Leveraging digital elevation models for data-driven assessment of evolutionary damage in built heritage

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Abstract

The paper aims to illustrate how implementing a digital elevation model enables an extensive comprehension of the current deformation crisis state of overturning masonry in the context of a case study. The approach explores the interoperability challenges and details in scan-to-HBIM processes, thereby elucidating how HBIM models can support operations that are intended to maintain and preserve extant historic assets despite the persistent challenges. This illustrative investigation underscores the effectiveness of applying digital technologies to advance the conservation and management practices of built cultural heritage, particularly in addressing structural concerns associated with historic masonry. The information should involve meticulous knowledge, anamnesis, visual inspection, and instrumental measures, as dataset accuracy is crucial in architectural heritage, where surveyed objects exhibit complex geometries and significant deformation. It is a deliberate, synthetic operation that develops a structural model for assessment. A key finding of the present paper is that the precision and detail of the model determine the accuracy of structural analysis results, emphasising the importance of accuracy consideration to achieve meaningful and reliable results. As a consequence, the building assessment demonstrated which parts of the building's façades were overturning while identifying the thorough kinematic phenomena progressively acting.

Keywords: Built heritage conservation, Damage assessment, Kinematic phenomena, Out-of-plane overturning mechanism, Scan-to-HBIM.

1. Introduction

Structural analyses of buildings often rely on simplified geometric models to expedite numerical computations, minimise processing demands, and streamline workflows. While this simplification can be both valid and practical, it is critical to ensure that such reductions do not compromise the reliability of the analysis results. The fidelity of the model plays a pivotal role in achieving accurate outcomes, particularly when capturing the essential physical behaviours and structural responses of the system under study. This requirement becomes even more pronounced when dealing with historic buildings of cultural significance, which present unique challenges due to their historical and architectural value. In the context of cultural heritage, the structure's geometry is rarely straightforward. These buildings frequently exhibit complex forms, asymmetries, irregularities, and accumulated damage resulting from ageing, environmental exposure, and historical modifications. These factors must be carefully considered when developing a geometric model, as over-simplification can lead to significant inaccuracies in interpreting structural behaviour or assessing vulnerabilities. For instance, a detailed model may be necessary to capture the nuanced effects of cracks, deformations, or missing elements that could influence load paths or stress distributions.

To address these complexities, modern geometric modelling methods have emerged, leveraging advances in digital technology and remote sensing. High-resolution techniques such as laser scanning and photogrammetry can produce highly detailed and accurate representations of a building's surface. These tools provide very useful data for reconstructing external geometry with unprecedented precision. However, they primarily capture visible surfaces and external morphology, and often lack critical information about interior structural features, subsurface defects, or concealed construction details [1]. Understanding the full structural behaviour of a historical building requires more

50 than surface-level data. Comprehensive investigations that integrate both advanced technology and traditional
51 diagnostic methods are essential. This holistic approach involves anamnesis, a thorough study of the building's
52 phenomenological history, construction techniques, and prior interventions. Instrumental measurements such as
53 ground-penetrating radar, infrared thermography, ultrasonic testing, and micro-drilling can reveal internal anomalies,
54 material properties, and hidden damage. These methods are further complemented by detailed visual inspections
55 conducted by experienced conservation professionals. Such experts can identify patterns of deterioration, assess
56 material conditions, and evaluate the effectiveness of previous repair work

57   Additionally, integrating these diagnostic results into the geometric model transforms it into a more complete and
58 functional representation. The enriched model becomes a powerful tool for simulation, enabling analysts to account for
59 specific material heterogeneities, localised weaknesses, and the interactions between damaged and intact elements. For
60 example, in seismic analysis, the accurate representation of cracks and voids can significantly influence the predicted
61 dynamic response of a structure. This, in turn, provides critical insights for risk mitigation and retrofitting strategies. In
62 the field of cultural heritage preservation, the goal of structural analysis is not solely to ensure stability. It also aims to
63 maintain authenticity and minimise interventions. Achieving this goal requires a delicate balance between technological
64 precision and an informed appreciation of the building's historical context. Each model thus becomes a bridge between
65 the past and future. It preserves the memory embedded within the structure while equipping engineers and conservators
66 with the data needed to protect it for generations to come.
67
68 *1.1 The pilot site*

69   The monastery of St. Catherine is located within the dense urban fabric near the Estense Castle, positioned behind
70 the ancient urban axis of Via degli Angeli, now known as Corso Ercole I d'Este [2]. This area also includes the former
71 Church of Santa Maria degli Angeli and the Palazzo dei Diamanti. The distinctiveness of the site stems from the initial
72 absence of comprehensive geometric data and its complex planimetric configuration. Specific planovolumetric
73 transformations were identified through meticulous inspections and direct observation of this extensive complex.
74 However, it is important to emphasise that the current descriptions still require substantial documentary evidence to
75 understand the nature and extent of these transformations fully

76   The lack of detailed geometric data at the outset of the project highlights the critical role of on-site inspections in
77 uncovering key planovolumetric features of the building. Consequently, the initial investigations focused primarily on
78 the structure's chronological stratification. Archival documents were examined to shed light on its original layout,
79 formal characteristics, and geometric configuration, particularly those aspects that have been altered over time. A
80 meticulous review of numerous indirect historical sources housed in the Ferrarese Diocesan Archive revealed several
81 original rooms that had been lost due to substantial architectural transformations. This process enabled the identification
82 of historically significant spaces that had been obscured by the passage of time and successive modifications. To
83 document the current condition of the monastery, data were collected through a comprehensive survey methodology
84 tailored to the site's distinctive typological and geometric complexity, ensuring increased precision in capturing both
85 the material stratification and the spatial articulation of the architectural organism [3–4]. The primary goal of this
86 documentation strategy was to leverage state-of-the-art technologies and tools, accounting for the site's specific
87 challenges, while ensuring high accuracy in the survey and data processing phases.
88

Figure 1. (*left*) Ferrara, aerial view from the south. At the image centre, the Dominican monastery of St. Catherine.
(*right*) The monastery of St. Catherine in the urban fabric of the Ferrara Herculean addition.

