UAS and TLS 3D data fusion for built cultural heritage assessment and the application for St. Catherine Monastery in Ferrara, Italy

Matilde Balestrieri[1], Irene Valmori [1], Manlio Montuori [2]*

[1] Matilde Balestrieri & Irene Valmori Private practice, viale Villa Eugenea 26, Civitanova Marche, Macerata, Italy; via Pomposa 87, Ravenna, Italy {matilde.balestrieri13; irenevalmori97}@gmail.com

[2] University of Ferrara, Department of Architecture, via della Ghiara, 36 – 44121 Ferrara, Italy manlio.montuori@unife.it

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Abstract

The present research, conducted at the Monastery of St. Catherine in Ferrara, Italy, is an integral component of a broader investigation focused on comprehending, recognizing and enhancing the tangible values of the Dominican priests and their sacred sites in Ferrara, utilizing advanced digital surveying techniques. The architectural legacy of this monastery serves as a insightful link to the city's history and inhabitants. Regrettably, its typological features are frequently overlooked or altered, underscoring the need to grasp these characteristics as a fundamental step in ensuring their preservation. Given the monastery's distinct typological and geometrical attributes, an integrated survey approach was implemented to gather essential data for reconstructing the building in its existing state, encompassing both an urban and detailed scale. This comprehensive assessment sought to evaluate the critical conditions of the construction that required improvement.

The objective of this paper is to underscore the advancements achieved in assessing structural health behaviour, incorporating data obtained through terrestrial laser scanning (i.e., TLS) and structure-from-motion techniques, coupled with an unmanned aerial system (i.e., UAS), to generate a three-dimensional data model that accurately captures the entire spatiality of the building and its urban context. As a result, the building assessment demonstrated which parts of the building's facades were overturning, while identifying the thorough kinematic phenomena progressively acting. The related considerations lead to a structural project perfectly shaped on the unique characteristics of the complex supported by data as accurately as possible, which also positively influenced the entire architectural design process.

1. Introducion

Structural analyses usually use geometric models that are significantly simplified to facilitate and expedite numerical computations. Occasionally, this method is valid and convenient, provided that it does not affect the analysis results. Nevertheless, the model must be accurately and precisely represented to encompass the necessary outputs, depending on the analysis's circumstances and objectives. This is the case with built cultural heritage. The geometry can be significantly affected by the complex forms and noteworthy damages frequently present in the surveyed sites in this field. Numerous methods are available to generate highly detailed models of a building's surface. However, these methods do not account for interior defects or constructive features. This information can be acquired through a thorough investigation and anamnesis of the case study based on visual inspection and instrumental measurements. Understanding the numerous benefits of 3D new metric survey technologies for 3D modelling reconstruction, the research leads a comprehensive 3D data acquisition process, utilising various sensors and exploring their potential fusion. In addition, it required the use of UAS photogrammetry to efficiently gather data on the building's rooftop at a low cost. This data is then combined with terrestrial measurement techniques. As the need arises to identify the minimum network configuration for combining TLS and UAS photogrammetry data fusion, on-site procedures should be updated by registering TLS and UAS point clouds using a multinetwork configuration. Furthermore, the results of the data fusion should be assessed by measuring the registration error of the UAS with regard to the TLS coordinate system using different network configuration samples. Based on the experimental findings, the sample network design for the registration points exhibits excellent performance since their positioning is evenly distributed, and there are fewer errors in the registration of both point clouds. Therefore, the effectiveness of data fusion between TLS and UAS photogrammetry relies on carefully choosing the registration points through multiple network configurations. In this manner, the operator's conscious synthetic procedure is employed to generate the model for bearing structures analysis. In order to demonstrate that the results of structural analyses can benefit from the model's accuracy and level of detail backed by an integrated survey approach, the investigation focuses on a fundamental building component, specifically a long and slender facade that is a genuine component of the monumental black friar monastery dedicated to St. Catherine in Ferrara, home to cloistered nuns. The facade is modelled, integrating distinct methods, each with a varying level of detail. Furthermore, an evolutionary assessment of failure mechanisms is performed to address the actual state of conservation and characterize the fractures that are incorporated into the most precise models.

1.1 Pilot site

Located in the dense urban tissue site not so far from the Estense Castle, the Monastery of St. Catherine occupies a position behind the ancient axis of via degli Angeli – today, Corso Ercole I d'Este – where the former St. Maria degli Angeli church and Palazzo dei Diamanti stand. The site's uniqueness is rooted in its intricate planimetric layout and the initial absence of comprehensive geometric data. Specific planovolumetric

