Cloud-to-BIM-to-FEM: Structural simulation with accurate historic BIM from laser scans

Luigi Barazzetti *, Fabrizio Banfi, Raffaella Brumana, Gaia Gusmeroli, Mattia Previtali, Giuseppe Schiantarelli

Politecnico di Milano, Department of Architecture, Built Environment and Construction Engineering, Gicarus Laboratory, Via Ponzio 31, Milan 20133, Italy[1]

The complexity of historic constructions, with irregular geometry, inhomogeneous materi-als, variable morphology, alterations and damages, poses numerous challenges in the digital modeling and simulation of structural performances under different types of actions. Although recent developments in Building Information Modeling have introduced advanced simulation capabilities, the numerical characterization of historic buildings is still a challenging task for the lack of reliable procedures for structural simulation.

This paper presents an innovative two-step methodology (Cloud-to-BIM-to-FEM) able to convert a historic BIM into a finite element model for structural simulation. The generation of the BIM (Cloud-to-BIM) is carried out with an accurate survey that integrates geometrical aspects, diagnostic analysis based on destructive and non-destructive inspections, material information, element interconnections, and architectural and structural considerations. The BIM is then turned into a finite element model (BIM-to-FEM) with a geometric rationalization which preserves irregularities and anomalies, such as verticality deviation and variable thickness. After setting material properties, loads, and boundary conditions, the structural simulation is run with a detailed model that respects the uniqueness and authenticity of the historic building, without the typical excessive geometric simplifications of the shape.

A real case study is illustrated and discussed to prove that a rigorous Cloud-to-BIM-to-FEM workflow allows the generation of an accurate historic BIM from a set of laser scanning point clouds. Structural simulation was carried out with a 3D mesh derived from the BIM in order to take into consideration the geometrical irregularity of a castle. Here, the advantages and disadvantages of the proposed approach are illustrated and discussed.

Keywords:
BIM
FEM
Interoperability
Point cloud
Structural
simulation

---

* Corresponding author at: Politecnico di Milano, Gicarus Laboratory, Via Previati 1/c, Lecco 23900, Italy. Tel.: +39 02 2399 8779.
E-mail address: luigi.barazzetti@polimi.it (L. Barazzetti).

[1] http://www.gicarus.polimi.it.

Published Journal Article available at: http://dx.doi.org/10.1016/j.simpat.2015.06.004

1. Introduction

The economic challenges in the field of Architecture, Engineering and Construction (AEC) industry have led to an incred-ible interest in efficient methodologies to improve coordination and productivity [1]. One of the most promising technologies is Building Information Modeling (BIM), which allows an organized workflow during the different stages of the project: program, design, construction, operation, and demolition [2].

Although the acronym BIM refers to buildings, methodologies and techniques can be extended to several civil infrastructures such as highways, bridges, and dams. A database connected to a graphical representation based on a parametric 3D model allows better visualization, coordination, and management of construction projects with a reduction of costs and errors [3].

As mentioned, the economic crisis has affected many sectors, including the construction sector. This has led to a particular attention in adaptive reuse projects, as well as conservation and restoration projects [4]. Energy efficient policies and sustainability initiatives are currently in progress to modernize old structures with expected reductions of greenhouse gas emissions, energy, electricity and water consumption [5,6]. BIM technology is not only limited to new constructions. BIM can be used to restore, adapt and reuse existing valuable constructions, including historic structures. This is a complicated task which requires a deep investigation of preservation policies towards sustainable management, disaster prevention, improved risk management, conservation and cost effective maintenance and restoration techniques [7].

Accurate as-built information is mandatory for projects on existing constructions. Existing drawings (plans, sections, elevations, 3D models, etc.) and existing reports are important tools to initialize restoration, rehabilitation or reconstruction projects based on BIM technology. On the other, this information is rarely sufficient and must be integrated with new data. In several cases the complete lack of data and the imprecisions of existing drawings can be overcome only with a new survey of the building [8,9].

The creation of the 3D model requires the acquisition of geometric data, which can be measured with traditional measuring tools (e.g. measuring tapes and distometers) or advanced instruments and techniques such as total stations, photogrammetry and laser scanning [8,9]. The use of huge laser scanning point clouds in BIM software is very attractive and has become a reality for software like Autodesk Revit (www.autodesk.com) and Microstation (www.bentley.com). Additional plugins able to reduce manual (interactive) editing are available for simple objects, such as regular walls and pipelines. On the other hand, the survey is not only limited to the geometric part. The survey includes technological aspects, material data, and data from destructive and non-destructive inspection techniques [10].

The creation of the 3D model must be carried out by considering the requirements of BIM technology. The model is not only a virtual representation of the construction. It is a vital part of the project, where the different elements of the building become advanced objects with parametric intelligent. Elements can be modified without redrawing and are structured in a complete database of the building. Objects have relations to other objects and attributes.

This paper focuses on BIM and its integration with structural simulation, which is a specific part of the design phase aiming at establishing structural safety under different conditions such as gravity, earthquake, and wind. The particular case of historic (H)BIM is addressed for the lack of solutions able to handle (H)BIM generated from point clouds for advanced structural simulation purposes.

In fact, commercial packages were mainly developed for modern buildings with regular geometry. Historic buildings have a very complex geometry that cannot be rigorously reconstructed in BIM software. Although laser scanning point clouds provide dense representations of the external surfaces, geometric anomalies (such as verticality deviations) pose new challenges in the generation of an as-built BIM model [11]. In technical literature, very few applications faced the use of detailed (H)BIM (from laser clouds) for structural simulation [12,13]. The creation of new (H)BIM libraries is a very time consuming operation, especially when the use of advanced parametric surfaces with irregular geometry cannot be simplified. An excessive simplification of the geometry revealed by point clouds could provide a level of detail insufficient for documentation and conservation analysis [14]. Additional issues concern the distribution of the model to the different operators involved in the project, which require interoperable formats (e.g., IFC). The use of advanced shapes (e.g. NURBS curves and surfaces [15]) can provide an uncorrected exchange of information with local conflicts or missing data.

The mechanical characterization of the materials used in historic buildings, as well as their internal composition, is another big challenge. Very heterogeneous materials (bricks in combination with mortar, stones, etc.) have a variable morphology with alterations, repairs, or additions occurred overtime. Material decay, cracks, disconnections and other damages could have a significant influence on the structural performances. Finally, a deep historic analysis cannot be neglected since the different construction stages reflect the modifications of the building [16].

This paper proposes a novel two-step methodology able to create a historic as-built BIM from a set of registered laser scanning point clouds (cloud-to-BIM). The BIM is converted into a Finite Element Model (FEM) for structural analysis (BIM-to-FEM) with Midas FEA (www.cspfea.net). Although most software vendors are adapting their packages to work with irregular shapes, several limitations occur when the aim is an accurate BIM of historic constructions. The use of the developed tools allows an accurate BIM-based reconstruction of complex elements.

The second phase of the work consists is the reuse of the BIM for structural analysis. The developed approach relies on a discretized of the BIM into a 3D mesh suitable for the simulation. The work can be intended as a “BIM centered” approach, where finite elements are derived without the need to redraw a new model limited to the structural simulation.

The method was tested on the South wing of Castel Masegra, a castle in the city of Sondrio (Italy). A BIM of the castle was generated to sustain the reuse of the complex, starting from a set of laser point clouds and photogrammetric measurements via dense matching, as well as inspections via IR Thermography, coring, flat-jack tests, and historical information. The creation of the parametric model is carried out with by taking into consideration the requirements of a BIM project for restoration and conservation. Structural simulation was carried out using the BIM as starting point for the generation of the mesh for finite element analysis. The work was partially carried out with Autodesk Revit (the generation of the BIM), Midas FEA (structural simulation), and a set of tools developed by the authors. Particular attention was paid to the translation of the BIM model into a interoperable format for BIM (IFC in this case). However, some issues were found for complex surfaces imported into other packages (e.g. Tekla, www.tekla.com). This means that future work is mandatory to improve the exchange of information, especially in the case of advanced surfaces.

The structural simulation presented in this paper has different aspects beyond the investigation of the structural integrity of the castle. The research work was carried out (i) to determine how an accurate (H)BIM from laser clouds can be used for structural analysis and simulation, (ii) to check the main difficulties in the analytic description of the construction (including morphology and material aspects, which requires initial assumptions and empirical data), and (iii) to evaluate the numerical performances and the required simplifications for numerical computations that may exceed the memory capacity of computers.

2. Data collection

2.1. Brief site description and historical information

Castel Masegra is one the three castles that dominated the city of Sondrio. The actual structure, with its trapezoidal shape, is the result of complex architectonic transformations lasted for ten centuries (Fig. 1).

Information concerning the origin of the castle and its history until the XV century is not supported by archive documents. Information is deduced from texts in which various authors (e.g. [17,18]) have reported, following certain and verifiable events, legends and oral traditions re-elaborated in a different way, so that they are discordant. The most ancient documents come from the XV century. They refer to the period in which the castle passed from the Capitanei family to the Beccaria family. This is probably the most important period for the architecture of the castle since there is a radical transformation of existing structures, for which concerns both the architectural system and function. Starting from a defensive function, Castel Masegra gradually became a noble residence with the creation of new spaces.

The recent archeological investigations revealed that the Masegra cliff is probably the oldest settlement of Sondrio, already inhabited starting from the pre-Roman epoch (V-II century A.D.). The castle rose up at the beginning of the XI century (some sources report 1041 A.D., some 1048 A.D.) as defensive structure for the village of Sondrio. Thanks to its position, it assumed a central role not only at a local level, but also in the wide castle system of Valtellina (Northern Italy) for both commercial and defensive functions.

The oldest remains suggest a structure much simpler than the actual, similar to other fortresses of the period found in Valtellina and Lombardy. It was made up of a long wall along the perimeter that contained the principal buildings, and other buildings inside.

The castle has been destroyed and rebuilt several times, especially between the XII and the XIV century A.D., but accurate data sources able to delineate a precise chronology of the modifications are missing. For these reasons, today the caste is made up of different buildings around two internal courtyards. Some buildings can be visited by tourists, whereas other parts are under restoration. The work described in this paper is part of a large reuse project, whose principal aim is the valorization of the castle.