89 *1.2 Research background: TLSs and UASs dataset fusion*

90   The continuous advancement of technologies such as terrestrial laser scanners (TLSs) and unmanned aerial systems
91   (UASs) has significantly facilitated data acquisition processes. The Leica P40 TLS survey campaign was carried out in
92   two phases: planning and acquisition. More than 200 laser scanner station points were pre-estimated. In situ scans were
93   optimised by room size and complexity. Acquired data were processed in Leica Cyclone r2020.1®, aligned with <4
94   mm tolerance, and exported after registration into a unified 3D point cloud database. A single three-dimensional
95   coordinate system was then established, with the origin point (Fig. 2) located at the centre of the cloister. The point
96   cloud was subsequently decimated and exported in .pts format. To support this operation, due to the large file size and
97   processing demands, the building was divided into four segments: the west wing, the east wing, the south wing, and
98   the former church (Fig. 3).
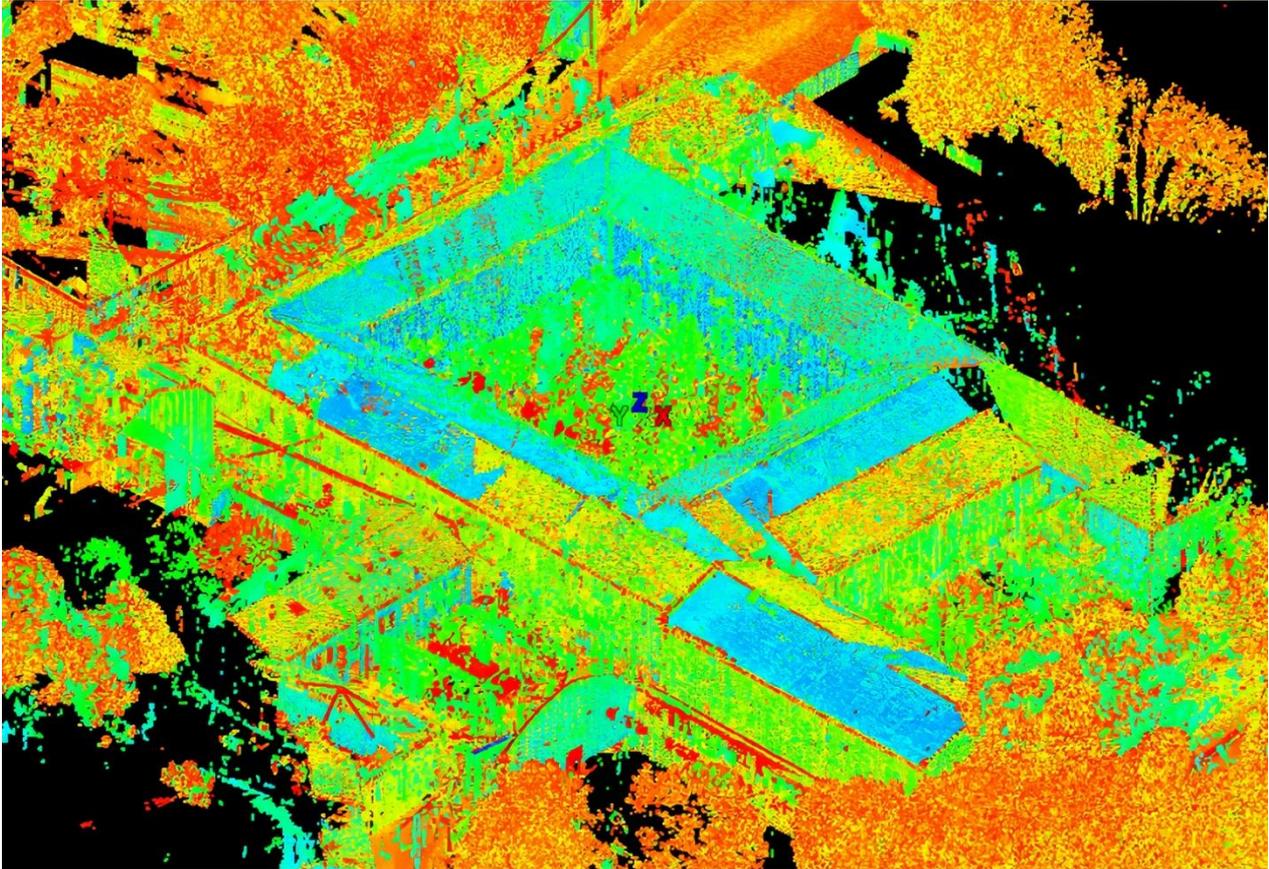
99
100   Figure 2. Perspective view of the registered 3D point cloud processed in Leica Cyclone r2020.1®, registered within
101   a single coordinate system centered on the cloister.