transformations were identified through extensive inspections and direct observations of this wide-ranging facility. However, it is noteworthy that the existing descriptions need more substantial documentary support for a thorough understanding of these changes (De Fino, Galantucci and Fatiguso, 2023). The absence of in-depth geometric data at the project's outset underscores the significance of on-site inspections in revealing essential planovolumetric characteristics within the building.
Hence, the preliminary investigations into the factual consistency of the building have predominantly delved into its chronological stratification, while archival documents have surfaced to shed light on its original implant, formal, and geometric attributes, particularly those that have undergone alterations over time. Actually, the meticulous analysis of manifold indirect sources within the Ferrarese Diocesan Archive unveiled several original rooms that, over the centuries, were lost due to profound architectural alterations. This process enabled the recognition of historically significant spaces previously obscured by the passage of time and transformations.
A comprehensive survey approach is adopted to collect the data required to reconstruct the monastery's current state, taking into account its unique typological and geometrical characteristics (Tucci, Bonora, Conti and Fiorini, 2017). Considering these factors, the documentation approach's primary objective was to leverage the latest technologies and instruments. The aim was to acquire actual data for the precise architectural analysis of the former monastery, addressing both morphological and historical inquiries surrounding its evolution (Volk, Stengel and Schultmann, 2014). Utilizing cutting-edge tools was pivotal in meeting the critical requirements for accurate and comprehensive documentation of the actual state of conservation toward the project intended to improve the structural behavior of the old brick masonry walls.

1.2 Research background

The anamnesis assessment of built cultural heritage is a critical process, especially in the aftermath of significant earthquakes that result in damage to monuments, heritage buildings, and landmarks (Letellier et al., 2007). The authorities are frequently unable to access the site due to extensive damage, and traditional methods for damage assessment are time-consuming. When conducting surveys of intricate constructions and significant cultural monuments that suffered damages from an earthquake impact, implementing new 3D documentation technologies facilitate the acquisition of precise and accurate results. High-quality 3D models of damaged buildings can be

Figure 1. Ferrara, aerial view from south. In the center, the Dominican monastery of St. Catherine.

Figure 2. The monastery of St. Catherine in the urban fabric of the Herculean addition.

generated using terrestrial laser scanners. TLS offers the advantage of reducing field time and gaining precise metric data without handling the measured subject, which is not always feasible or preferable. Furthermore, unmanned aerial systems can record the pilot site in high-quality images with a very high spatial resolution using a high-resolution digital camera. Vertical or oblique aerial images can be captured during low-altitude flights, enhancing the operator's safety in a damage scenario. Processing these imagery datasets with specific algorithms can generate 3D models that are highly precise. The structure-from-motion algorithm (i.e., SfM) is frequently employed in terrestrial and aerial photogrammetry when the results must be generated promptly (Westoby et al., 2012).
Data acquisition is facilitated by the increasing evolution of new technologies, such as TLSs and UASs, which are subsequently processed to generate precise and accurate 3D models of detailed objects. Nevertheless, a single sensor is unable to obtain a comprehensive understanding of a large object, even when multiple surveys are implemented (Xu et al., 2014). By utilising each technique in its respective contexts, combining TLS and UAS photogrammetry techniques enables the acquisition of exhaustive models of complex subjects, thereby demonstrating the most optimal operating conditions. The potential for rapid modelling, even of entire areas, is significant due to the methodological development for data acquisition and the ever-increasing computational power that has reduced machine processing times. The raw dataset obtained from the technologies mentioned above is combined to generate 3D models that are sufficiently dense in comparison to the actual object. The two technologies integrate and interact to address potential obstacles and can be implemented in the development of various assessment processes.
The airborne perspective supports the observation of the upper portions of buildings, including rooftops. In contrast, the terrestrial perspective can add to the data from lateral views to obtain a comprehensive registration of the pilot site. In order to enhance the quality of 3D mapping in various applications, numerous methods have been devised for the geometrical integration of the two categories of datasets (Wu and Tang, 2015). A practical framework for integrating UAS photogrammetry and TLS for the 3D mapping and monitoring complex heritage assets integrates ground-based survey methods and UAS photogrammetry through the Cloud Compare platform, thereby confirming its leading role in the analyses and further interpretations of built cultural heritage (Balletti et al., 2015). The results of incorporating both methodologies included maps, orthophotos, and 3D models (Reiss et al., 2016). The information contained in those products is crucial for stakeholders to effectively preserve built cultural heritage, archaeological assets, the environment, and other assets in pilot