Fig. 1. Some images of Castel Masegra and the plan dated back to 1700, which shows the spaces inside the castle and some information about the state of conservation (Stadtbibliothek, Zurich).

2.2. Laser scanning data acquisition and processing

The geometrical survey of complex historic sites requires the use of advanced measurement instruments and techniques [19,20]. The geometrical reconstruction of the castle started with the acquisition of 182 laser scans with a Faro Focus 3D. Data density was set to 44 million points per scan. Point precision in the instrumental reference system is expected to be better than ±3 mm. Digital images were not acquired with the integrated camera because of the limited geometric and radiometric resolution. The acquisition of the scans in the different rooms and the courtyards, as well as the exterior, took less than a week.

Scans were registered with chessboard and spherical targets. Direct scan-to-scan registration was not carried out to avoid error propagation. Indeed, the complexity of the site, with different buildings with a variable number of floors, required a robust geodetic network to provide a stable reference system with limited geometric distortions. The geometric network of the castle was measured with a robotic total station Leica TS30 (±0.6 mm distance precision, ±0.15 mgon angular preci-sion) and is made up of 68 stations. Laser targets were also included in the network and assumed as fixed constraints during scan registration. The materialization and measurement of the geodetic network took 5 days.

Laser scans were registered with the combination of scan-to-scan and scan-to-network points. Global registration provided an overall precision better than ±3 mm, which is more than sufficient for the required scale of the project (1:100). The extraction of horizontal and vertical slices with a limited thickness (1 cm) gave an immediate evaluation of the geomet-ric irregularities of the walls. The conversion of slices into project boards (plans and sections) highlighted verticality issues and walls with a variable thickness.

Overall, the generated plans (6) cover an area of 2700 m^2 and where coupled with 15 vertical sections. A detail of the South wing of the castle (that is the building studied with the structural simulation) is shown in Fig. 2. The different colors correspond to the chronological phases. This information will be incorporated in the BIM (Section 3) and FEM (Section 4) to obtain a better simulation of structural performances.

A diagnostic analysis was needed to combine material properties and geometrical information. It is necessary to consider the temporal deterioration of the materials (in particular mortar) and the historical evolution of the building with progressive modifications and restorations (e.g. infills, new openings, restoration or substitution of damaged elements with new materials): alterations of original conditions have an impact on structural behavior.

An investigation of the structure under analysis (in terms of composition and structural behavior) requires different techniques such as non-destructive (thermography, sonic tests, geo-radar), minor destructive (flat jack, coring), or destructive (sampling) [21,22]. The choice of the technique is directly correlated to the achievable information. Although destructive techniques are the most reliable in terms of accuracy, they have an impact on the building, especially in the case of elements with high cultural value, such as frescoes, decorations, and stuccos. Destructive (or slightly destructive) tests can be performed in areas without decorations and characterized by similar masonry typologies.

For the case of Castel Masegra, non-destructive tests (NDTs) and minor destructive tests (MDTs) were planned in order to characterize construction materials and techniques, state of conservation, mechanical properties of masonry, foundation levels, thickness of vaults and retaining walls. Some images of the different inspections are shown in Fig. 3.

In the South wing of the Castle, four flat jack tests (single and double) were carried out. The first two tests were performed in the room with the barrel vault. A test was carried out in the room of the groin vault (ground floor), and the last one in the North wall of the corridor (first floor). The results obtained from single flat jack tests are useful to calibrate the structural simulation and evaluate its accuracy. The results obtained from the double flat jack tests were instead used to evaluate the deformability modulus.

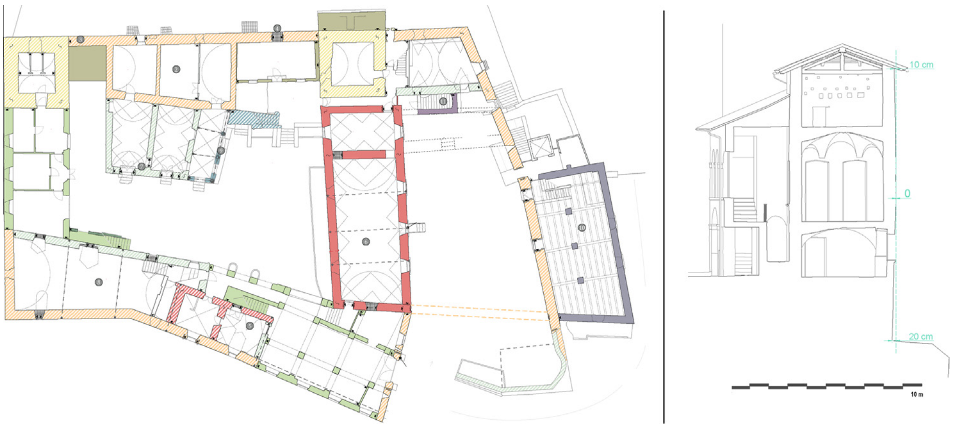


Fig. 2. The plan of the castle (ground floor) with the subdivision based on the different stages of construction; a cross-section that shows the verticality issue of the external wall of the tower (the out of plumb is 20 cm).

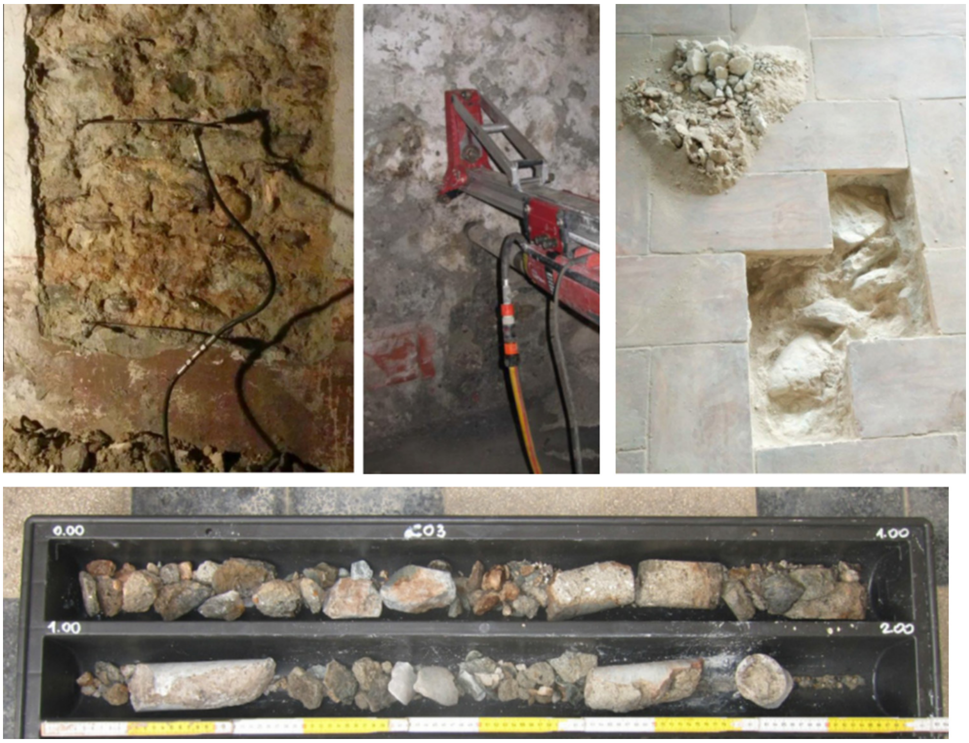


Fig. 3. Some destructive tests used to define material properties: flat-jack (top-left), coring (middle and bottom), and the inspection of the floor to measure vault thickness (top-right).

Coring is another important operation able to investigate masonry. The principal purpose is a better description of construction typologies. In the case of an historic masonry structures, it is important to investigate not only the superficial texture, but also the internal masonry structure. Horizontal and sub-vertical coring was performed for the characterization of walls and foundations, respectively. In the South wing, two horizontal (in the partially buried room) and two sub-vertical inspections were carried out. As the collected sample was very damaged, the interior of the borehole was observed using a videoboroscopy.

For which concerns the vaults, a simple inspection was carried out to discover the thickness. A small part of the pavement was removed to reach the bearing layer. This is a very simple and minor destructive technique (the infilling material can be replaced) which provides the vault thickness and its texture.

3. Building information modeling and finite element model from point clouds

3.1. Historic BIM generation from laser point clouds

Historic BIM generation is a complicated task since the tools available on the commercial market are not sufficient to represent the irregularities of historic buildings. BIM software and object libraries are mainly developed for modern constructions, where standardized elements with parametric representation are used for the design phase. Historic buildings have complex elements and the use of predefined BIM libraries is a limitation.

Existing libraries can be used when a detailed and accurate representation of the irregularities is not needed. On the other hand, a solution based on new procedures able to better represent the geometric complexity requires a special attention. Although methods able to improve existing solutions can be developed to facilitate the use of BIM, one of the aims of BIM technology is the interoperability for the different professional operators (architects, engineers, restorers, archeologists, etc.) [23]. The implementation of methodologies limited to specific operators does not fulfill the requirements of a BIM pro-ject. For this reason, the work on the castle was carried out with the commercial package Revit for simple and regular shapes. Complex objects were instead modeled with the NURBS-based procedure proposed by [24], which provides a result fully integrated in Revit. In particular, the intrados of the vaults was reconstructed from NURBS curves and profiles that interpolate the laser point cloud. Then, the thickness was parametrized by means of a dynamic offset of the surfaces, including the associated layer information [25].

A particular attention was paid to the definition of the generative NURBS profiles of vault wedges to obtain a rigorous geometric representation. Modeling of the shape needed a simplification without strong variations of the curvature. The surface had to match the boundaries so that adjacent surfaces can be joined to become a single solid. This aspect is very important for the finalization of the work: finite element analysis needs some well-defined solid entities turned into consistent meshes, without self-intersections or open edges. This result differentiates modeling for visualization purposes (rendering and visualization) from modeling for structural purposes. As the BIM will be converted into a 3D model for finite element analysis, the work must integrate all the requirements needed for a rigorous structural analysis, starting from the first modeling phases to the definition of material properties, loads, and boundary conditions.