102   The UAS photogrammetric acquisition was performed using a DJI Mavic 3 Enterprise, with mission planning
103   optimized to achieve a ground sample distance of 4 mm/pixel, suitable for 1:20 scale documentation. Flights were
104   conducted approximately at 20 m altitude for nadir mapping and at distances of 10 m for façade capture, ensuring
105   proper image overlap (≥80%) and minimal angular distortion. Images were processed in Agisoft Metashape
106   Professional r2.0.10, enabling the generation of high-resolution orthomosaics, adaptive textures, and 3D meshes for
107   characterizing the damaged state of the masonries (Fig. 4). These datasets were subsequently processed to generate
108   precise and accurate 3D models of detailed objects. However, no single sensor can provide a comprehensive
109   understanding of a large structure, even when multiple scans are conducted [5]. To overcome this limitation, the
110   integration and interaction of both technologies were employed. By geometrically aligning the two datasets, this
111   approach supported the development of a variety of assessment processes [6].

112   A practical framework that combines UAS photogrammetry and TLS for 3D mapping and monitoring of complex
113   heritage assets has been developed. This methodology integrates ground-based survey techniques and aerial
114   photogrammetry through the CloudCompare v2.12.4 platform, reinforcing its pivotal role in the analysis and
115   interpretation of built cultural heritage [7]. The integration of both methods results in maps, orthophotos, and 3D
116   models. Data fusion enhances the accuracy of 3D representations by combining information from multiple sensors.
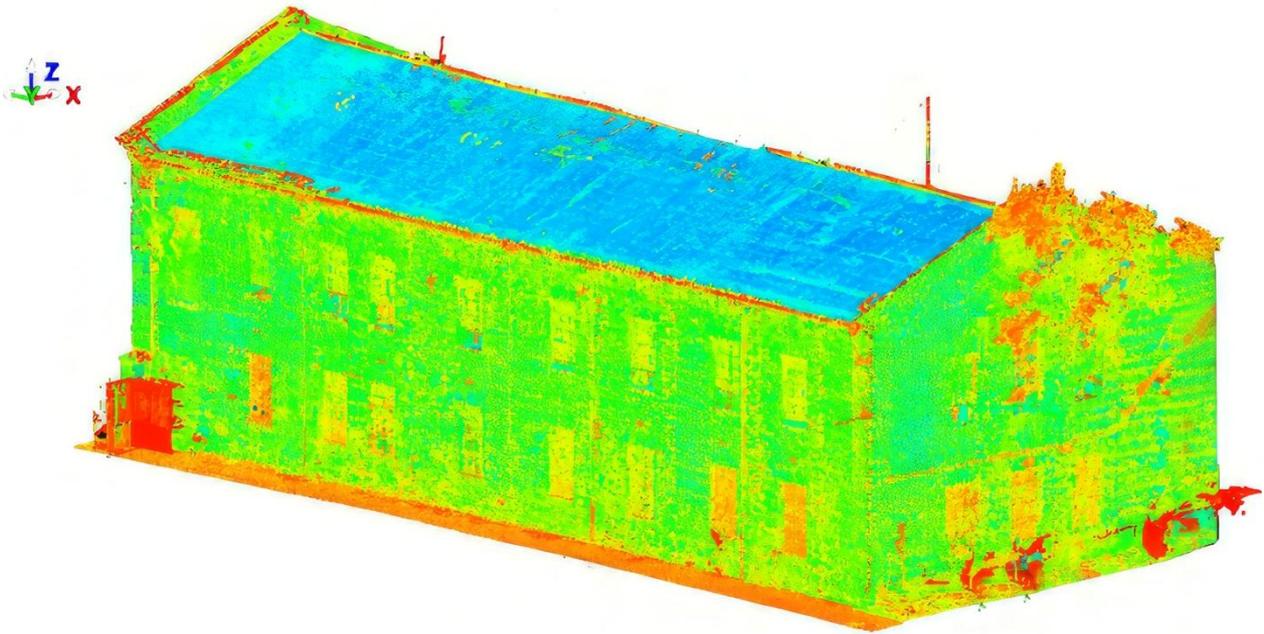
Figure 3. A detailed axonometric view of the TLS point cloud processed in Leica Cyclone r2020.1® True Space mode, showcasing the former church of St. Catherine.

117 This process is particularly important for advanced tasks of visualization, typological classification, and quantitative
118 assessment in heritage studies. The choice of data acquisition method depends on factors such as the object's geometry,
119 surface morphology, required accuracy, and the logistical constraints and financial sustainability of the operation. While
120 various approaches exist, each comes with inherent limitations and operational trade-offs. Terrestrial Laser Scanning
121 (TLS), for example, is restricted by its line-of-sight, which reduces its effectiveness in occluded or confined areas, such
122 as narrow courtyards or interiors with complex partitions. Its performance can also be affected by reflective or
123 absorptive materials, surface moisture, and ambient lighting conditions. Unmanned Aerial Systems (UASs) offer a cost-
124 effective and efficient means of surveying, particularly for capturing high-resolution images of inaccessible zones, such
125 as rooftops, upper cornices, or structures at risk of collapse. However, UAS-derived 3D models can suffer from
126 indistinct textures, radiometric inconsistencies, and a general lack of geometric density in shadowed or reflective areas,
127 reducing their reliability for detail-critical applications. Ground-based digital cameras represent another low-cost
128 solution for 3D modelling. Yet, like TLS, they are constrained by line-of-sight issues and require careful control of
129 camera calibration parameters and network geometry to avoid reconstruction errors.

