of San Domenico in Siena and the Teatro Comunale in Bologna.

The suggested workflow is broken up into three distinct stages. In the first place, a digital survey is carried out to generate a 3D point cloud that faithfully depicts the building's structural components in their current state. This point cloud, which discretizes the geometry of surveyed building parts, is also called the "Basic 3D Model" (B3M). After that, during the second step of the method, the point cloud is reconstructed as a three-dimensional NURBS topological model, and then visual programming (VP) algorithms are used to remove the possible deformations that have taken place over time on the scanned structural components. The output model of this stage is named the "Ideal 3D Model" (I3M), as it represents the unaltered theoretical configuration of the structural elements, as the architects and the master carpenters conceived it at the time of construction. In the final step, the I3M is compared to the B3M to determine the geometrical deviation between the deformed (current) and undeformed (theoretical) states. This comparison enables the understanding of the structural behaviour of the analyzed building's parts and the formulation of coherent hypotheses about the overall condition of the building, which can then guide interventions for its structural improvement.

The paper is organized as follows. Section 2 provides the background of the research, including the tools, technologies, and approaches used. Section 3 offers a conceptual overview of the methods employed, delving deeper into each stage of the process. Section 4 presents a case study demonstrating how the method can be applied to different types of construction while maintaining a consistent approach. Finally, in Sect. 5, we highlight the most intriguing results of our analysis, including the facades and columns of the Basilica of San Domenico and the timber trusses of the Teatro Comunale.

2 Background

2.1 Terrestrial Laser Scanning

In recent decades, the digitization of the existing building stock has become increasingly commonplace, particularly with regard to preservation and management. In this context, laser scanner surveying has emerged as a fundamental tool for quickly and accurately collecting and representing geometric and dimensional information in the form of three-dimensional point clouds.

Nowadays, 3D scanners can automatically, systematically, and rapidly acquire an object's spatial coordinates or surface. The basic principle upon which different types of laser scanners operate is the emission of a beam, light field, or pattern onto the object, followed by the analysis of the returned signal. For this reason, laser scanners are classified as active optical sensors, as they emit energy in the form of light. For instance, TLS technology is based on the emission and reception of a beam, light field, or light pattern. It differs from photogrammetry, which does not involve the active emission of light. Overall, laser scanners are a valuable tool for efficiently and accurately capturing and representing the geometry of an object or environment in a digital format.

During the scanning process, the device records angular data, distance, and reflectance related to the material properties of the scanned surface. The laser projects a beam onto the surface of the surveyed object, and a sensor measures the time of flight (TOF) or phase shift (PS) of the returned beam and calculates the distance between the device and the object. By performing and aligning multiple scans, the complete geometry of the object can be determined. Laser scanners usually capture the surrounding reality as a series of points in three-dimensional space, known as a point cloud. This point cloud is structured, with each point associated with a group of neighbouring points.

2.2 Parametric 3D Modeling

Parametric modeling is a digital modeling technique that has garnered significant attention within the fields of architecture and construction in recent years. It is often referred to as "feature-based modeling" due to the fact that objects are created through a series of processes or "features" with specific attributes that are controlled by parameters. This approach enables constant control over the geometry and underlying mathematical rules of a model. It involves a separation from traditional Computer-Aided Design (CAD) techniques and has been embraced by many professionals due to its flexibility and innovation.

Three primary techniques for parameterizing geometries are available: geometric constraint solving, textual scripting, and nodal (or visual) scripting. Geometric constraint solving involves connecting different parts of a model through dimensional and geometric constraints. For example, this technology is used to directly model parametric BIM object families. Textual scripting utilizes text-based programming languages (e.g., C#, Python, etc.) to execute programs. It allows for maximum versatility and accessibility to computer system resources but requires a high level of computer knowledge.

On the other hand, nodal programming utilizes visual and non-textual objects and does not require programming knowledge. It uses a graphical interface with two screens: one for drawing the node diagram and the other for visualizing the generated geometries. By relying on graphs and flowcharts, visual programming (VP) makes parametric modeling more accessible to non-computer operators who lack textual programming skills. This way, complex modeling systems can be created by appropriately connecting nodes and arrows in sequence.