Simple and regular shapes were instead directly modeled in Revit. Structural elements were classified following the predefined structure of the software database: category, family, type, and instance. 3D modeling was carried out from the 2D drawings created from the laser cloud. The preliminary use of 2D drawings is a valid tool to distinguish areas where an accurate 3D modeling is required from parts that can be simplified with predefined objects. Plans, sections, and elevations correctly positioned in space provide the reference frame for the reconstruction of the model. This is a fundamental point towards the creation of an accurate BIM consistent with the preliminary products of the geometrical survey.

Starting from the sections, the main deviations from verticality of exterior walls were identified, whereas the interior wall appeared reasonably vertical. Revit tools for openings (“windows” or “doors”) were not directly used. The basic functions of the software allowed one to define a large number of predefined parameters. However, a limited correspondence was found for the complex openings of the castle. The accurate modeling would require the definition of ad hoc families for the different types of openings. As their accurate modeling is not necessary for the structural analysis, the openings were modeled as “voids” in the BIM.

An image of the final BIM of the castle is shown in Fig. 4. The proposed methodology provided a complete BIM for simple and complex shapes, which are combined into a parametric database. Although the software cannot directly generate such a complex shape, modeling can be carried out in external environments. Objects are then imported following the parametric modeling principles along with a categorization based on Revit families to preserve BIM interoperability [26].

3.2. From BIM to finite elements

Some software available on the commercial market allow the integration between finite element analysis and BIM technology. For instance, Robot Structural Analysis (www.autodesk.com) or 3D FEM professional (www.sofistik.de) are

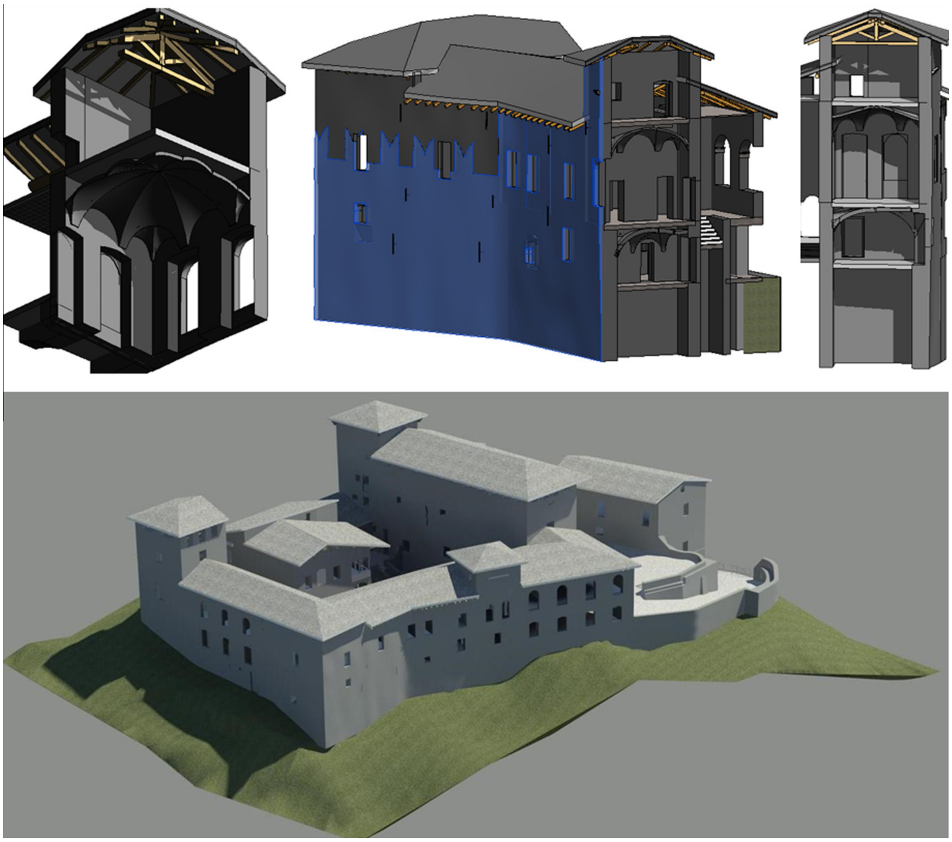


Fig. 4. Some images of the final BIM of Castel Masegra.

integrated with Revit and provide advanced structural simulation capabilities for finite element analysis of large and complex structures. Scia Engineer (www.nemetschek-scia.com) enables Revit users to analyze complex and large 3D models. FEM-Design is integrated with Revit Structure, Tekla and ArchiCAD (www.archicad.com). It performs advanced static and dynamic calculations including earthquake analysis. These packages were developed for modern buildings with regular elements, such as straight columns, simple beams and vertical walls.

The approach proposed in this paper improves the analysis towards a new approach where structural anomalies are included in the simulation. The BIM and its geometric information are turned into a tetrahedron solid mesh to preserve the information captured by laser clouds. The aim is an exhaustive description of the complex shape that characterizes load-bearing elements (mainly vaults and irregular walls) for their direct use into a structural analysis based on finite elements.

The problem can be intended as the conversion of the (H)BIM into a Finite Element Model (BIM-to-FEM), without the creation of new models limited to the structural simulation. The idea is an intelligent conversion of the BIM into a tetrahedron solid mesh for structural analysis, without losing the high level of geometric detail encapsulated into the original point clouds.

The input for Midas is a mesh of closed surfaces with a perfect face-to-face correspondence. A tetrahedron solid mesh can be automatically generated from the volume enclosed by 2D surfaces, which can be extracted from the (H)BIM. In the case of adjacent objects the same face must be replicated to create independent solids. Surface intrusions or other conflicts must be removed beforehand.

The choice of a tetrahedron solid mesh mesh is motivated by the geometric simplicity of the structure and the partial automation of the BIM-to-mesh conversion. The basic element of the 3D mesh is a tetrahedron, which is a polyhedron with four sides, three of which meet at each vertex. Tetrahedralization is carried out with elements with variable dimensions to allow smooth transitions. Regular tetrahedrons made up of equilateral triangles are looked for. The main drawbacks of this kind of mesh concern the final number of elements and the larger CPU cost during the simulation, which can be much larger than those of other existing meshing algorithm.

The average size of the 3D mesh was set to 0.2 m to take into consideration the thickness of the load-bearing walls. This is a good compromise in terms of final number of elements with a representation of the objects with at least 3–4 elements along the thickness.

The creation of a mesh suitable for finite element analysis is not only a geometric conversion of the different BIM objects into a new meshed form. Different BIM objects must become local meshes with a perfect node-to-node and face-to-face correspondence to guarantee the continuity of the model. Small objects and irregular edges can be transformed into very distorted elements with elongated features. Although the geometric consistency can be easily preserved, the new shape can have elongated triangles. For this reason, the automated conversion into a consistent mesh remains a very complicated task, especially for the kind of analysis required that is not only based on geometric constraints, but also on structural considerations and interpretation of functional behavior. The results of the auto-meshing algorithm were therefore manually edited and readapted to fit the requirements of the software for structural analysis (Midas FEA). In particular, the following corrections were carried:

- small objects without static relevance (e.g. the opening jambs) were eliminated. Such elements should be removed to avoid the generation of small finite elements and a dramatic increment of the total number of the degrees of freedom in the numerical problem;
- distorted objects require a correction: the approximation error in the 3D mesh increases with object distortion. The use of a pure geometric conversion could result in the collapse of some elements (near zero volume), which means that additional reshaping is needed;
- lack of geometric node-to-node and face-to-face correspondence: different elements must have a rigorous a geometric correspondence. In the case of a fully automated conversion of the BIM objects, edges and faces of corresponding objects resulted in some local intersections or other geometric inconsistencies;
- variable density: although the method can handle elements with variable size, an excessive number of elements was found for complex shapes. An example is shown in Fig. 5, where small and large elements were used to provide a mesh-based representation of complex objects. Data filtering was carried out with reshaping techniques to combine small elements (according to a prefixed threshold) into larger faces.

The correction of the previous issues was a time consuming operations for the lack of algorithms able to automated the process. In fact, the conversion is not only a geometric problem. As things stand at the present, an expert operator has to (i) check the errors and (ii) perform manual corrections. The interpretation of different objects requires an investigation of material aspects, logic of construction, architectural and structural considerations. The application of automated methods for object recognition is still in its infancy for historic constructions with irregular geometry, inhomogeneous materials and architectural alterations.

For these reasons, the correction of the 3D mesh was carried out manually. The analysis started with a revision of the walls characterize by a variable thickness. The different parts of the walls were combined into single solids. Boolean operations (union, subtraction and division) were used to initialize the project, but most corrections and refinements required local revisions of the single surfaces.

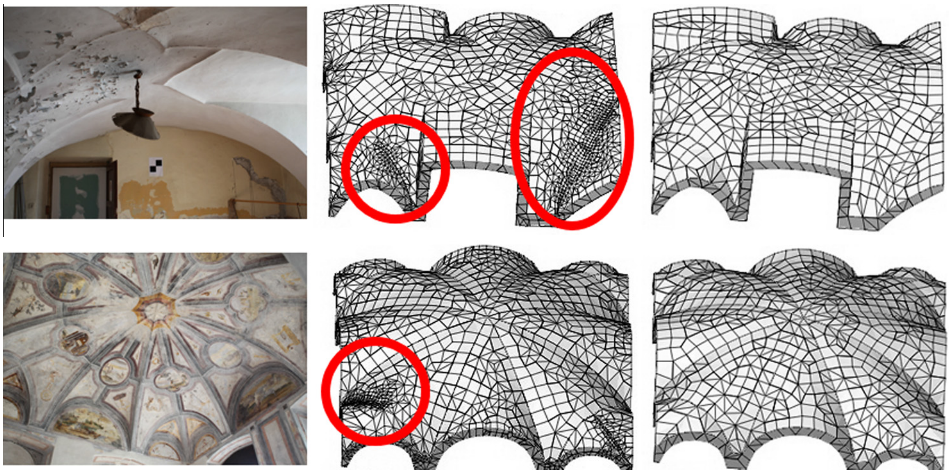


Fig. 5. A geometric conversion could provide small or elongated triangles which need additional reshaping.