130 Given the strengths and weaknesses of each technique, a multi-source and multi-scale integration of data becomes
131 not only advantageous but necessary for generating accurate and semantically rich 3D digital twins. The proposed
132 multi-sensor data fusion method employs a wavelet-based decomposition and reconstruction algorithm to create a
133 refined 3D building model by integrating TLS and UAS datasets. This hybrid approach enhances spatial continuity and
134 surface detail, ensuring both metric reliability and visual fidelity. The TLS dataset was also used to validate the model
135 [8, 9], which demonstrated an accuracy of 2.3 mm higher than the TLS-only model, confirming the effectiveness of the
136 fusion strategy in improving both geometric precision and interpretative potential.

Figure 4. The orthomosaic of the south-facing elevation along Via Roversella, generated in Agisoft Metashape Professional r2.0.10®. On the right, the eastern wing reveals substantial structural transformations of the former church's liturgical hall, resulting from its 20th-century conversion into a vocational high school.

2. Damage mechanisms assessment in load-bearing structures

2.1 Built heritage modelling in HBIM environment

The advancement of information technology offers a significant opportunity to transform conventional practices in built cultural heritage conservation and the construction sector. Such an approach is particularly relevant for activities concerning the monitoring and management of existing architectural heritage, where accurate data acquisition and interpretation are essential to support informed conservation strategies and long-term maintenance planning.. In this context, the proposed methodology relies on an integrated 3D metric survey as the basis for generating Digital Elevation Model (DEMs), further supported by the development of a Historic Building Information Model (HBIM) [10–12]. This model plays a key role in identifying the most appropriate interventions to improve the structural behaviour of brick masonry elements [13]. Photogrammetric processing, when compared to the geometric database derived from TLS-based point cloud data, proved to be highly effective. It provided accurate working material that enabled a reliable representation of the external surfaces, fully consistent with the building's actual 3D configuration [14]. The use of as-built BIM techniques in heritage modelling aims to reinforce the relationship between geometric modelling and information management. Among the key attributes considered are temporal evolution, spatial constraints, and damage documentation, all of which contribute to a comprehensive understanding of the building's lifecycle and inform targeted conservation actions. [15]. In particular, HBIM is well-suited for reconstructing built heritage based on available descriptive data, including historical records, bibliographic sources, archival photographs, and drawings. Analysing the evolutionary and transformative phases of lost architectural elements proves especially valuable, as these aspects directly influence the structural assessment of load-bearing systems, providing critical insights into original construction logic, material discontinuities, and potential weaknesses within the historic fabric. [16]. The monastery is not merely a virtual model. It serves as a critical component of the conservation project, where the various parts of the Dominican cloister complex are transformed into intelligent parametric objects. These elements contain structured relational data as well as detailed quantitative and qualitative attributes. Ultimately, the HBIM model functions as a parametric design environment, capable of storing, updating, and linking information in a coherent and dynamic framework [17].

2.2 Digital elevation modelling

Digital Elevation Models represent the elevation distribution of a terrain or a specific surface in archaeological contexts. They are exported in raster format, allowing each image pixel to be associated with elevation values expressed through a predefined colour scale [18]. In this study, DEMs were employed as analytical tools derived from an indirect survey of the pilot site, which proved to be particularly complex due to its stratigraphic configuration. Unlike their more established application in archaeological excavation analysis, DEMs are still rarely used for studying building façades and even less so in structural assessments [19]. This represents an underexplored field of research.

In contrast to horizontal ground strata, the elevations of the masonry walls were visualised through false-colour textures mapped onto vertical planes, offering a detailed representation of their current condition. At the level of architectural interpretation, it became possible to systematise conventional stratigraphic evidence based on materials and construction techniques. Damage patterns affecting the walls were also considered, particularly when they revealed stratigraphic discontinuities that would otherwise be difficult to detect. More importantly, these patterns served as indicators of active structural damage mechanisms. The analysis focused on the southern sector of the monastery, along Via Roversella. Here, a strong correlation emerged between the current condition of the structural elements and the architectural stratification gathered over time.

This approach proved especially significant for the analysis of macroelement kinematics within the broader conservation project. The front elevation was analysed by projecting it onto an ideal reference plane. This surface was defined as perfectly orthogonal and aligned through the midpoint of the masonry thickness, allowing a normalised reading of the façade. The method revealed multiple phases of transformation, namely the opening of new windows, the closure of others, and the insertion of intermediate floors associated with changes in use, which were graphically represented and subsequently interrogated from a structural standpoint. In particular, a zone of high concern was identified where an incipient out-of-plane rotation appears to localise, plausibly activated by the thrust transmitted by the roof struts (Fig. 5). The evidence from TLS point cloud processing, including systematic slices at 1 m pitch, supports this interpretation and indicates areas of potential concern. To support this preliminary kinematic interpretation, the TLS point cloud was processed through a systematic sequence of horizontal and vertical slices extracted at a constant 1 m pitch, thereby generating a modular grid and the corresponding wireframe representation of the façade. This slicing-based modelling enabled a first-order verification of geometric continuity between the interior and exterior faces,