VP languages are commonly employed in Cultural Heritage (CH) due to their ability to create complex data processing systems without high programming expertise. As the adoption of parametric modeling continues to grow, many professionals have started utilising these techniques in their work.

2.3 Reverse Engineering for Improved Built Heritage Structural Knowledge

Historical buildings' structures often exhibit a high degree of complexity in their geometric, construction, and technological characteristics. For instance, timber roofs often have various structural patterns, methods of cutting and assembling elements, metal connections, and elements with variable or irregular cross-sections. At the same time, masonry façades often show numerous architectural details on their surface, such as half pilasters, buttresses, protrusions, and recesses. The digital interpretation of these complexities needs precise and accurate surveying tools, as well as advanced 3D modeling techniques, able to capture the unique features of each structural category while adhering to their specific semantic rules.

As anticipated, digital tools for surveying existing buildings have gained widespread adoption among professionals due to their ability to quickly and accurately acquire data at a reasonable cost. LIDAR (Laser Imaging Detection and Ranging) and TLS techniques have become prevalent. Moreover, there are numerous methods for generating 3D models in various formats from scanned point clouds, including the interpolation of surveyed points using meshes or 3D reconstructions based on NURBS surfaces. However, the application of raw survey data to create 3D models for understanding the structural behaviour of heritage buildings is still in its early stages. While there have been some notable efforts in this direction in recent years, they have been mainly geared towards research rather than practical-professional purposes.

For instance, Bertolini et al. [1] utilized TLS point cloud data to manually render a finite element model (FEM) for analyzing the state of the roof at the Castello del Valentino. Andriasyan et al. [2] employed TLS or Structure From Motion (SFM) data to reconstruct the geometry of elements within historic buildings into information models using parametric algorithmic modeling techniques. Santos et al. [3] developed a method for analyzing the structural health of historical timber structures with irregular sections by combining LIDAR data with data from non-destructive tests and storing them in a Heritage Building Information Model (HBIM) for numerical analysis using FEM. Youn et al. [4] applied a similar approach to analyze the structural behaviour of a Korean historic building before and after a restoration project. Among other examples, Moyano et al. [5] used TLS tools to acquire accurate geometric data of a historic portico in Spain. In their investigation, the cloud of survey points was converted to 3D models and then compared with them through VP algorithms to detect hypothetical structural deformations of the columns. Instead, Wang et al. [6] have developed a fully automatic method for generating the axes of some masonry columns from the output data of a TLS survey to transform the clouds into FEM models and perform numerical calculations.

3 Method

3.1 Methodological Approach

The experimental methodology described in this study aims to understand, evaluate, and interpret the behaviour of some heritage building components by analyzing the hypothetical displacements and deformations that they have gone through over time. This method considers the geometric and typological properties of these building parts and their evolution over the years. It has been tested and applied in various case studies and refined through years of research. As a result, some tools and procedures have been developed. These latter can be generalized to different kinds of construction elements, including linear features such as beams and columns, surface features such as façades and slabs, and more complex systems such as timber trusses.

The main premise of the method is to take advantage of the vast amount of spatial information that can be obtained from a survey conducted using digital instruments such as the TLS. This instrumentation allows for the detailed examination of parts of the building which are difficult to access or observe using traditional (manual) tools due to their inaccessibility, height, or obstruction generated by other elements commonly found in such places. These highly accurate geometric data are first used to analyze the geometry of the structural elements in detail. Afterwards, these data are processed to draw conclusions about the deformational state of the surveyed building parts and, therefore, of their state of preservation. In addition, the integration of geometric data with information from historical-archival research enables the construction of solid hypotheses about the actual behaviour of the whole surveyed building, aiding in the structural understanding of these constructions for conservation designers.

3.2 Method Articulation

In summary, the 3D points related to every single structural element are extracted from the point cloud of the entire building, got through laser scanning, and the section curves of the component are vectorized using parametric modeling software. By extruding these curves into space, two three-dimensional models are obtained; they are defined as the Basic 3D Model (B3M) and the Ideal 3D Model (I3M). The B3M represents the current state of the structural elements, while the I3M recreates their hypothetical original condition based on solid and reasoned assumptions. The comparison of these models with the point cloud allows for the detailed analysis of the hypothetical displacements of the elements, the deduction of punctual and comparative information on their behaviour, and the development of global considerations on the health of the structure. This information can be used to plan monitoring and maintenance cycles or, if necessary, to support structural renovation or reinforcement interventions.