Openings were strongly simplified. Door and window frames are not necessary and edges were joined to provide a good continuity with the walls. These modifications were carried out with Boolean algebra and local corrections not only for the volume covered by the objects, but also in a bounded area around the openings to generate a regular transition without breaklines. Vaults are probably the most complicated objects to in a 3D modeling approach based on a BIM transformed into a finite element model (Fig. 6). As mentioned in the previous section, laser scanning point clouds capture only the intrados, whereas the extrados can be parametrized to modify the model without redrawing. The generation of the 3D mesh required a good representation of the connection with the wall. In the case of openings close to vaults, an excessive elongation of the surface should be avoided with the introduction of small elements.

Another significant issue was found for the battlemented front, that defines a sudden subdivision with an irregular discontinuity line. The presence of tips in the BIM led to a global thickening of the mesh. The generation of such fragmented parts is another complicated issue. Different iterations can be carried out to join consecutive elements with an average size much smaller than the average mesh resolution. Fig. 7 shows the merlons reshaped to avoid unnecessary elements provided by the preliminary BIM-to-mesh conversion, without affecting the discontinuity lines that could have an important role in structural analysis.

Finally, the roof was included in the model to evaluate its structural performances (Fig. 8). Although some numerical analysis tend to consider the roof as a dead load, the incorporation with simplified linear elements with constant cross-section is

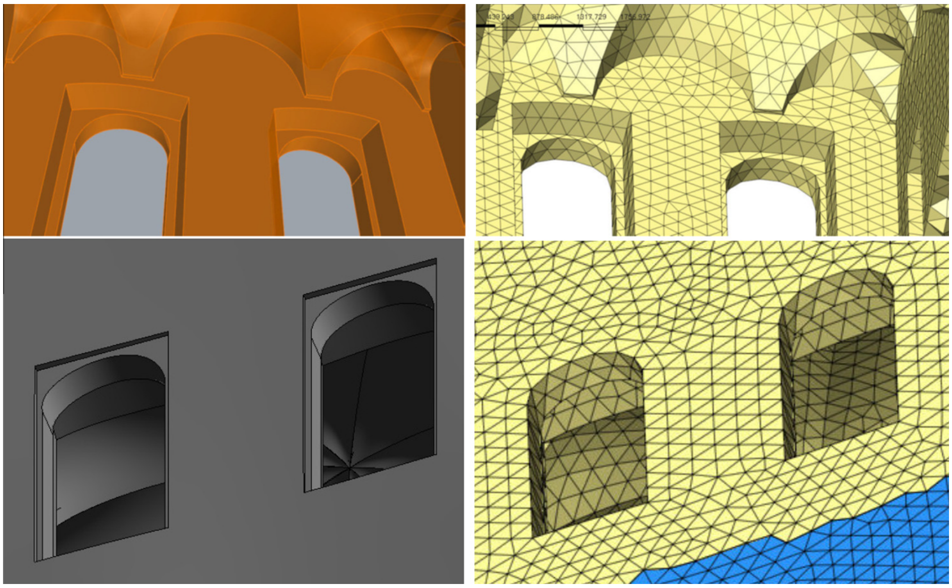


Fig. 6. BIM-to-FEM conversion of vaults and openings.

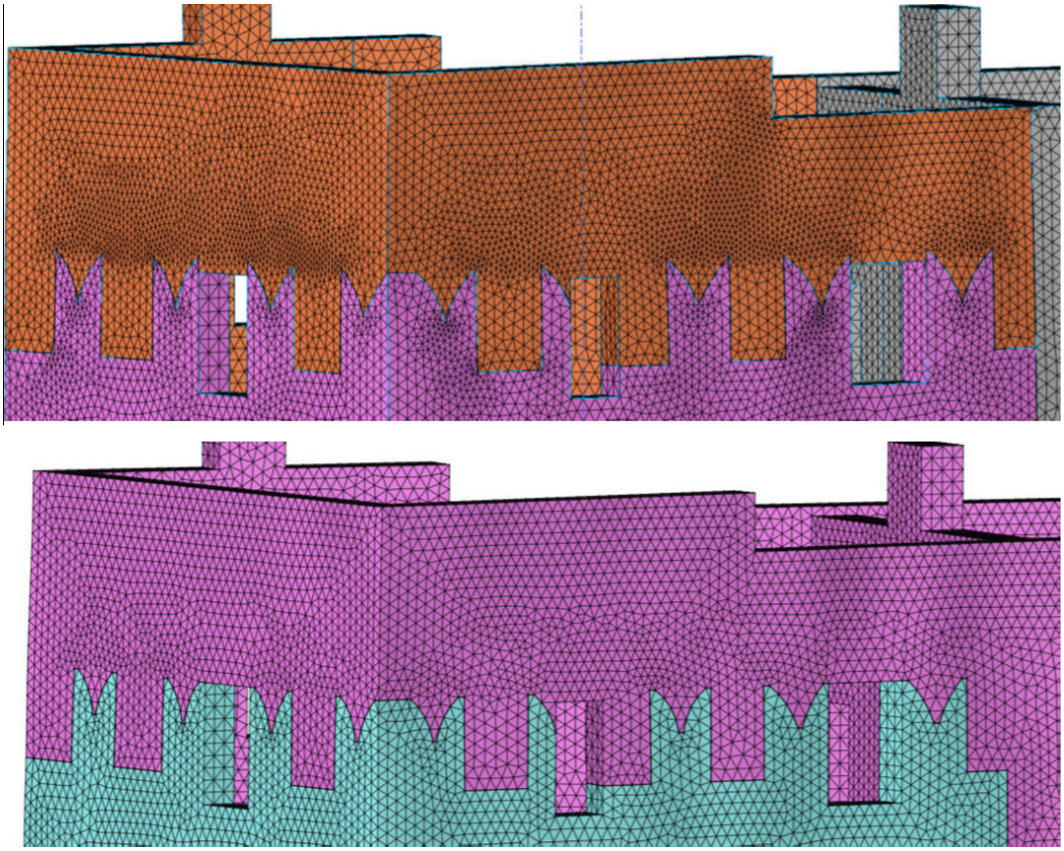


Fig. 7. The excessive fragmentation of the battlemented front (top) and the iteration carried out to reduce the number of elements close to the merlons.

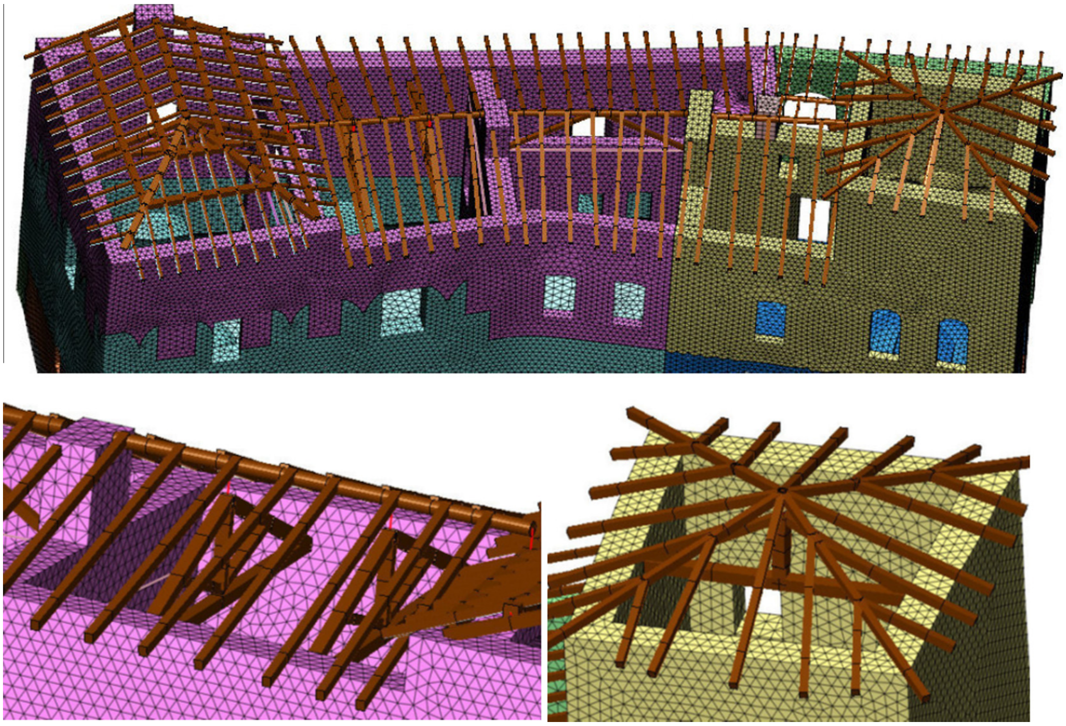


Fig. 8. The roof included with mono-dimensional elements with additional rotational constraints.