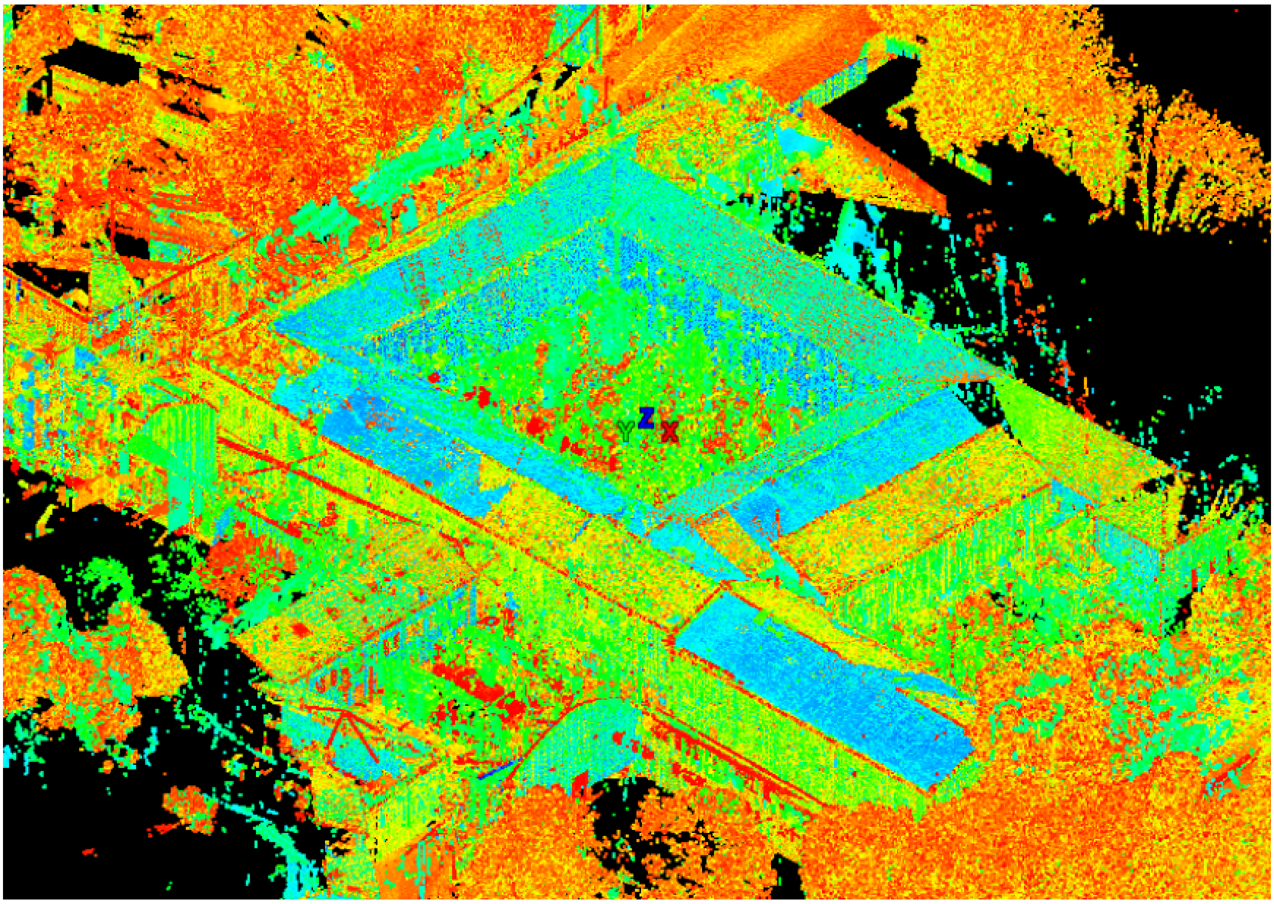

Figure 3. Perspective view of the TLS point cloud processed in Leica Cyclone®.

sites. This demonstrates the utility of combining TLS and UAS when applied to architectural and landscape assets (Chiabrando et al., 2016). Based on the respective advantages and disadvantages of the two types of datasets, the fusion of datasets derived from TLS and UAS photogrammetry gives a more significant potential for a variety of applications than that of a single type of data acquisition.

1.3 TLSs and UASs dataset fusion

Data fusion merges datasets collected from multiple sensors to generate a more accurate 3D model of the subject under investigation than one that can be derived from a single sensor. The visualization, classification, and assessment of a building are significantly influenced by its 3D modelling. The selection of a suitable data acquisition technique is conditioned upon the object's geometrical and morphological properties, the requisite accuracy, and the cost. Various data acquisition techniques are employed. Nevertheless, TLS is restricted to specific applications. For instance, the TLS's coverage area is limited by the sensor's line of sight in 3D building model applications. An unmanned aerial system is a surveying instrument that is both cost-effective and efficient, capable of capturing precise images of inaccessible areas. Structure from motion techniques are employed to generate the point cloud data.
Nevertheless, the 3D model generated from the UAS is restricted by its indistinct textures. The ground-based digital camera (i.e., DSLR) is another low-cost data acquisition technique presently employed in 3D modelling applications. Regrettably, digital cameras are subject to a line-of-sight limitation. Consequently, it is possible to argue that each data acquisition technique has advantages and disadvantages. Therefore, data fusion is a critical concern in developing precise 3D digital twins. The proposed method is a multi-sensor data fusion technique that combines the TLS and UAS data sets using the wavelet analysis method to produce a 3D building model. The building's features, such as the margins and segments, are extracted and compared to conventional ground survey techniques to validate the proposed method. It has been demonstrated that the proposed data assimilation method has enhanced the identification of the building's features.
Furthermore, the data fusion approach generates an accurate 3D building model by incorporating camera imagery. The cloud registration and bundle registration issues have been resolved to determine camera poses and dense model construction. The TLS survey has been used to validate the proposed model. Compared to the TLS survey, the model's accuracy was slightly 2.3 mm. Therefore, it is evident that an accurate comprehension of the geometries and the actual state of damage is a critical factor in assessing the structural behaviour of a building that will be subject to restoration and structural consolidation interventions. This will enable the intervention to be minimised and the design strictly necessary. Three processes (TLS, UAS, and DSLR) were compared and analysed to ensure an accurate characterization of the geometries and morphologies of the pilot site, which must be completed before the onset of project activities. After the accuracy and efficacy of the three techniques have been compared, the point cloud generated by the fusion of the three contributions will be used to conduct the next stage of damage mechanism assessment. Actuality, all three methods are capable of producing exact point clouds. Following the UAS and TLS approaches, the fusion model was the most precise, with the point cloud accuracy increased, yielding the most accurate outcomes. The integration of UAS