The investigation method consists of four main steps: data collection, data modeling, data analysis, and critical interpretation of the results. A fifth monitoring phase can also be added to these steps (Fig. 1).

In the first phase of the experimental methodology, the elements to be analyzed are identified, and a preliminary survey is conducted to acquire relevant spatial data using laser scanning techniques. After the survey, the various TLS scans are aligned using

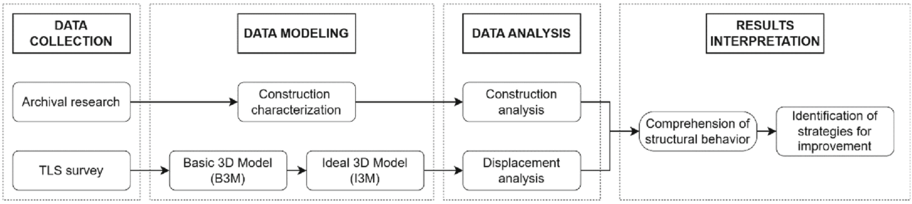

Fig. 1. The investigation method workflow.

dedicated programs to create a point cloud, which accurately represents the current state of the structural elements. The point cloud is then edited to remove unwanted objects, such as furniture, pipes, ducts, and scaffolding. In parallel with the registration of the scans, historical-archival research is conducted on the building's records to identify the main evolutionary stages of the structural system that have occurred over time.

In the data modeling phase, the point cloud is transformed into semantically defined three-dimensional parametric models using generative algorithms. These models are then compared with the original point cloud to highlight deviations between the models and the actual geometry from which they are defined. This data collection is summarised in tables, graphs or reports, providing a knowledge base for assessing the hypothetical deformation state of each element.

The displacement analysis phase involves the interpretation of the displacements of every single structural element to formulate hypotheses about the overall behaviour of the building system and to identify the criticality of the connected structural parts. The interpretation of all the acquired and processed information represents the first critical step in order to figure out the surveyed building components' behaviour and serves as the starting knowledge base for planning any maintenance or structural improvement interventions.

The process can be repeated periodically or after unpredictable catastrophic events, such as fires, storms, or earthquakes, to monitor the building elements' displacement and deterioration trends, assess the building's health, and retrieve further data. This can be defined as the monitoring phase.

4 Case Studies

The presented paper describes the application of the assessing method on two case study heritage buildings in Italy: the Basilica of San Domenico in Siena and the Teatro Comunale in Bologna. The method has been previously tested on several other historic masonry buildings, but this is the first time it has been applied systematically to identify the specific vulnerabilities of specific building elements. In particular, it has been tried out the masonry façades and columns in the Basilica of San Domenico and timber trusses in the Teatro Comunale. While previous works [7, 8] have helped assess specific vulnerabilities in these and other buildings [9–12], this study, for the first time, represents the approach comprehensively, showing how the authors took advantage of the previous analyses to systematize the method.

4.1 Façade Modeling

Linear kinematic analysis, which decomposes masonry structures into macro-elements, is commonly used to assess out-of-plane mechanisms (1st mode) in historic masonry buildings. This kind of assessment is feasible because studies on buildings that have experienced earthquake damage have shown that their seismic behaviour is characterized by the autonomous structural response of the macro-elements rather than the structure as a whole. This expected behaviour is often due to disconnections between construction elements in historic masonry buildings, which can be exacerbated by earthquake action and do not provide structural continuity.

Although standard qualitative assessment methods are widespread and used for understanding masonry building construction and cracking framework while aiding numerical assessments, they depend heavily on the technician's judgment and interpretation of the activated kinematic chains. For this reason, it was decided to use the point cloud data collected through TLS and process them through parametric modeling to improve and support evaluations and turn them into more objective results.