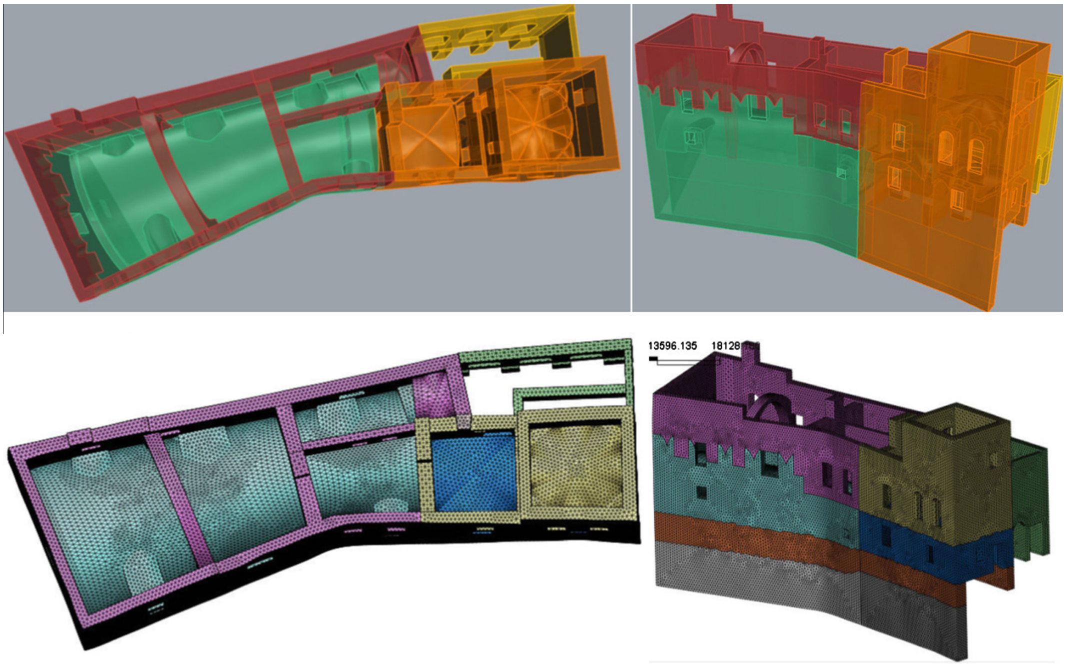


Fig. 9. The final mesh from the BIM colored according to the different construction stages.

extremely useful to complete the model. Roof objects were exported from the BIM and remodeled following their main directions with a proper connection in the nodes. Rigid links were added where the axes of intersecting elements are not coincident. An additional internal subdivision of the beam into four elements was carried out to obtain information about the deformation. Problems were found between the connections of the beam and the mesh. The elements have only three degrees of freedom (3 translations), whereas beam schematized as linear objects have three additional degrees of freedom (3 rotations). A solution was found with the introduction of some rotational constraints for the nodes characterized by this incongruence.

Finally, the global mesh was split into multiple parts in order to assign appropriate material characteristics based on destructive inspections (flat-jack tests). The subdivision includes the historical analysis of the castle along with additional considerations about the state of conservation of the mortar in humid areas (the North-West part of the basement) and dry zones.

The final mesh is made up of 720.393 elements (Fig. 9), which were individually checked by using the aspect ratio (*AR*), which is an internal check of mesh quality based on the percentage of deformed elements. *AR* can be estimated as the ratio between height (*h*) and side (*s*) of single elements. The result of this test showed that only a limited percentage of elements (2%) have an aspect ratio smaller than 0.5, that is usually considered a good threshold. Most elements have a value larger than 0.65, which can be assumed as a good compromise for practical purposes.

Fig. 10 shows the distribution of the deformed elements in the final 3D mesh. Most deformed elements are located close to the intersection between complex vaults and walls, as well as in the discontinuity lines along the merlons. On the other hand, the overall distribution seems regular without strong local concentrations that could result in a wrong estimate in specific areas. For these reasons, the final mesh seems adequate for a finite element analysis that preserves the original geo-metric complexity of the shape.

4. Structural simulation based on construction stages

4.1. Input parameters

Different simulations can be carried after the generation of the FEM model. The simulation presented in this work is a linear elastic analysis under self-weight, which provided also a global check of the mesh and information about some initial assumptions. For instance, a good setup of boundary conditions can be found with an iterative process. In addition, gross errors can be easily recognized with the inspection of strange stress or deformation patters under self-weight. The opportunity to carry out more complicated simulations (non-linear, seismic, etc.) will be investigated in future developments. As things stand at the present, the proposed cloud-BIM-FEM approach aims at demonstrating the opportunity to (i) generate a complex (H)BIM, (ii) convert the H(BIM) into a 3D mesh, and (iii) run a finite element analysis.

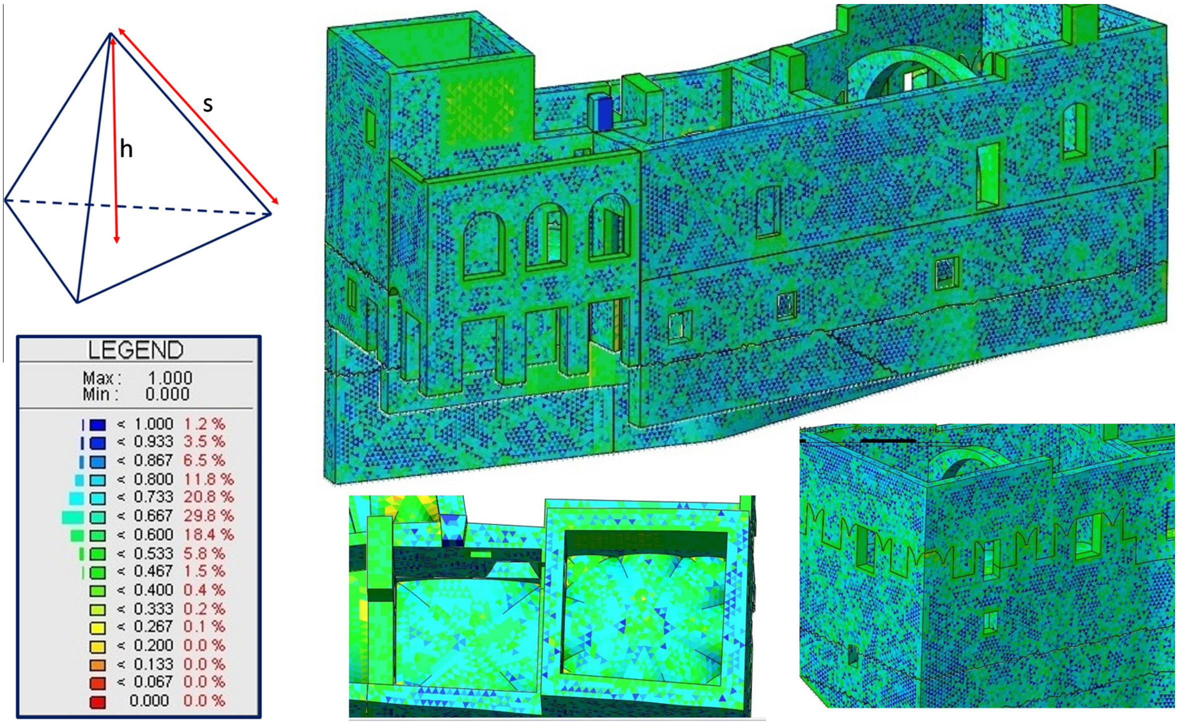


Fig. 10. Aspect ratio distribution for the final mesh.

The structural analysis required the manual assignment of loads. The specific weight was set to 22 kN/m^3 after the inspection of stone typology and dimension. The Poisson coefficient was set to 0.2, whereas the elastic modulus was firstly set to 3000 N/mm^2 following the NTC regulation [27]. Then, a more sophisticated analysis was carried out by considering the elastic modulus derived from loading–unloading tests. The subdivision based on the historical transformations of the castle allowed one to set specific parameters for the different parts of the mesh.

The self-weight of the different elements was automatically computed from the model, whereas the dead load was applied as a distributed load. The objects modeled only in the BIM (i.e. removed in the finite element model) where converted into dead loads (e.g. the infilling materials of the vaults). The load on vaulted elements was included as a function of spatial coordinates to avoid unrealistic load distributions. In fact, an uniformly distributed load gives an irregular distribution of the forces with an excessive load on the keystone. The used load was estimates as $p(z) = \gamma_{fill} \cdot (H - z)$, where γ_{fill} is the average specific weight of the infilling material, H is the interdistance between the floors (the considered room and the floor above), and z is the elevation of the extrados. Although the laser point cloud cannot reveal the surface of the extrados, the advantage of a parametric BIM representation allows a direct estimation of the extrados along with an immediate computation of the load. This is a hypothesis which can differ from the real shape. However, the finite element analysis and other analysis (e.g. costs) can be carried out in a fully automated way with some acceptable approximations. It is important to mention that the measurement phase cannot provide the complete model, for which some approximations and assumptions are always required.

The weight of wooden slabs was calculated and distributed on the walls following the span direction. The finishes (pavements and infilling vaults) were included as distributed dead loads applied on the corresponding vaults or slabs. The specific weights were set with the standard values available in technical literature. A precise load analysis was carried out for objects with a known stratigraphy, whereas an average value was set for structures without layer information.

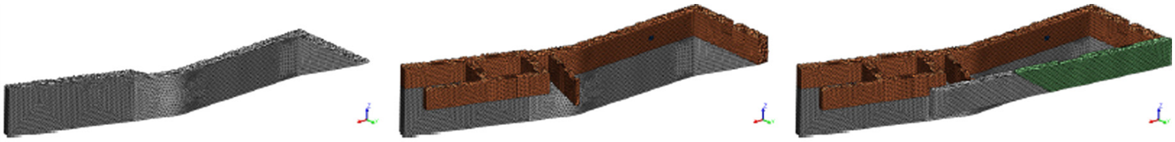
The soil thrust $s(z)$ was modeled as a linear function of the depth, assuming a granular structure. The chosen parameters are a friction angle $\phi' = 30^\circ$ and specific weight $\gamma_{soil} = 20$ kN/m^3. The basic relationship for the estimation of the thrust is $s(z) = K_{a,0} \cdot \gamma_{soil} \cdot (H_{soil} - z)$, which depends on point elevation z and ground floor elevation H_{soil}, whereas the coefficient $K_{a,0}$ assumes different values for the case of (i) active thrust $K_a = \frac{1-\sin\phi'}{1+\sin\phi'}$ (soil only on one side of the wall) and (ii) passive thrust $K_0 = 1 - \sin\phi'$ (soil on both sides).

A proper setting of boundary conditions was one of the most important issues. The castle raises on a cliff and the different parts have different foundation levels. Three foundation typologies were used to associate the modulus of subgrade reaction: (i) superficial foundation (East wall of the dovecote tower) with a medium–low value (0.03 N/mm^3), (ii) deep foundation with a medium–high value (0.06 N/mm^3) for the other walls of the tower and the adjacent buildings, (iii) foundation on rock (0.5 N/mm^3) for the North, South, and West walls.