and TLS technologies mutually compensates for their respective weaknesses in image acquisition via scanning or aerial photography, depending on the situation and the subject investigated, even though the UAS approach is advantageous for performing processing quickly. The fusion method is the most suitable for investigating built cultural heritage, necessitating a more detailed point cloud, as it capitalises on the benefits of both UAS and TLS methods.

2. Damage mechanisms assessment in load-bearing structures

2.1 Built heritage modelling in hBIM environment

The advancement in information technology presents an opportunity for a groundbreaking transformation of conventional practices within the domains of built cultural heritage conservation and the construction sector, particularly concerning activities related to the control and management of existing architectural heritage. In this context, the proposed methodology capitalizes on an integrated 3D metric survey as the foundation for a digital elevation model (i.e., DEM), supported by the the development of an hBIM model (Yang et al., 2020). This model becomes instrumental in defining the most suitable interventions to enhance the structural behavior of brick masonries. The photogrammetric elaboration, in comparison to the geometric database containing the spatial coordinates of every single element of the point cloud coming out from the TLS campaign, was mostly exhaustive in giving the suitable working material to eventually deliver a truthful representation of the external surfaces, flawlessly coherent with its actual 3D configuration (Fang, Sun and Zhang, 2021). The application of a digital process, achieved through integrating a Graphisoft ArchiCAD® structural model into Rhinoceros3D®, facilitates a comprehensive understanding of the current crisis state of overturning masonries. The delineated workflow delves into interoperability challenges and details in scan-to-hBIM processes, clarifying how hBIM models can nonetheless underpin operations aimed at maintaining and preserving existing historical assets, even from a structural standpoint, albeit with persistent challenges. This illustrative exploration highlights the efficacy of leveraging digital technologies in advancing the conservation and management practices of built cultural heritage, particularly in addressing structural concerns associated with historical masonries.

Conventional practice in structural analysis involves simplifying geometric models for quicker numerical solutions. Though this is often true, the appropriateness of this approach depends upon the objectives of the analysis. The accuracy of representation becomes crucial when it comes to architectural heritage, where surveyed objects exhibit complex shapes and significant damage (Sánchez-Aparicio et al., 2023). This information involves meticulous knowledge, anamnesis, visual inspection, and instrumental measures. It is a deliberate, synthetic operation that leads to the creation of a model for structural analysis. A key finding of the present approach is that the precision and detail of the model determine the accuracy of structural analysis results, emphasizing the importance of conscientious consideration of accuracy in order to achieve meaningful and reliable results.

The objective of incorporating the as-built BIM technique into heritage modelling is to emphasise the thorough relationship between object modelling and information, which encompasses a variety of attributes, temporal change, spatial constraints, and damage documentation (Parisi et al., 2019). In particular, hBIM is appropriate for the restitution of built cultural heritage from the existing description data, including historical documents, bibliographic references, photographs, and drawings. This is particularly true for analysing the evolutionary and transformative phases of past-disappeared elements, which impacts the assessment of load-bearing structures.

Therefore, as previously reviewed, the as-built hBIM model is used to store, model, and manage tangible, valuable constructions and historical aspects by applying reality-based recording data. A library of parametric and semantic elements, including walls, roofs, stairs, doors, and windows, is developed and utilized to facilitate the quality assessment of failure mechanisms in an as-built hBIM environment, with the support of archival documents and reality-based recording data (Adami et al., 2023). The monastery is not merely a virtual representation in the model. It is a critical component of the conservation project, in which the various components of the Dominican cloistered compound are transformed into sophisticated objects with parametric intelligence, including strict relationship information and quantitative and qualitative descriptions.