The modeling process applied on masonry façades consists in transforming the surveyed point cloud, namely the façade's B3M model, into the façade's I3M one, using generative algorithms (Fig. 2). In this case, the I3M represents the hypothetical undeformed configuration of the wall in which all out-of-plane deformations are removed. In other words, the façade's I3M coincides with the average "plane" of the façade, also definable as the "Ideal Plane" representing the ideal condition of a perfectly vertical wall.

The wall point cloud is first cleaned and divided into inner and outer surfaces to generate this Ideal Plane. Then, a Grasshopper© algorithm vectorizes the horizontal cross-sections of the wall and selects the portion that best represents the planar condition of the facade, removing any protrusions or recesses. A linear regression plane is computed starting from the cross-sections to determine the I3M, representing the ideal condition of the wall, namely the Ideal Plane.

The I3M serves as an excellent approximation for evaluating out-of-plane deformation. By comparing it to the B3M, it is possible to identify the areas of the façade that most deviate from the average vertical mean plane. This information, obtained by the I3M and B3M comparison, can be used to assess the current condition of the façade, interpreting its behaviour through the identification of the areas that may require more attention or repairs.

4.2 Column Modeling

Masonry columns are frequently found in traditional Italian buildings in many places, including porticoes and church naves. They are intended to transfer the structural loads of horizontal elements, like vaults and arches, to the ground or underlying structures.

To properly preserve vaulted structures, it is necessary to thoroughly understand their various characteristics, including form, construction, static and seismic behaviour, and many other relevant factors. Therefore, examining those structures that support masonry vaults, such as columns, can be essential for understanding their behaviour and ensuring long-term preservation. In fact, in many cases, irregularity in column displacements can

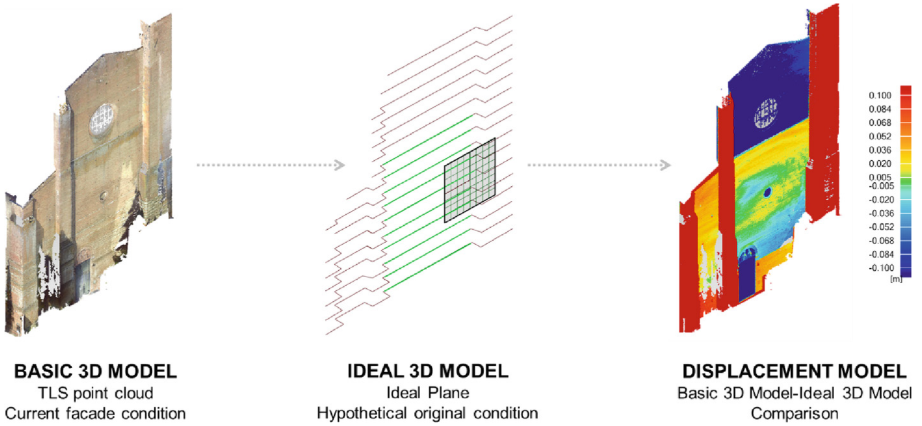

Fig. 2. Facades. Basic 3D Model (B3M), Ideal 3D Model (I3M) and Displacement Model (DM).

be linked to specific crack patterns in the above vaults, allowing for a better understanding of the operational state of the structures and guiding structural intervention efforts.

The TLS point cloud of each masonry column, representing its current condition (B3M), is transformed into a parametric 3D model (I3M) using a VP algorithm. The I3M represents the hypothetical initial condition of the structure, generated considering the absence of transverse deformations. These transverse deformations may be caused by the horizontal thrust of arches and vaults resting on the columns, as shown in the case study presented in this paper. Axial deformations are disregarded when modeling the I3M since these may be deemed negligible compared to transverse deformations, which are often present in this kind of construction element. A second fundamental assumption for the model generation is the null displacements at the base of the column.

From the computational point of view, the algorithm takes as input the point cloud data of each column. It then selects horizontal bands of 3D points, vectorizes the transverse cross-sections of the column, determines their centroids, and projects the centroids and respective section curves onto a vertical axis passing through the centroid of the lowest elevation section, which represents the base of the column. The I3M model is then created from the projected curves using a loft function, generating a perfect vertical column (Fig. 3).