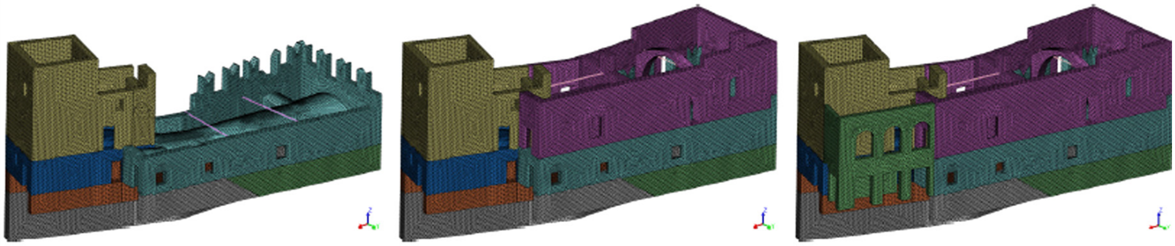
4.2. Model calibration and validation

As the castle is the result of different geometric and material transformations, the structural analysis with Midas FEA was carried out by using the temporal evolution encapsulated into the construction stages (Fig. 11). The different parts were gradually added to the simulation with a preliminary analysis under self-weight (for each stage). Then, parts of the castle belonging to the following stage were added on the deformed configuration. This combined data processing was carried out to simulate the historical transformations of the castle, which can have a strong effect on load distribution. The aim of the work was a global limitation of irregular load distributions, with local stress concentrations in areas with different material properties. In fact, in the case of large variability of elastic parameters, the weaker part tends to hang to the stronger one, forming unrealistic stress patterns.

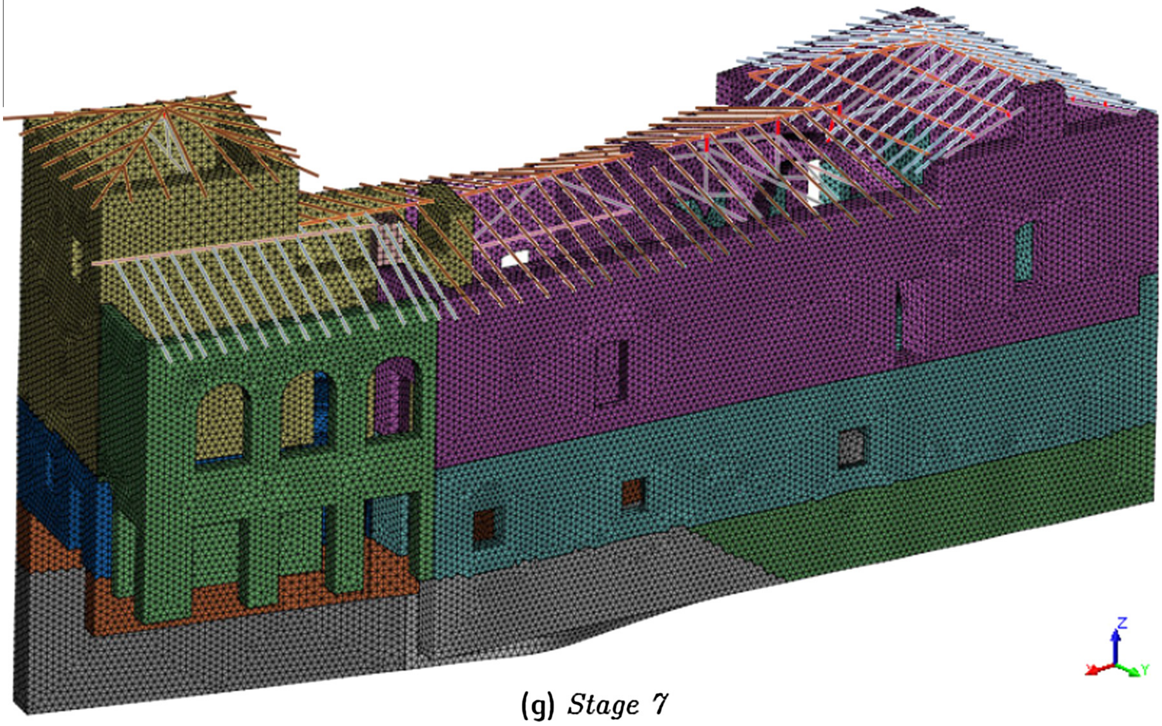
Another advantage of the multi-step approach is the reduction of stress concentration for the different foundation levels, where the presence of fixed restraints do not allow any settlement. Although this effect was not completely corrected, a strong attenuation was achieved. The main disadvantage of the multi-stage analysis is the increment of CPU time, that



(a) *Stage 1* (b) *Stage 2* (c) *Stage 3*



(d) *Stage 4* (e) *Stage 5* (f) *Stage 6*



(g) *Stage 7*

Fig. 11. The composition of the different construction stages used in the finite element analysis.

depends on the number of stages. If the single-stage analysis took less than 5 min, the complete use of the seven stages took more than 40 min. On the other hand, the final CPU time is a reasonable compromise for practical purposes.

Data validation can be carried out by comparing the stress values obtained from the simulation with the same parameters measured from single-jack tests. This allows one to (i) validate some of the initial hypothesis and to (ii) re-calibrate the parameters. Three simulations were carried out as follows:

(1) simulation without information about material properties and foundation typologies: the values provided by the national regulation NTC were used with additional fixed restraint conditions applied to the base of each wall;
(2) simulation with known material properties (flat-jack test) and fixed restraints applied to the base of each wall;
(3) simulation stages with known material properties (flat-jack test) and variable levels of subgrade stiffness, as described in the previous section.

A comparison between measured (v_{jack}) and simulated data (v_{sim}) is shown in Table 1. A good correspondence was achieved for tests M3 and M9, located on the South wall (room with the barrel vault) and the North wall (corridor at the first floor). In the case of tests M2 and M4 (North wall in the room with the barrel vault, and West wall of the dovecote tower, respectively) the simulation does not correspond to the stress measured by flat-jacks. The relative error was estimated as $\%err = (v_{sim} - v_{jack})/v_{jack}$, from which it is evident the good correspondence for two experiments, whereas the simulation in M2 provides a large error and simulation M4 failed. The discrepancy of the results shows the complexity in the assignment of good initial parameters (input) in the case of historic constructions, where material properties measured in few localized areas are used for a global estimation. In addition, empirical information and assumptions are mandatory for the lack of reliable numerical data homogenously distributed in the whole model.

On the other hand, post-validation cannot be limited to a simple comparison of the obtained values. Additional investigations (recalibration of the model, interpretation, etc.) can explain why the model did not capture the correct stress. For instance, the discrepancy for M4 can be explained with a deep investigation of the tower. The tower has a rotation in the East direction because of the settlements of the very superficial foundation of the East wall. The West wall (deeply founded in soil) is subjected to a bending moment so that it is in tension. This effect was not taken into consideration in the model. A possible improvement of the simulation could be the choice of a different stiffness for the foundation of the tower. However, this requires an exhaustive characterization of the foundation, including soil and rock subgrades, and mechanical properties. This information is not available at the moment and requires additional data measured on site. The explanation of the failure of test M2 is probably due to the overall lack of information concerning subgrade materials and foundation depths.

It could be said that the model gives good results in the areas where boundary conditions are simple or known, whereas problems arise where additional input parameters should be coupled with further analysis on-site. The model seems adequate to fulfill structural requirements, whereas improvements should be carried out to take into considerations geotechnical aspects.

A complete evaluation of the final accuracy is feasible only with the acquisition of new data with destructive tests. However, this is not simple and should be avoided in the case of historic constructions, where the preservation of the integrity of the building cannot be neglected. For these reasons, an additional evaluation was carried out with the interpretation of the simulated results and the observation of existing crack patterns. The results of the second simulation (fixed restraints) were used for the lack of information about the soil.

4.3. Validation with local crack patterns

As mentioned in the previous section, another method that can be used to validate the simulation is the comparison of stress patterns with in-situ observations. Generally speaking, a local stress concentration in the model should correspond to existing damages, such as detachments and cracks.

A comparison between the simulation and crack patterns is shown in Fig. 12a, where the presence of an unloading arch on the East wall of the dovecote tower is clearly visible. An inspection of the wall explains the achieved result: the unloading arch is due partially infilled openings that weaken the wall below the vault corbels, where the load is transferred to the walls. The simulation gives a local stress concentration clearly visible by plotting the first principal stress, which corresponds to the direction of maximum tensile stress and is quite parallel to the wall itself in the reference system of total station measurements.

Table 1
Comparison of the results obtained from the Single Flat Jack and the different models.

	M2 MPa	M2 % err	M3 MPa (% err.)	M3 % err	M4 MPa	M4 % err	M9 MPa	M9 % err
Simulation 1	0.202	*124*	0.328	*30*	0.244	–	0.116	*29*
Simulation 2	0.245	*172*	0.342	*27*	0.239	–	0.098	*9*
Simulation 3	0.291	*223*	0.386	*18*	0.223	–	0.104	*16*
Flat Jack	0.09		0.47		Tens.		0.09	

Numbers in italics are relative percentages.