190 providing evidence compatible with predominantly monolithic behaviour within the wall plane and, conversely, not
191 supporting the presence of non-integrated facing leaves whose differential deformation could promote peak-load-
192 induced local instability. Although the deformation is not readily appreciable along the longitudinal development of
193 the slender masonry walls, the bottom-right overlay of the extracted slices against ideal horizontal and vertical reference
194 lines documents, albeit in a barely perceptible manner, the onset of the rotation mechanism. A more explicit and
195 metrically controlled representation of this phenomenon is provided later in the paper through DEM-based processing,
196 which allows the deformation field to be visualised and quantified with higher sensitivity. The point of most significant
197 structural instability corresponds to two distinct stratigraphic units.
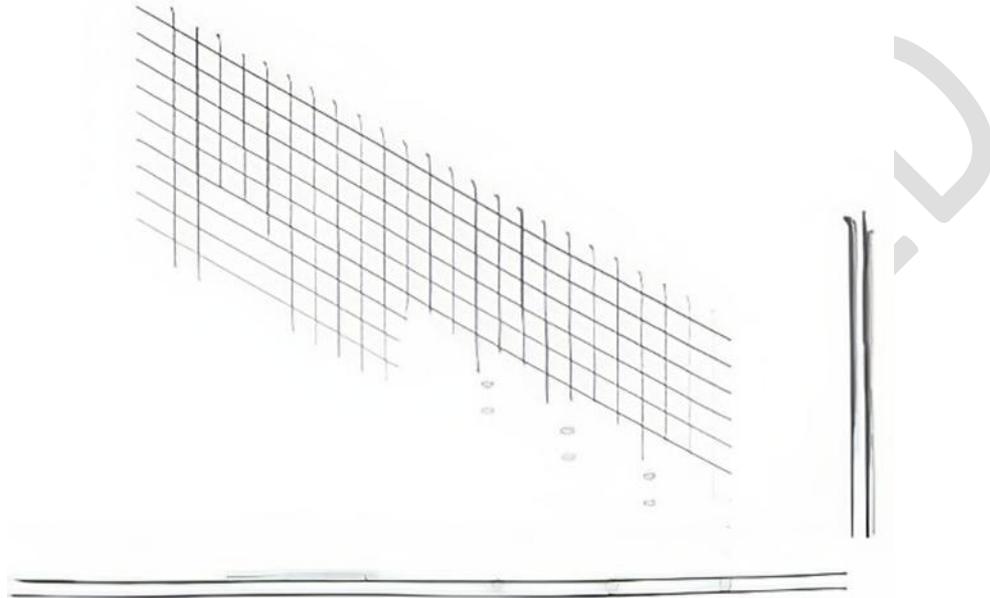
198
199 Figure 5. Front elevation along via Roversella, TLS-derived horizontal and vertical slices extracted at 1 m pitch and
200 assembled as a modular grid/wireframe for preliminary screening of out-of-plane rotation; the inset overlay against ideal
201 axes suggests.

202 These units reflect a shift in the roofing technique, which also marks the spatial division between the liturgical hall
203 used by cloistered nuns and that intended for laypeople. This architectural modification induced a progressive
204 superficial depression, which became more pronounced over time, ultimately resulting in the current generalised
205 deformation of the façade. The deformation later extended to the entire central section. The case study, the former
206 liturgical hall of the Dominican monastery, is morphologically defined as an assembly space enclosed by structural
207 macroelements: lateral walls, façade, apse, timber trusses, and reinforced concrete floors added during its later
208 adaptation for educational use. These macroelements, collectively, constitute the structural system of the building.
209 Through evolutionary damage analysis, the study identified both unique and recurring collapse mechanisms for each
210 macroelement, many of which are widely documented in the literature. This was achieved using the limit equilibrium
211 method, specifically following a kinematic approach to structural analysis.

212 The analysis of potential in-plane and out-of-plane damage mechanisms in brick masonry walls has led to notable
213 and insightful results. These analyses are particularly significant, as they aim to evaluate the forces that activate these
214 mechanisms in relation to wall geometry and the dimensional relationships among structural elements [20, 21]. The
215 collapse mechanism of a masonry macroelement is typically characterised by the formation of zones with concentrated
216 deformation. These zones separate the macroelement into quasi-rigid blocks that behave kinematically, leading to
217 collapse when subjected to perturbing forces. The initial singularities most likely to generate disaggregation are found
218 at the connection points between macroelements, where the load-bearing structure is most vulnerable. In such zones,
219 relative roto-translations may develop between adjacent elements.

220 To support the identification of the most appropriate safety interventions, the contribution of DEMs in the
221 evolutionary damage analysis of macroelements is highlighted here. One particularly hazardous behaviour observed is
222 the horizontal flexural deformation of the brick wall, as clearly illustrated by the DEM. In this condition, the masonry
223 wall is joined to perpendicular walls, but its top edge is unrestrained. When subjected to seismic action orthogonal to
224 its plane, the wall exhibits a horizontal arching effect (Fig. 6). Specifically, the horizontal thrust from the roof is

225 transferred to the wall. At the orthogonal intersections, this thrust splits into two components: one orthogonal to the
226 wall, which is absorbed by the tie rods of the roof trusses; and one parallel to the wall itself. In the limit equilibrium
227 condition, three hinges typically form, one near the centre of the wall and two at the intersections with the truss ends,
228 where tensile stresses are highest.