By comparing the I3M to the original point cloud data, deviations between the deformed and undeformed columns can be identified as long as potential safety issues with the structures above, such as arches and vaults, can be highlighted.

4.3 Timber Truss Modeling

In the field of Construction History, timber trusses were often used in Italy as covering systems for large spaces, such as churches and theatres. Trusses may be susceptible to material degradation or structural vulnerabilities, proper of past construction techniques; therefore, it is essential to evaluate them critically to preserve their authenticity while ensuring structural safety.

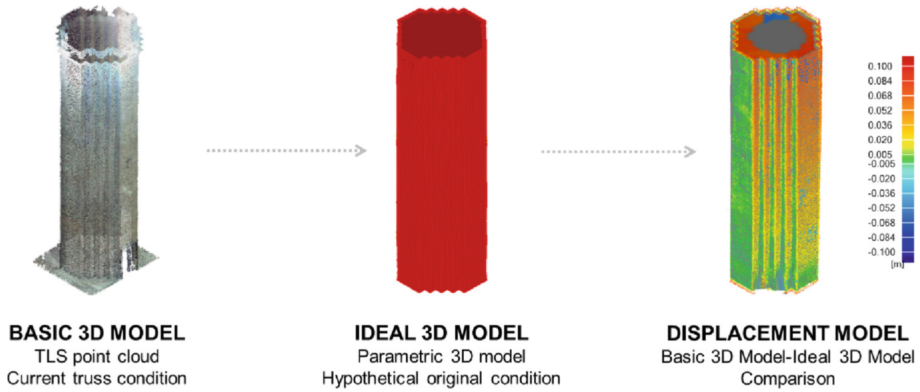

Fig. 3. Columns. Basic 3D Model (B3M), Ideal 3D Model (I3M) and Displacement Model (DM).

Gathering information about these structural systems is vital for three main reasons: understanding their history and the changes they have undergone over time is necessary for appreciating their material culture and preserving their historical value; knowing their current state is crucial for developing a conscious conservation design, planning maintenance, and allowing for the daily use of the buildings they cover; investigating and monitoring their conservation state can provide valuable information about the overall health of the heritage buildings in which they are located.

In order to gather this information, TLS point cloud data and historical data from archival research are collected and modelled to improve the understanding of such timber frame systems. The point cloud data of each timber truss, the B3M, is transformed into a 3D model, the I3M, using generative algorithms in the Grasshopper© software. As for facades and columns, the B3M represents the current condition of the truss, while the I3M depicts the hypothetical initial state of the timber structure. To create the I3M, in-plane and out-of-plane displacements of the truss are removed based on specific theoretical assumptions formulated in previous research by examining the in situ behaviour of timber trusses. These assumptions include the lateral bearings remaining in their original position, the projection of each member's centroidal axes onto the vertical plane of the truss, slight bending deformations in the tie-beams, inward translation and lowering of lateral rafter-post joints, rotation of bottom rafters around the virtual centre of lateral bearings, and the absence of beam axial deformations.

Therefore, the I3M parametric model is compared to the original TLS point cloud to assess displacements and deformation states, producing the so-called Displacement Model (DM). The comparison between the point cloud and the 3D model reveals the differences between the current condition of the truss and its original undeformed state. The geometrical deviations identified between the B3M and the I3M are considered the possible deformations that the timber elements have undergone over time and are represented in the DM using a chromatic scale (Fig. 4).

The prime deformations examined are the lowering and rotation of the joints between posts and rafters and the bending deformations of the tie beams.

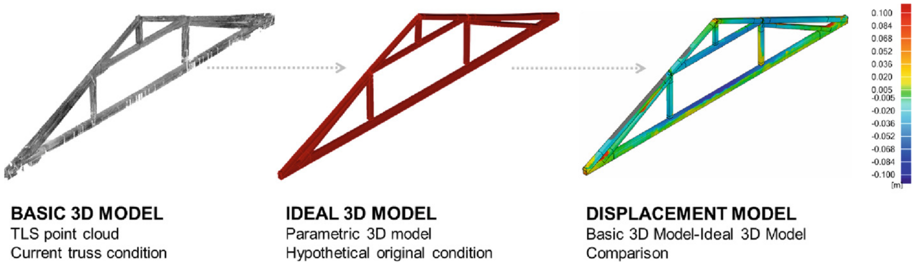

Fig. 4. Timber trusses. Basic 3D Model (B3M), Ideal 3D Model (I3M) and Displacement Model (DM).