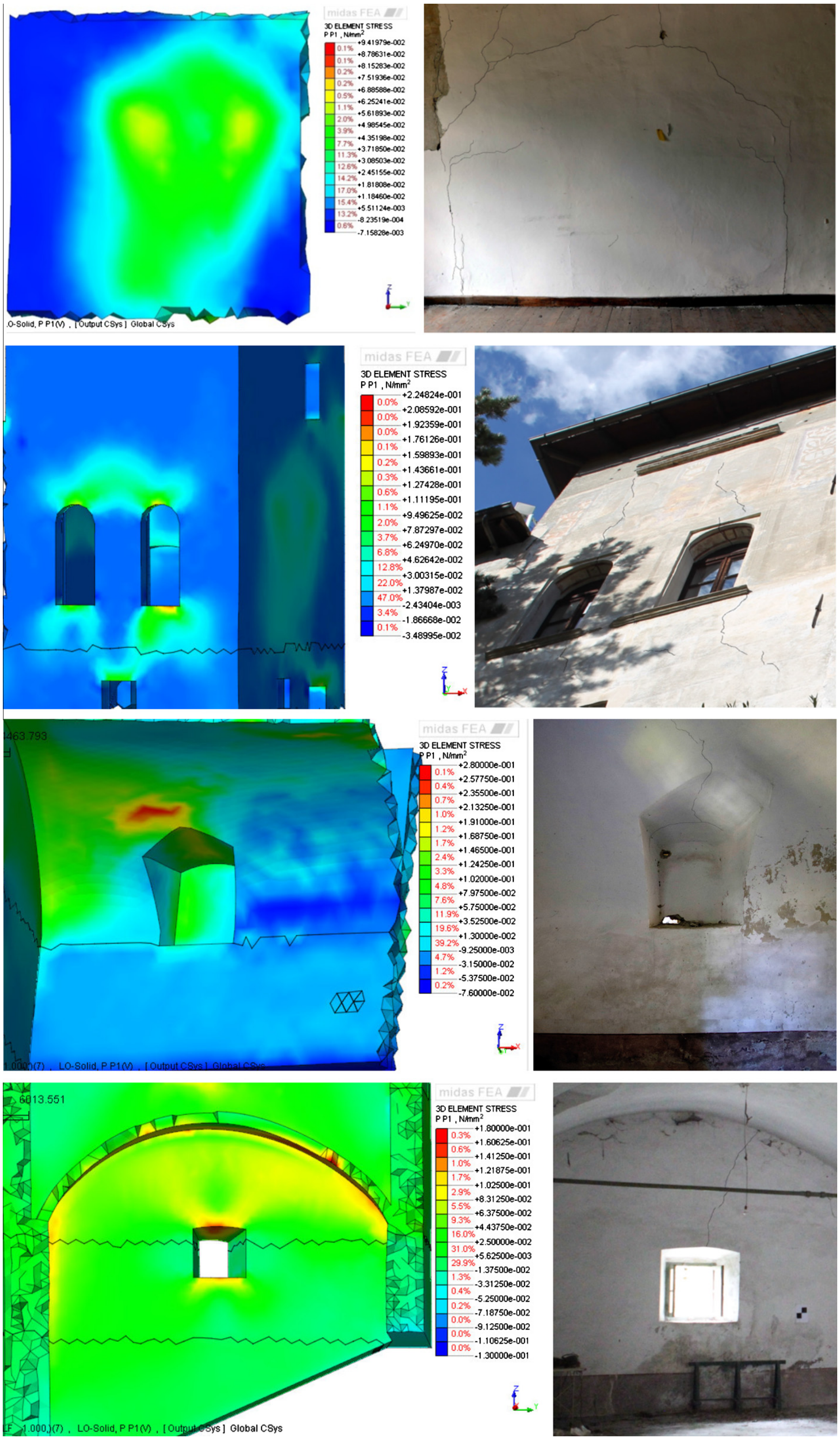


Fig. 12. Comparison between local stress concentration after simulation and cracks and detachment found with an inspection.

A similar effect was found on the other side of the room (Fig. 12b). Here, the conditions are even worse than the previous case, since windows are still opened in the South wall. The real crack pattern follows the overall indications provided by the model, with a very satisfactory comparison between simulated data and cracks.

Another interesting example is located in the South-West room, on the lunettes of the barrel vault. The model is able to predict crack location and propagation (Fig. 12c). In the same room, a similar example was discovered for the opening in the West wall (Fig. 12d).

The simulation can also be compared with other on-site observations. Shown in Fig. 13 are the results obtained in terms of stress for the whole building. The color bar of the stress plots was adjusted to remove the influence of stress concentration in correspondence of the foundations. The stress values are lower than the ultimate strength of masonry estimated by flat jack tests. No particular problem is expected in terms of resistance. The tensile stress due to the lateral trust of the vaults (in particular the barrel vault) is clearly visible. The same result can be highlighted in terms of displacements, where the effect in correspondence of the sides of the barrel vault is evident.

Another stress concentration can be found in correspondence of the anchorage of tie-rods. The modeling of the anchor rods redistributes the stress in a more realistic way, although its influence is quite limited. Interesting results were obtained in parts with different materials. The great settlement of the lowermost part of the North wall is well defined. This is mainly due to the very bad conditions of the masonry in this area, that are confirmed by the experimental tests. The differential displacement between the tower and the North arcade is another issue that deserves to be mentioned.

The visual inspection and an accurate interpretation of these results reveal the importance of an analysis based on construction stages, that can avoid unreal correlations between weak and strong parts. An additional analysis was carried out by considering the vaults with a live load of 5 kN/m^2 provided by the NTC regulation. The value refers to crowded spaces, such as museums. This load was applied on each vault as an uniformly distributed pressure load. The aim of the simulation is to describe the influence of this load on the vaults for a future reuse of the spaces of the castle.

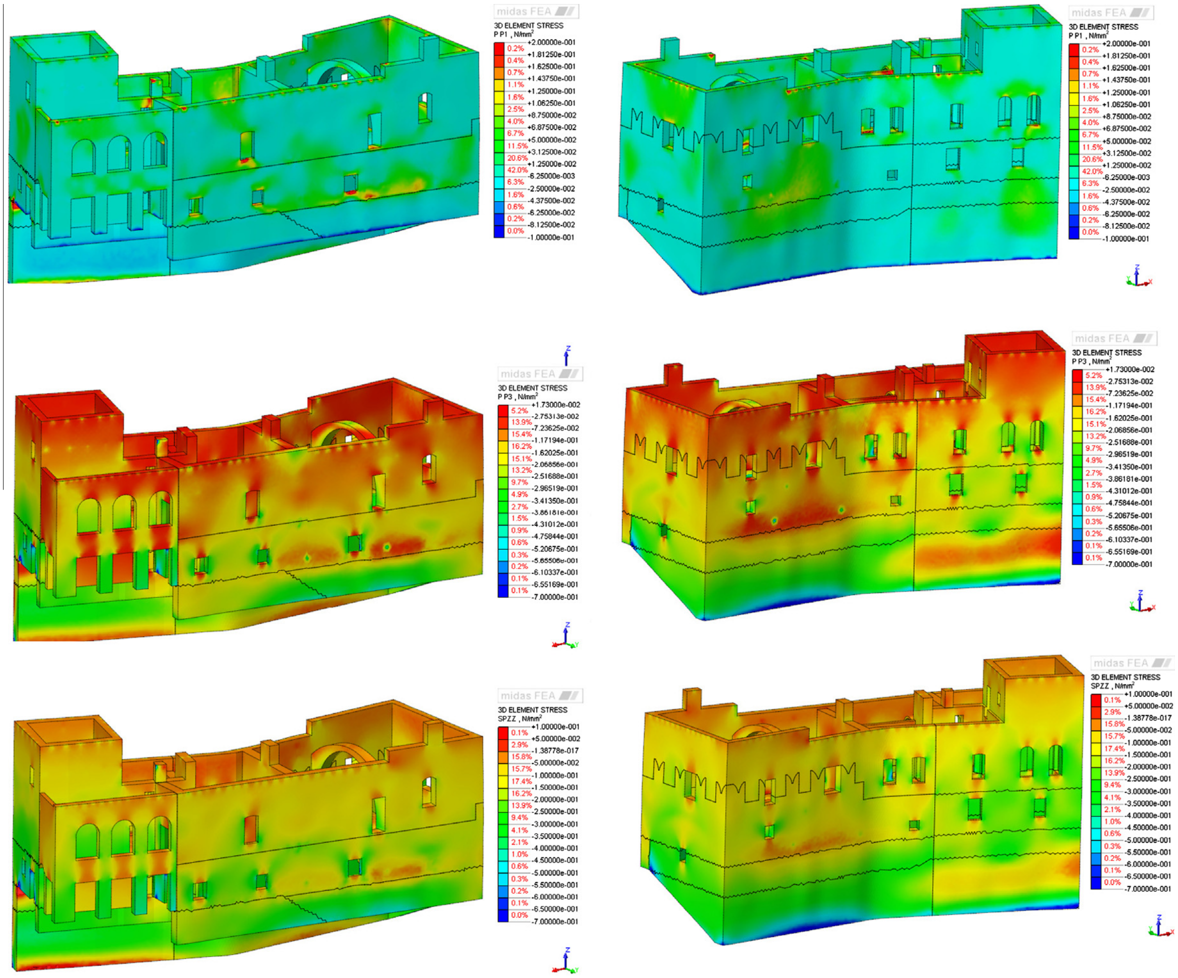


Fig. 13. A visualization of stress plot after the finite element analysis with the complete model: first principal stress (top), third principal stress (middle), and vertical stress (bottom).