The hBIM model serves as a parametric design toolset that enables information storage and modification linkage. The elements can be modified by changing parameters, while the relationships to other objects remain unaltered. In an effort to document the built heritage, the implementation of the hBIM modelling workflow integrates both descriptive and reality-based data (Bagnolo et al., 2019). The parametric elements related to the monastery compound are initially built using Graphisoft ArchiCAD® software, with the support of merged TLS-UAS datasets. The refinement of parameters and the acquisition of a current-state diagnosis are facilitated by implementing inverse engineering, which maps the parametric elements to the reality-based data (Fai and Rafeiro, 2014).

Consequently, the hBIM initiative organizes the protocol

Figure 4. Former church of St. Catherine, south elevation. Orthomosaic processed in Agisoft Metashape®.

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generated simultaneously or directly by analysing documentation and reality-based data. In other words, the manual interpretation and 3D structure similarity measurement are essential processing steps that need to be performed to integrate the standard morphologies and BIM components into the 3D point cloud (Zhang et al., 2016).

2.2 Digital elevation modelling

DEMs are the digital graphic representation of the elevation distribution of a territory or a specific surface in the archaeological field. They are exported in raster format, enabling each image pixel to be associated with elevation data represented by a preset colorimetric degree (Chukwuma and Smit, 2022). Their utilization was intended to generate an analysis tool derived from the indirect survey of the pilot site, which was particularly intricate in terms of stratigraphic context. The management of digital models in a GIS environment allows the use of such items to conduct indirect investigations that are typically challenging to perform. For example, constant cross-sections of an entire wall under investigation, which is difficult to access, are now feasible. The residual error levels do not affect the structural analysis or the conservation project's performance, and the time savings are significant.

In comparison to the application in the study of archaeological excavations, the use of DEMs is significantly less explored in the study of building facades and even less in the structural field. This field still needs to be investigated. In contrast to the ground strata, the elevations of the investigated masonry walls are identified by a false colour texture that accurately reflects their current condition in relation to a vertical plane. At the architectural interpretation level, it was therefore feasible to rationalise on the most conventional stratigraphic evidence, defined by the materials employed and the construction methods. Additionally, the manifestations of damage to the walls, which were in some instances indicators of stratigraphic changes in the otherwise challenging-to-read building, and, most importantly, the activation of damage mechanisms, were considered. This method established a close relationship between the current state of the structural elements and the archaeological stratification that has accumulated on them by concentrating attention along the southern sector of the monastery along via Roversella. This is particularly significant in the context of the analysis of the kinematics of the macroelements for the conservation project. The front elevation is analysed by projecting it onto a reference plane constituted by an ideal surface perfectly orthogonal and clearing through the middle of the masonry thickness. This method demonstrates how the original building was modified over the centuries by opening new windows, infilling others, and constructing new intermediate floors following the change of use. Additionally, the transformation phases are analysed. This allowed for the graphic representation of a high static urgency caused by the out-of-plane rotation initiated by the roof struts' thrusting (Figure 6). The deformation is not visible to the sight along the longitudinal development of the slender walls. The DEM representation of the elevation is only made appreciable through the accuracy of the integrated TLS-UAS survey, which allowed

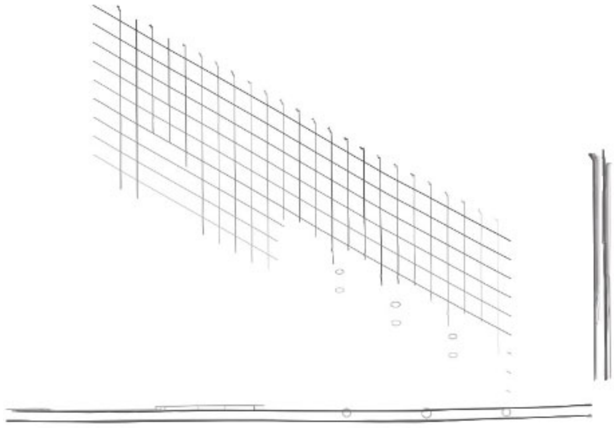

Figure 5. Front elevation along via Roversella, constant pitch cross-section planes for the out-of-plane overturning assessment.