5 Results

The chromatic scale in the following figures highlights deviation trends for some investigated heritage structures. Moreover, the tags in the images report the numerical values of the most significative displacements detected for these structural elements.

5.1 Façade Displacements

The combination of displacement analysis with analysis of crack patterns, as well as historical research and in-situ inspections, allowed for the confirmation of hypotheses about the behaviour of the facades of the Basilica of San Domenico, leading to interesting and consistent results.

This study shows the analysis performed on the exterior surface of a transept's façade to understand its behaviour and any potential issues. Following the proposed method, by dividing the façade into its lower and upper parts, the algorithms identified the deviation trends between the B3M and the I3M illustrated in Fig. 5.

The lower part of the façade exhibited a relative offset of approximately 9 cm between its base and top, with the top projecting outward from the building (rotation about the x-axis). The upper part of the façade displayed similar displacements. It was also rotated in the horizontal plane with respect to its ideal plane (rotation about the z-axis), with the side of the facade adjacent to the bell tower projected outward from the building. Based on the combined results of these analyses, it appears that the façade has undergone a simple tilting. This hypothetical movement seems to be related to the movements of the bell tower, although further research is needed to confirm this hypothesis.

5.2 Column Displacements

In the case of the columns inside the transept of the Basilica of San Domenico, the integration of displacement analysis with crack pattern analysis and the incorporation of historical research and in-situ inspections resulted in coherent findings about their behaviour. Similarly, this combination of approaches also provided insight into the behaviour of the vaults in the basilica's crypt.

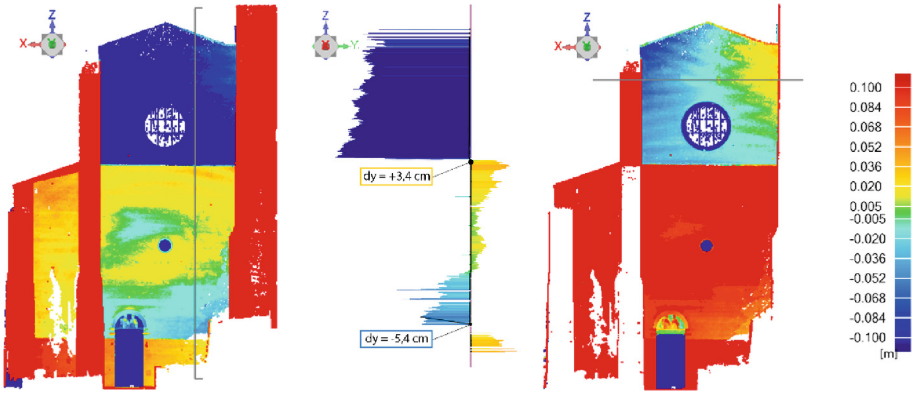

Fig. 5. Displacement analysis of a transept façade of the Basilica of San Domenico in Siena, Italy. Green points lie on the façade mean plane, red points deviate from the mean plane towards the outside of the building, and blue ones towards the inside. The deviation values are magnified by 100 for improved readability in the sections.

As shown in Fig. 6, qualitatively symmetrical displacements were observed for the two central columns. However, the right central column exhibits higher quantitive deviations compared to the left central column, with a relative offset of approximately 7 cm over a length of 580 cm.

The overall displacements of the columns in the crypt underline a deformation mechanism caused by the thrusts of the overhead central vault, which is more significant than the lateral ones. The deformation mechanism is highlighted by a large crack located in the centre of the vault, highlighted in red in Fig. 6. The results of this analysis suggest the need for interventions in the crypt to limit this phenomenon and prevent structural collapses. For example, metal chains could help absorb the thrusts of the vault on the column heads.