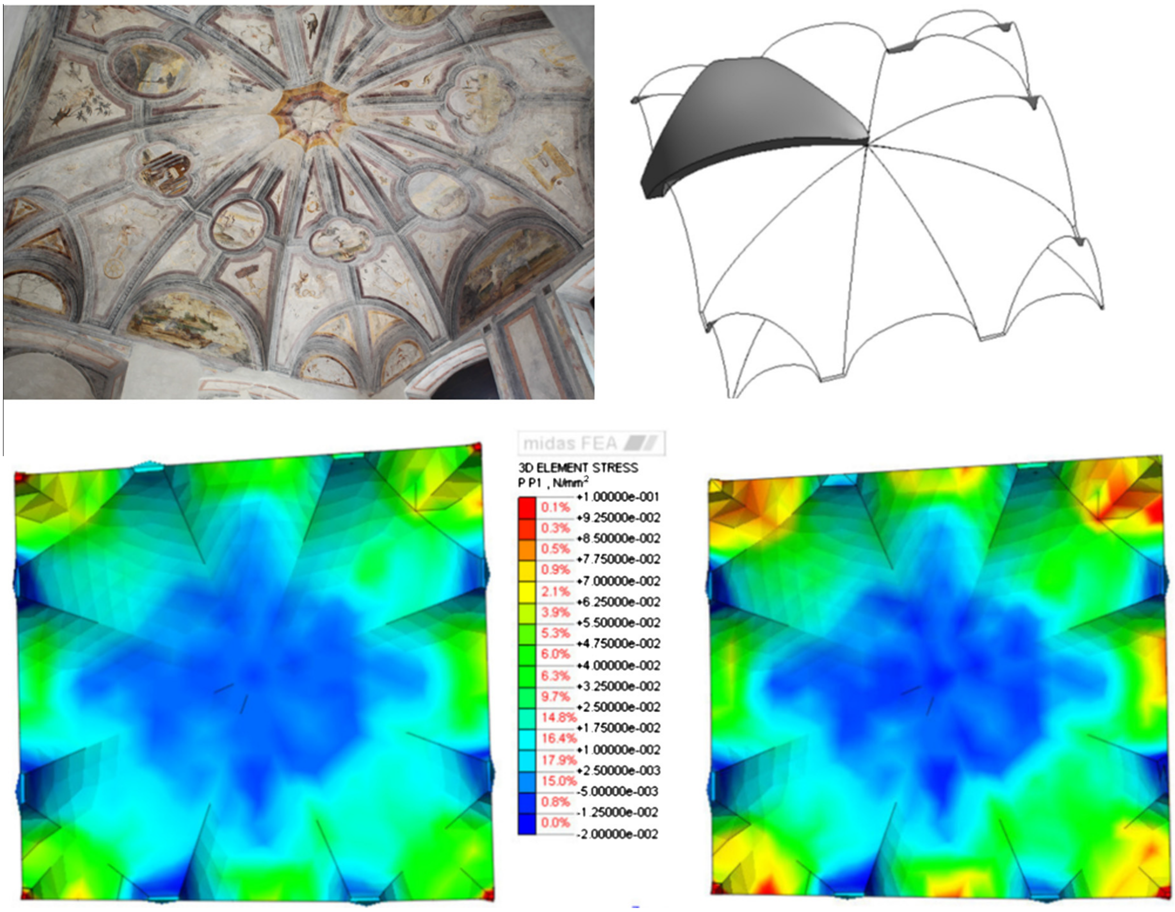


Fig. 14. The increment in the first principal stress with the live load (bottom right) on the vault could lead the re-aperture of the restored cracks.

The first test was carried out with the umbrella vault. Although the floor above is not open to public, there are frescoes and decorations that makes this room very attractive. Shown in Fig. 14 is the distribution of the principal stress. The same graphical visualization was used in the color bar to highlight the difference. The most important result is given by the inspection of the first principal stress, that shows the zones subjected to tensile stresses. A significant increment of tensile stresses (almost doubled in the most critical zones) can be found, especially in the lunettes. A comparison between these results and the IR thermography of this area confirms that these parts present several cracks repaired during previous restoration works. The overload on the vault could generate a variation of crack aperture, which is not acceptable for a completely frescoed surface.

5. Conclusion

The proposed cloud-to-BIM-to-FEM methodology allows the generation of detailed historic BIM of complex architectures, which are then converted into 3D mesh for structural simulation via finite element analysis. The aim of this work was to demonstrate that an accurate BIM generated from point clouds can be simplified and meshed to fulfill structural analysis requirements.

The work can be intended as a BIM-centered approach, where structural simulation is an additional step in the project workflow. The work does not rely on the generation of a new model only for structural purposes. Most information is extracted from the BIM, preserving the integrity and consistency of BIM logic as a common data processing environment for the different operators involved in the project.

As the BIM reflects the geometric complexity of the historic construction, the finite element model reflects the geometric irregularity without an excessive simplification of structural elements. This is a fundamental aspect that improves traditional structural simulation based on regular elements and simplified shapes. The uniqueness and authenticity of historic buildings is preserved towards a more exhaustive simulation with a limited extra-cost in terms of processing time.

Future developments will require the implementation of advanced functions for automated or semi-automated BIM-to-FEM conversion. As things stand at the present, meshing algorithms are based on geometrical aspects. Additional constraints such as structural considerations, object interconnections and material properties, will require advanced algorithms for object recognition and active machine learning. Existing BIM-to-FEM solutions can be used only for modern and regular buildings with predefined object libraries.

Although manual editing was mandatory to obtain a consistent mesh for structural simulation, the potential of the cloud-to-BIM-to-FEM methodology is remarkable and deserves future work for the automation of the different phases, starting from better algorithms for mesh generation, editing, and refinement. The investigation under different actions, such as wind or earthquake, will be taken into consideration in new experiments. The aim is to turned the proposed cloud-to-BIM-FEM into a operational tool for simulation pre- and post-restoration, and simulation for risk management and disaster prevention.

Acknowledgments

This work was partially supported by the Interreg project "La Conservazione Programmata nello Spazio Comune Retico" (CPRE). The authors want to thank S. Della Torre, P. Crespi, and N. Giordano. We are thankful to the staff of Municipality of Sondrio and Foppoli Moretta e Associati s.r.l. for providing some datasets.

References

[1] D.E. Chelson, The Effects of Building Information Modeling on Construction Site Productivity, Ph.D. thesis, University of Maryland, 2010, 314 pages.
[2] C. Eastman, P. Teicholz, R. Sacks, K. Liston, BIM Handbook – A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors, John Wiley & Sons, Inc., 2008.
[3] G. Lee, R. Sacks, C.M. Eastman, Specifying parametric building object behaviour (BOB) for a Building Information Modeling system, Autom. Constr. 15 (6) (2006) 758–776.
[4] R. Shipley, S. Utz, M. Parsons, Does adaptive reuse pay? A study of the business of building renovation in Ontario, Canada, Int. J. Herit. Studies 12 (6) (2006) 505–520.
[5] A. Sodja, B. Zupancic, Modelling thermal processes in buildings using an object-oriented approach and Modelica, Simul. Model. Pract. Theory 17 (6) (2009) 1143–1159.
[6] H.A. Gabbara, D. Bondarenkob, S. Hussaina, F. Musharavatic, S. Pokharelc, Building thermal energy modeling with loss minimization, Simul. Model. Pract. Theory 49 (2014) 110–121.
[7] S. Della Torre, How the concept of preventive conservation implemented on built cultural heritage can work as a factor for regional economic development, in: PRECOAH 2011 International Conference on Preventive Conservation of Architectural Heritage, pages 14–22, Nanjing (China), 2011, pp. 29–30.
[8] S. Fai, K. Graham, T. Duckworth, N. Wood, R. Attar, Building information modeling and heritage documentation, in: CIPA 2011 Conference on the Proceedings of XXIIIrd International CIPA Symposium, 2011, 8 pages.
[9] S. Fai, M. Filippi, S. Paliaga, Parametric modelling (BIM) for the documentation of vernacular construction methods: a BIM model for the commissariat building, Ottawa, Canada, in: ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. II-5/W1, 2013, pp. 115–120.
[10] L. Binda, C. Tiraboschi, Flat-Jack test: a slightly destructive technique for the diagnosis of brick and stone masonry structures, in: 8th International Conference and Exhibition, Structural Faults and Repair, 1999.
[11] M. Murphy, E. McGovern, S. Pavia, Historic building information modelling – adding intelligence to laser and image based surveys of European classical architecture, ISPRS J. Photog. Rem. Sens. 76 (2013) 89–102.
[12] D. Oreni, R. Brumana, S. Della Torre, F. Banfi, L. Barazzetti, M. Previtali, Survey turned into HBIM: the restoration and the work involved concerning the Basilica di Collemaggio after the earthquake (L'Aquila), in: ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume II-5, ISPRS Technical Commission V Symposium, 23–25 June 2014, Riva del Garda, Italy, 2014, 6 pages.
[13] C. Dore, M. Murphy, S. McCarthy, F. Brechin, C. Casidy, E. Dirix, Structural simulations and conservation analysis – historic building information model (HBIM), Int. Arch. Photogram. Rem. Sens. Spat. Inf. Sci. XL-5/W4 (2015) 351–357.
[14] R. Brumana, D. Oreni, B. Cuca, L. Binda, P. Condoleo, M. Triggiani, Strategy for integrated surveying techniques finalized to interpretive models in a byzantine church, Mesopotam, Albania, Int. J. Architect. Herit. 8 (2014) 886–924.
[15] L. Piegl, W. Tiller, The NURBS Book, Monographs in Visual Communication, second ed., Springer-Verlag New York, Inc., New York, NY, 1997. 646 pages.
[16] R. Brumana, D. Oreni, A. Raimondi, A. Georgopoulos, A. Breggiani, From survey to HBIM for documentation, dissemination and management of built heritage: the case study of St. Maria in Scaria d'Intelvi, in: Digital Heritage International Congress, Marseille, 2013, pp. 497–504.
[17] S.B. Gavazzi, Il Castello Masegra di Sondrio: approfondimento documentario, 2004, 37 pages.
[18] L. Bonetti, S. Perlini, Masegra. Storia del Castello di Sondrio, 2013.
[19] A. Georgopoulos, Ch. Ioannidis, Ch. Chrysostomou, S. Ioakim, N. Shieittanis, M. Ioannides, Contemporary digital methods for the geometric documentation of churches in Cyprus, Int. J. Arch. Comp. 7 (1) (2009) 21–37.
[20] M. Santana Quintero, B. Blake, R. Eppich, I-Conservation of architectural heritage: the role of digital documentation tools: the need for appropriate teaching material, Int. J. Arch. Comp. 5 (2) (2007) 240–253.
[21] I. Lubowiecka, P. Arias, B. Riveiro, M. Solla, Multidisciplinary approach to the assessment of historic structures based on the case of a masonry bridge in Galicia (Spain), Comp. Struct. 89 (2011) 1615–1627.
[22] D.E. Bray, R.K. Stanley, Nondestructive Evaluation: A Tool for Design, Manufacturing and Service, CRC Press, 1997.
[23] S. Azhar, M. Khalfan, T. Maqsood, Building information modeling (BIM): now and beyond, Austral, J. Constr. Econ. Build. 12 (4) (2012) 15–28.
[24] D. Oreni, R. Brumana, F. Banfi, L. Bertola, L. Barazzetti, B. Cuca, M. Previtali, F. Roncoroni, Beyond crude 3D models: from point clouds to historical building information modeling via NURBS, Lect. Notes Comp. Sci. 8740 (2014) 166–175.
[25] L.A. Piegl, W. Tiller, Computing offsets of NURBS curves and surfaces, Comp.-Aided Des. 31 (2) (1999) 147–156.
[26] R. Drogemuller, J. Steel, B. Toth, Model interoperability in Building Information Modelling, Softw. Syst. Model. 11 (1) (2012) 99–109.
[27] NTC, Norme Tecniche per le Costruzioni, D.M. 14 Gennaio, 2008.