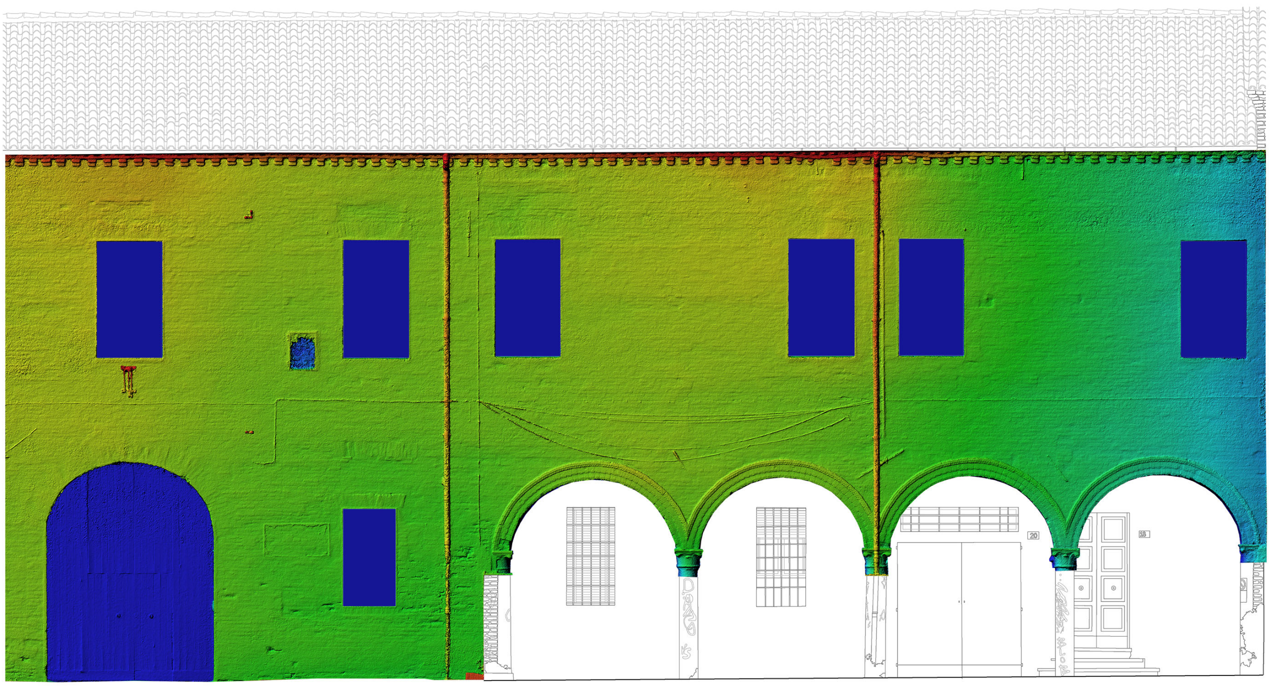

Figure 6. Front elevation along via Roversella, digital elevation model.

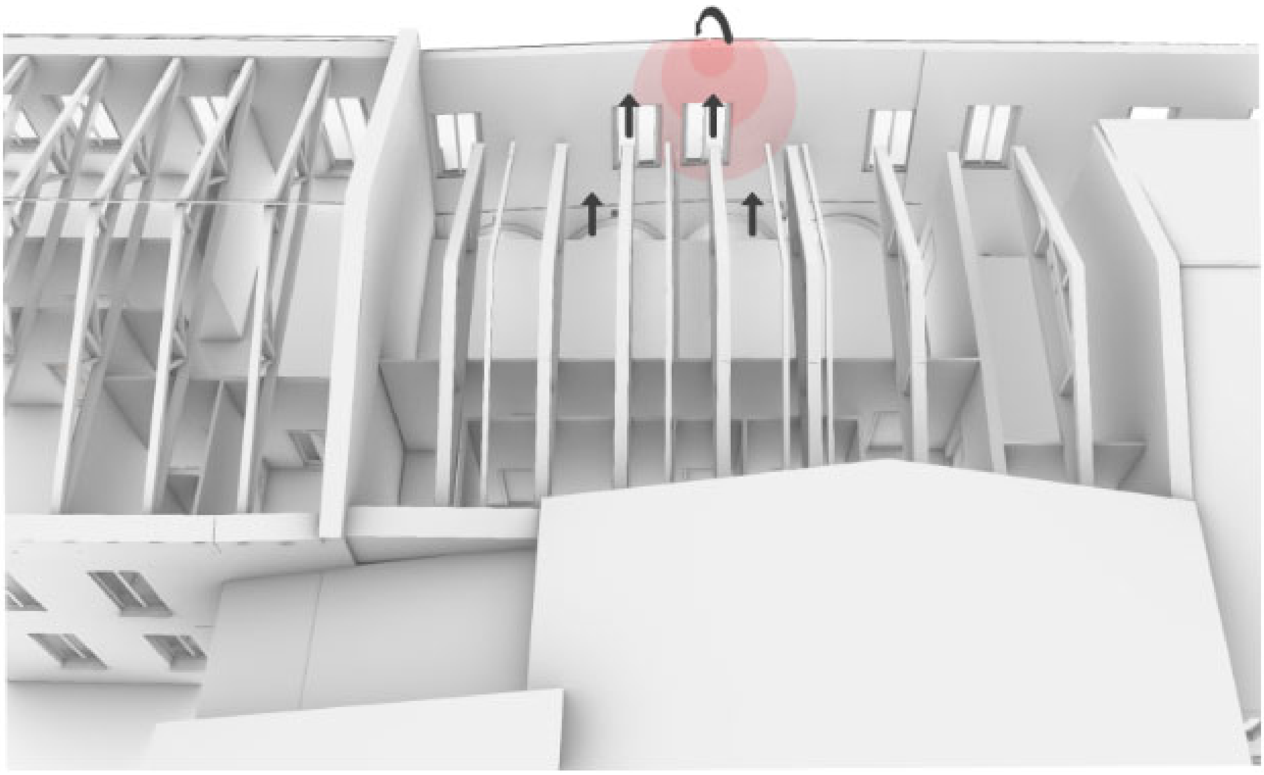

Figure 7. Former church of St. Catherine, south elevation, macroelement collapse mechanism.