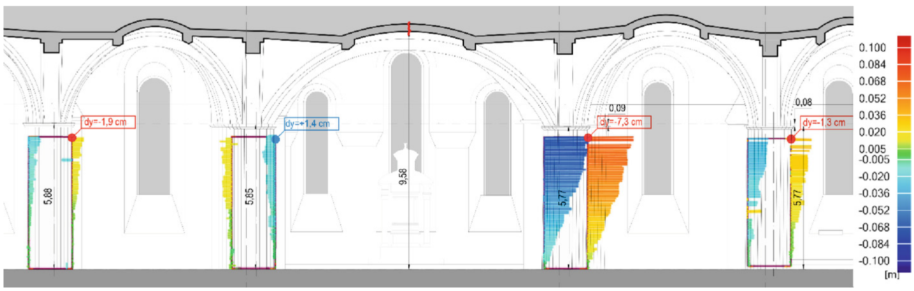

Fig. 6. Displacement analysis of some of San Domenico's crypt columns. Green points lie on the I3M, representing null deviations. Red points deviate from the I3M outside, while blue ones are inside. The deviation values are magnified by 100 for improved readability in the sections.

5.3 Timber Truss Displacements

Applying the method to the timber trusses of the Teatro Comunale provided valuable information on the conservation state of the building's roof system. Comparisons of the I3M and B3M, such as the one shown in Fig. 7, allow for the development of general evaluations about the current deformation states of the roof trusses. In this case, only the displacement analysis in the vertical plane of the trusses is presented, as it is more significant than the out-of-plane analysis.

The Theater's analyzed trusses exhibit similar behaviour in their plane to that identified for the truss in Fig. 7. According to the results, the behaviour of this truss is slightly asymmetrical in its plane with regard to the lowering of the post-rafter joints. In particular, modest lowering values of about 3 cm are detected for the right post-strut joint, and the lower values of the left post-rafter joint and the ridge joint are negligible. In addition, clockwise rotation is observed for the right queen post and counterclockwise rotation for the left queen post. The right queen post exhibits higher rotation compared to the one on the left, being this imbalance reflected in the king post, for which a slighter clockwise rotation is detected. The rotation values are closely related to the displacement values of the joints: the greater the lowering, the greater the rotation of the joint. When related to the span of the trusses (about 25 m), the lowering values indicate that the covering system suffered only a slight deformation and, therefore, is in good condition. The same can be said for the tie beam, which presents minimal bending displacements.

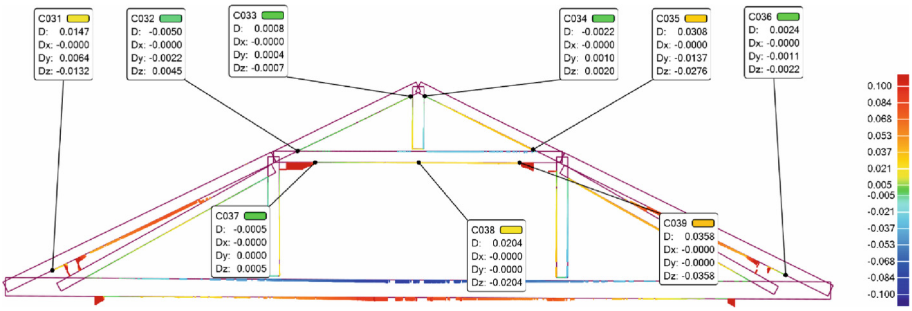

Fig. 7. Displacement analysis of a timber truss located in the Teatro Comunale of Bologna, Italy. Green points lie on the I3M, representing null deviations. Red points deviate from the I3M outside and blue ones inside.

6 Conclusion

The parametric 3D modeling method, which is used to evaluate and interpret the deformation states of some construction elements found in traditional Italian architectures, such as masonry facades, columns, and timber trusses, has proved to be reliable and valuable for examining heritage buildings from the structural point of view.

The use of TLS tools and visual programming algorithms on historical structures has demonstrated how crucial integration between digital technologies and building restoration practices is. Additionally, applying this research method provides information that is often difficult to obtain through traditional methods.

The displacement analysis that was applied to 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 behaviour of the investigated elements, as well as providing insight into the overall behaviour 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 behaviour 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.

Finally, applying the method to a variety of element types has contributed to the reliability of the process, which was initially developed only for timber trusses. 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 for understanding many other elements within a building in a more global and comprehensive approach.

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