229 The three-hinged isostatic arch becomes unstable when its hinges align. If the wall fails to engage contrasting
230 elements that provide an equal and opposite reaction, the collapse kinematics will be activated. This is the precise
231 condition found in the case under analysis. The wall is held by tie rods but is stressed by the anomalous pushing action
232 of a strut and by the hammering forces of the large roof framing elements. Moreover, the tensile strength of the masonry
233 is reduced, increasing the risk that the material forming the wall's outer face may detach. This detachment is caused by
234 tensile stresses that develop within the masonry core as part of the kinematic deformation. Additional factors contribute
235 to the onset of horizontal bending mechanisms. These include the presence of aligned openings just beneath the roof
236 band and the quality of the masonry itself, which affects the height of the detachment wedge.

237 The identification of horizontal bending mechanisms is significantly supported by the DEM, which provides
238 essential information on existing and potentially active macroelements, even in cases where visible damage is minimal.
239 When cracking is not yet present, potential out-of-plane collapse mechanisms may still develop, involving varying
240 extents of the wall surface [23]. However, it remains impossible to determine in advance which kinematic mechanism
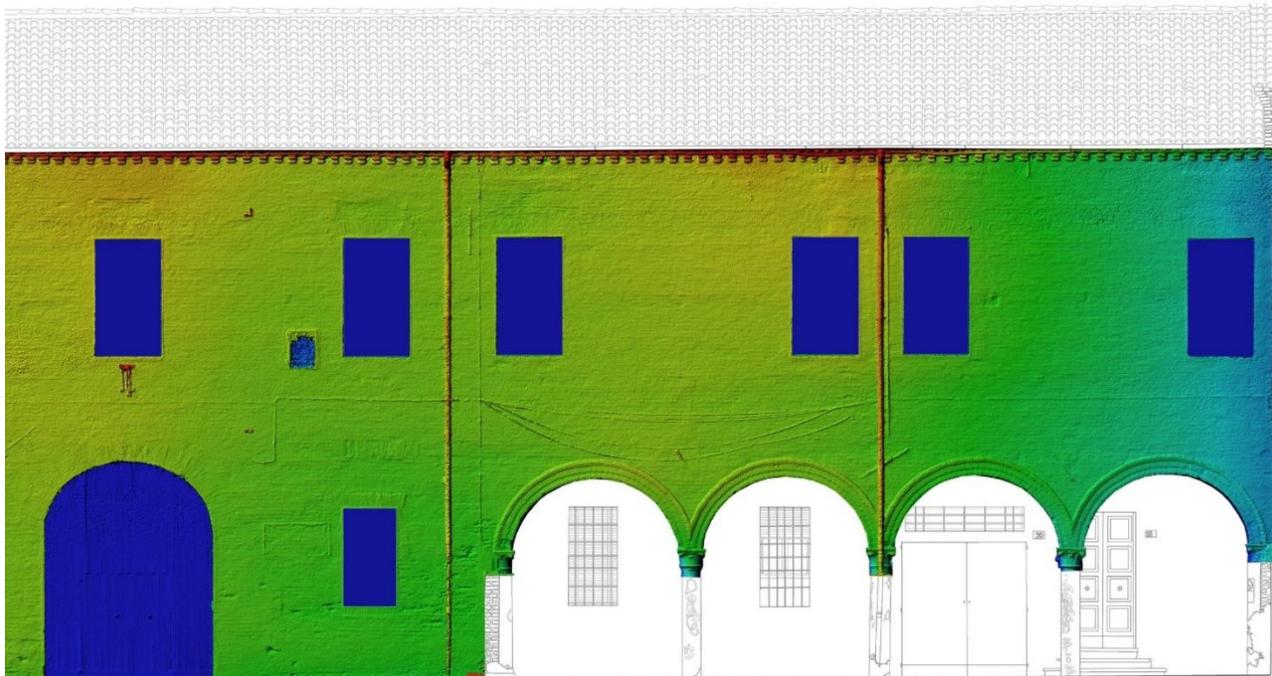
241 is most likely to occur. To define the most unfavourable scenario, it will be necessary to assess multiple collapse
242 conditions, each assuming different geometries of the masonry areas involved in the kinematic process [24]. To
243 determine the most unfavourable condition, it will be necessary to assess various collapse factors assuming varying
244 geometries of the masonry regions influenced by the kinematics [25].

Figure 6. Front elevation along via Roversella, digital elevation mode processed in Leica Cyclone r2020.1®. The false-colour DEM highlights deformation patterns that are not detectable through direct visual inspection. In particular, at the junction between the gutter pipe and the right-hand downpipe, the red hue representative of the wall surface indicates a strain distribution consistent with the activation of an out-of-plane overturning mechanism. This condition has then been attributed to the deterioration of the timber truss bearing support, which has led to a structural transition from isostatic to thrusting behaviour.