for the identification of the true extent of the phenomenon.
This method is advantageous for assessing the general statics of the building in anticipation of the conservation project. However, it is equally beneficial for interpreting the transformation phases when applied in conjunction with the stratification process analysis. The point of greatest static urgency is concentrated near two distinct stratigraphic units as the result of the modification in the construction technique used to construct the roof, which corresponds with the division of the liturgical hall between the cloistered nuns and the secular people. This modification caused a progressive superficial depression that became increasingly apparent over time, resulting in the current state of general deformation of the masonry. This deformation subsequently extended to the entire central portion of the façade.

2.3 Load-bearing structure failure mechanism

The case study under consideration, which is the former liturgical hall of the Dominican monastery, is morphologically defined as an assembly hall that is delimited by structural macroelements (including the lateral wall, façade, apse, and trusses, as well as the reinforced concrete floors that were introduced following the change in use for school activities). These macroelements, in combination, form the structural organism of the building. The evolutionary analysis of damage has identified unique and recurring collapse mechanisms for each macroelement that have been extensively documented in the literature (Doglioni and Mazzotti, 20027). This has been achieved through the limit equilibrium method, particularly in compliance with the kinematic methodology.
The analyses of the potential in-plane and out-of-plane damage mechanisms of brick walls have led to unique and intriguing findings. These analyses are of particular importance, as they are designed to assess the actions that activated these mechanisms in accordance with the geometry of the walls and the dimensional relationships between various structural elements. The collapse mechanism of a masonry macroelement is characterised by the formation of zones of accentuation of the deformation, which separate the macroelement into nearly rigid blocks. These blocks then assume a kinematic mechanism that results in collapse due to perturbing actions. The initial areas of singularity that are likely to generate disaggregation mechanisms are the connection sections between the macroelements of the load-bearing structure. This allows a macroelement to assume relative roto-translations concerning the surrounding portions. In an effort to raise awareness of the most effective interventions for enhancing the safety of the building, the DEM contribution in the evolutionary analysis of the damage associated with macroelements is here highlighted. This is particularly evident when the seismic events that have occurred over time are indicative and probative tests, especially if those suffered shattering trials were significant, such as the seismic sequence of May 2012.
The flexural behaviour of the brick wall in the horizontal plane poses a significant risk, as evidenced by the DEM representation. In this scenario, masonry walls are attached to the orthogonal walls and the upper side is not held back by any adevice. The seismic action orthogonal to the wall calls into question the structural response of the wall, which is characterised by a horizontal arch effect within the wall (Figure 7). In particular, the push action conveyed by the roof at the top of the wall is discharged onto the wall and, at the orthogonal intersections, is divided into an orthogonal component, that is absorbed by the tie rods of the roof trusses, and a component that is parallel to the wall. In the limit condition of equilibrium, three hinges are formed: one in the middle, the other two near the intersection between the wall in question and the heads of the trusses that support the highest tension state. The formation of a horizontal arch in the thickness of the wall precedes the activation of the mechanism. Collapse occurs when the wall lacks structural elements that can satisfy the reactions in the masonry plane, as indicated by the calculation scheme in the literature (Angelillo et al., 2018).
In this scenario, the wall is part of a structural scheme that provides adequate resistance due to the number of crosswise

trusses. Consequently, the collapse caused by kinematics is not triggered, and failure can only happen due to the compressed internal portion. In other words, the mechanism's development depends on the truss tie beams' capacity to sustain the component within the masonry's plane. The isostatic three-hinged arch scheme becomes labile when aligned, and the collapse kinematics is activated if the wall fails to locate contrasting elements that provide an equal and opposite reaction to this component. The situation described is precisely that of the walls being held back by tie rods, as in the case under examination. It is favoured by the thrusts at the head of the wall due to the anomalous presence of a pushing strut and the hammering action of the large frame elements of the roof. In addition, the masonry's tensile strength is diminished, which poses a risk of the material that forms the external face of the wall being expelled due to the tensile stress that develops in the masonry core due to the kinematics itself.