3. Result discussion

246 The integration of photogrammetric and TLS data through a multi-sensor approach enabled the generation of a high-
247 resolution digital elevation model, which proved to be a critical tool for identifying early signs of deformation in the
248 historic masonry structures of the Dominican nuns' compound. Assessing the behaviour of load-bearing structures in
249 built heritage contexts requires both precise 3D geometric modelling and advanced information management systems.
250 These are typically realised through digital twins generated via photogrammetry and laser scanning, alongside semantic

251 knowledge integration using geographic information systems and ontology-based tools [26]. The latest developments
252 in building information modelling (BIM) incorporate both 3D modelling and structured information management [27].
253 By leveraging the dense spatial granularity of the DEM, the study captured early displacements and strain patterns
254 across the south elevation, which could not be discerned through conventional visual inspection. This finding highlights
255 the diagnostic potential of DEMs in capturing the premonitory deformations that precede the onset of out-of-plane
256 failure mechanisms in historic walls and the development of an explicit crack pattern.

257   In the specific case of the via Roversella façade, the methodology implemented integrates laser scanning, computer
258 science, Geographic Information System (GIS), and particularly BIM as its foundational components [28]. The false-
259 colour rendering of the elevation data, mapped onto orthogonal projection planes, revealed a subtle yet coherent
260 horizontal flexure extending across the upper third of the masonry surface. This deformation, although imperceptible
261 through traditional surveying techniques, is consistent with the hypothesis of an evolving macroelemental mechanism
262 involving horizontal bending and rotation around the truss anchorage zones. The localised strain concentrations,
263 represented in red and yellow hues in the DEM visualisation, coincide with zones of structural discontinuity historically
264 associated with spatial transitions within the *endonartece* hall, such as the demarcation between the cloistered and lay
265 areas. This correlation confirms the DEM's capacity to interpret architectural transformations as potential precursors
266 to mechanical instability. The chronological stratification of the façade, reconstructed through archival analysis and
267 architectural interpretation, provided a more nuanced understanding of its structural behaviour. The area exhibiting the
268 highest deformation was also the segment most affected by 20th-century interventions, including the insertion of
269 reinforced concrete floors and alterations to the original roofing system. These modifications induced eccentric load
270 distributions and altered the thrust paths transmitted by the timber trusses, thereby amplifying the flexural demands on
271 the slender masonry panels. The DEM, in this context, became a medium through which these hidden effects could be
272 quantified and localised with high precision. Notably, the DEM allowed for the anticipation of collapse kinematics by
273 identifying deformation modes before the complete crack pattern associated with the masonry's settling response
274 manifested. This pre-diagnostic function is particularly significant in heritage contexts, where preventive conservation
275 strategies often need to operate in the absence of overt structural symptoms. The identification of stress trajectories and
276 micro-deformational anomalies supports a predictive understanding of macroelement behaviour, particularly when
277 integrated with knowledge of mechanical discontinuities, construction techniques, and load-bearing hierarchies. In this
278 regard, the study demonstrated that the DEM could simulate an intermediate condition between the as-is configuration
279 and the limit equilibrium state, effectively capturing a transitional phase in the structural lifecycle. This capability is
280 especially relevant for walls exhibiting three-hinged arch behaviour, where the incipient collapse mode is governed by
281 the alignment of hinges and the degeneration of in-plane restraints. The current case study revealed that the pushing
282 action of the roof queen-post timber truss system, compounded by the absence of adequate counter-thrust mechanisms
283 in the longitudinal direction, promoted a partial and localised overturning mechanism in the affected masonry (Fig. 7).
284 The DEM detected this deformation as a differentiated surface deflection, offering a direct false-colour visualisation of
285 the deformation gradient along the affected wall surface.

286   The integration of the DEM into the structural interpretive framework thus represents a methodological advancement
287 that enriches the traditional visual and analytical toolset available to heritage engineers. The use of advanced geometric
288 modelling technologies within HBIM environments enhances the capacity to assess the condition of complex building
289 envelopes. By encoding deformation signals within a continuous digital surface, the DEM bridges the gap between
290 metric data acquisition and structural interpretation, providing an early warning system that aligns with the principles
291 of non-destructive, reversible, and minimally invasive conservation. The approach adopted in this study demonstrates
292 the value of employing DEM analysis not as a post-event mapping technique but as a proactive monitoring strategy
293 capable of influencing decision-making processes in structural conservation.
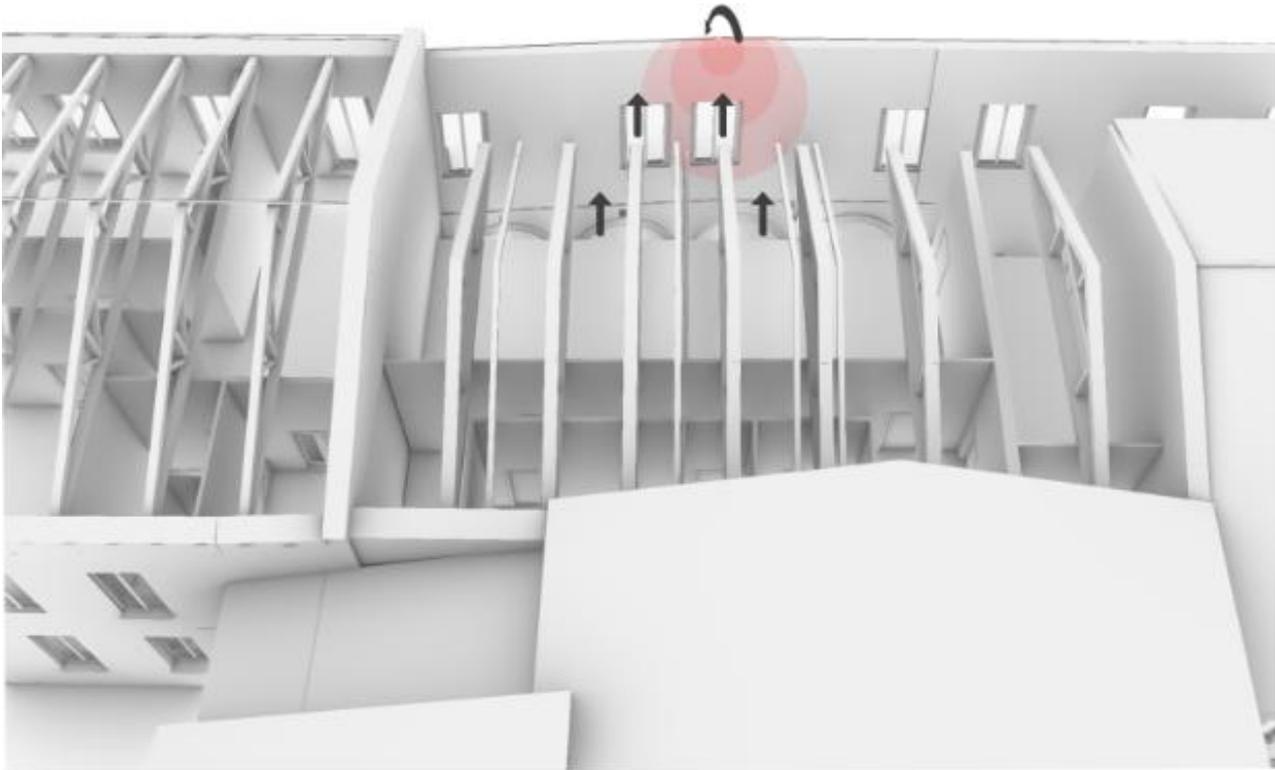
294
295 Figure 7. Former church of St. Catherine, south elevation, macroelement collapse mechanism. The representative three-
296   dimensional model of the collapse mechanism is developed using Graphisoft Archicad 27®, providing a more
297 straightforward interpretation of the triggering cause linked to the degradation of the roof queen-post timber truss system
298   lying behind the masonry wall.

4. Conclusions and future perspectives

300   The outcomes of the present investigation illustrate the potential of DEM integration into HBIM workflows as a
301 decisive step forward in the structural diagnosis of built heritage. The ability to capture micro-deformations before the
302 emergence of visible damage redefines the role of elevation models within conservation practice, elevating them from
303 mere representational devices to analytical instruments that can inform structural assessments. This evolution aligns
304 with the overarching aim of preventive conservation: to detect, interpret, and mitigate vulnerabilities before irreversible
305 failure occurs.

306   A critical implication of the proposed methodology lies in its capacity to embed the DEM as a structured information
307 layer within the broader HBIM environment. This interoperability transforms the DEM from a static visual product
308 into a dynamic data component capable of dialoguing with other informational strata, such as historical documentation,
309 material diagnostics, and performance simulations. In this sense, the DEM becomes a semantic and geometric medium,
310 linking the morphological reality of the building with the predictive logic of structural analysis. The case study has
311 demonstrated that a DEM-enhanced HBIM model can effectively support the identification of stress concentrations,
312 the recognition of stratigraphic discontinuities, and the modelling of localised instability scenarios. By spatialising these
313 phenomena within the digital model, the HBIM environment transcends its original descriptive function and assumes
314 a prescriptive role in defining conservation priorities. The integration of DEM data facilitates this transition by offering
315 a high-resolution understanding of deformations, thereby allowing the simulation of mechanical responses under
316 various boundary conditions and anticipating potential collapse mechanisms.

317   Future research directions should focus on expanding the use of DEM as a permanent layer in HBIM platforms,
318 moving beyond episodic applications toward systematic integration within digital twins of heritage structures. Such
319 integration requires the development of standardised protocols for DEM generation, classification, and updating, as
320 well as the definition of metadata schemes that preserve the interpretative value of the elevation data over time. The
321 implementation of interoperable data pipelines will be crucial to ensure consistency across software environments and
322 analytical domains. Moreover, the increasing use of IoT-enabled monitoring systems and AI-based anomaly detection
323 tools opens new opportunities for real-time updating of the DEM layer. This dynamic linkage would allow HBIM
324 models to evolve from static repositories of past and present conditions into predictive environments that continuously

assess the stability of architectural macroelements. In this context, the DEM could act as a sentinel system capable of issuing alerts when deformation thresholds are exceeded, thus triggering preventive interventions. From a methodological standpoint, the recognition of the DEM as a structural information layer repositions HBIM as a tool not only for documentation and management but also for real-time structural decision-making. The integration of this layer into the HBIM paradigm responds to the growing need for models that are both historically accurate and structurally insightful. This dual capacity enhances the utility of digital models in supporting conservation strategies grounded in material authenticity, structural integrity, and long-term sustainability.

In conclusion, the interoperability between DEM and HBIM systems represents a key vector for innovation in heritage conservation. The ability to integrate elevation-based deformation data within a comprehensive digital model transforms the HBIM into a multifunctional tool that supports design, analysis, and monitoring. This convergence marks a shift toward a more smart and responsive approach to preserving built heritage, one in which structural understanding, digital representation, and conservation action converge within a unified methodological framework.

5. Funding

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419