The presence of aligned apertures in the band under the roof and the quality of the masonry, which influences the height of the detachment wedge, are the primary factors contributing to the horizontal bending mechanism, which may entail variable geometries of the macroelements involved in the kinematics. In the present case, the identification of the horizontal bending mechanism is facilitated by the DEM, which provides critical information on the macroelements that have formed and have the potential to be activated despite the minor damage. If walls do not yet exhibit a crack pattern, the potential out-of-plane collapse kinematic mechanisms can develop with the involvement of more or less large portions of masonry. Nevertheless, it is not possible to estimate which kinematic mechanism is the most likely. To determine the most unfavourable condition, it will be necessary to assess various collapse factors by assuming varying geometries of the masonry regions influenced by the kinematics.

3. Results discussion

Combining both unmanned aerial system photogrammetry and terrestrial laser scanning, the research endeavour was able to develop an extremely accurate three-dimensional model of the Dominican compound and its church. The behaviour assessment of built heritage-bearing structures entails the 3D modelling of the geometry, typically achieved through digital twins developed through photogrammetry and laser scanning techniques, as well as the information management of semantic knowledge using geographic information systems and ontology tools. The most recently developed BIM technique integrates information management and 3D modelling. Heritage documentation is one of its contemporary applications, which led to the development of a historic building information model in conjunction with the historical inventory documentation gathered through several archives' surveys. The Graphisoft Archicad® application is employed for this purpose. This paper provides a concise overview of the applications of these information techniques to the documentation of built cultural heritage. The techniques are implemented through laser scanning, computer science, GIS, and particularly BIM. Traditional methods for heritage documentation include ontologies and 3D computer graphics. Additionally, the investigation examines the functions of BIM in heritage documentation. It engages in a comprehensive examination of the potential for hBIM to be expanded by integrating with other techniques to facilitate the organisation of conservation projects. The integration has the potential to enhance the functionality of hBIM, such as the automatic semantic segmentation of 3D point clouds from reality-based modelling, the organisation and analysis of spatial information by GIS, and the modelling of knowledge by ontology. Additionally, accurate parametric modelling can be achieved through computer graphics. A methodology for analysing the degradation of the church's components is proposed based on the reflection properties of the laser scanner beam, red–green–blue images, the evolutionary assessment of the failure mechanisms, and the generated model. This investigation's primary hypothesis is predicated on examining the digital elevation model in relation to the south façade of the former church building. Furthermore, the method is presented as a high-quality model visualization method that integrates two photogrammetric techniques (TLS + UAV) and is significant in assessing the risks of church degradation to support an aware approach to conservation projects.

Hence, the research addresses the impact of the geometric model on the structural analysis of the south-front slender wall. Selecting an excessively stylized model results in an inaccurate estimation of the volume, mass, stress values, stress regions, and fracture morphologies. The genuine constructive technique holds significant importance in the research for two key reasons. Firstly, it allows us to consider the actual structural unit weight and rigidity of the various materials, thereby providing a more accurate understanding of the structural elements. This, in turn, enhances the credibility of our research.

Additionally, the case study demonstrates that a more precise estimation of the percentage of mass associated with the principal modal shapes is obtained when the accurate, constructive technique is considered. Nevertheless, a stylized model that considers historic construction techniques still needs to be improved. Actually, it does not permit the precise determination of the actual values of stresses or the accurate location of the maximal values. Consequently, it is advisable to opt for a more comprehensive model. Finally, the element's damage assessment is also significant. The absence of fractures in this study would result in underestimating the compression stresses in dynamic analysis and tensile stresses in static analysis, which is problematic in brittle materials such as brick masonry walls. Cracks in modal analysis impact the percentage of the mass, which affects not only the bending but also the torsional deformation despite the slenderness of the south front. Additionally, the case study indicates that the absence of minor fractures results in a negligible difference in stresses but not in buckling load and mass associated with the modal mechanisms. In general, the significant distinctions that emerged from the comparison of the results of all the models indicate the necessity of exercising caution in the selection of the model and the integration of results from other diagnostic tests to facilitate a more comprehensive and integrated strategic approach to the study and evaluation of the built cultural heritage. By demonstrating the importance of meticulous modelling, the research advocates for a straightforward approach to structural analysis of architectural heritage, recognizing precision's transformative effect on the interpretation and understanding of structural behaviour within complex, damaged forms.

Consequently, the bearing structures assessment displayed the specific areas of the building's facades that were overturning and the comprehensive kinematic phenomena that were gradually in action. As a consequence of the related considerations, the structural project is precisely adapted to the unique characteristics of the complex, supported by data as accurately as possible. This also positively influenced the entire conservation design process.

Author Contributions

The three authors have meticulously crafted this research paper in a collaborative endeavour. In particular, Matilde Balestrieri contributed paragraphs 1 and 2.1, Irene Valmori composed paragraphs 1.1 and 1.2, and Manlio Montuori was responsible for paragraphs 1.3, 2.2, 2,3, and the exhaustive discussion of the final results. The coordinated efforts have headed a cohesive and insightful contribution to the UAS and TLS 3D data fusion for built cultural heritage assessment.

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