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Point clouds turned into finite elements: the umbrella vault of Castel Masegra

L Barazzetti, R Brumana, S Della Torre, G Gusmeroli, G Schiantarelli

Department of Architecture, Built environment and Construction engineering (ABC), Politecnico di Milano, via Ponzio 31, Milan, Italy

Email: luigi.barazzetti@polimi.it

Abstract. The paper presents a workflow for finite element model generation from point clouds acquired via photogrammetry and laser scanning. The case study is a room with an umbrella vault in Castel Masegra, located in Sondrio (Italy). The complexity of the room required an accurate geometric survey from a set of dense point clouds, from which a detailed BIM as well as 2D drawings were generated. Finally, a tetrahedral mesh was derived from the geometric model and was used to run a finite element analysis. The aim of this work is to describe the procedure developed and illustrate the main challenges found.

1. Introduction

This paper investigates the possibility to transform an accurate and dense point clouds into a 3D finite element model that preserves (as well as possible) the geometric irregularities captured by laser scanning or photogrammetry. The case study chosen for this purpose is Castel Masegra, the castle that dominates the city of Sondrio, originally built in the XI century and then modified several times.

The conversion of a point cloud into a finite element model may appear as a simple task. In fact, several automated procedures for mesh generation are available in commercial software. However, several aspects have to be taken into consideration to obtain a compatible and regular mesh that represents the constructive logic of the buildings (e.g. elements and joints), especially when geometric "anomalies" have to be preserved. Such approach is also underlined in [7], the possibility of enhancing working with more refined model allows to better understand the infinite anomalies of historic structures.

An additional issue taken into consideration during this project was the simultaneous creation of a BIM [1] for the whole castle. The idea behind our modeling work was to reuse the BIM for the generation of the FEM, instead of separating the production of the two models. On the other hand, the creation of BIM and FEM is much more than a "pure" geometric problem. The interconnection between the different constructive elements parts and their materials required particular attention. Modeling included geometrical aspects along with structural considerations, in order to understand and (numerically) replicate the constructive elements and their mutual interaction.

The information contained in the architectonical model were accurately investigated to obtain a model suitable for structural analysis. A large variety of issues had to be dealt with, such as the node-to-node correspondence (compatibility of the mesh), very distorted or small elements, and small local imprecisions. Such effects couldn't be neglected: any small error or local inconsistency effectively make it impossible either to generate a mesh or to obtain any sensible result from the analysis.

The paper will provide an overview of the steps of the work carried out on the south wing of the castle. Here, the tower has a significant out of plumb and other geometric anomalies, as shown in Fig. 1. Moreover, an umbrella vault is located at the first floor of the tower. It represents an interesting case study to test the proposed method, which aims at preserving the complexity of the shape. The next sections will briefly describe the workflow, from the digital surveying, to the modelling and analysis processes.
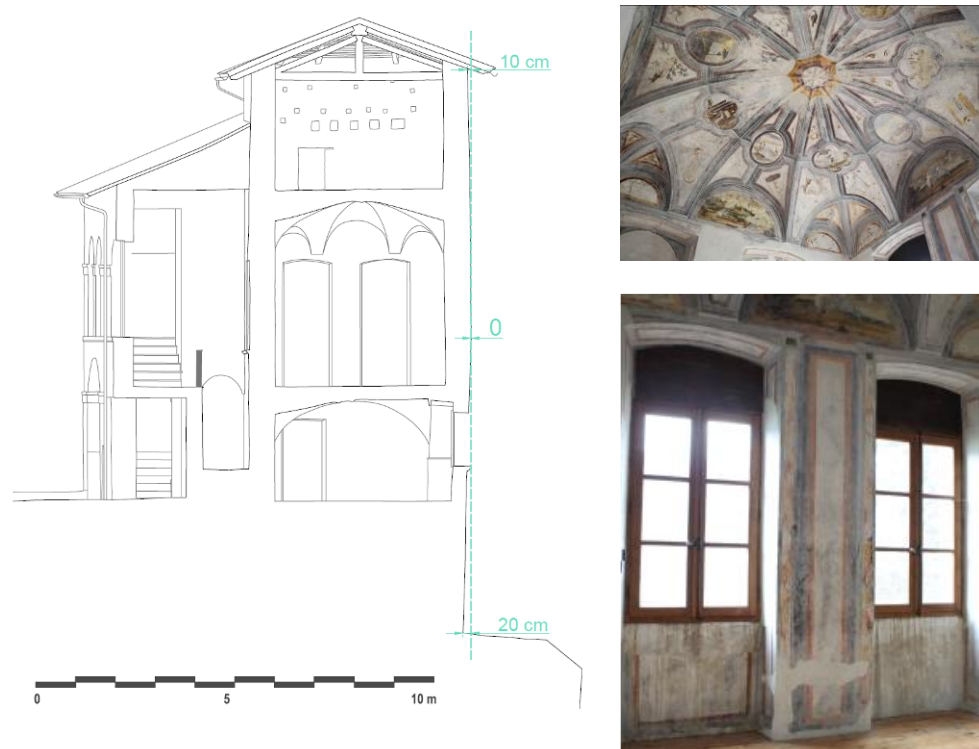

Figure 1. An image of the tower considered in this paper and the umbrella vault.

2. Geometric survey

The geometric survey was carried out with photogrammetric and laser scanning techniques. A geodetic network was also measured with a total station and adjusted via least squares. The network provided a stable reference system for registering images and laser scans.

A dense point cloud of the entire castle was acquired with a Faro Focus 3D. 176 scans were registered into a consolidated point cloud of about 7.5 billion points. Average registration precision was ±2-3 mm. The point cloud provided the data to generate a detailed BIM of the castle, which was realized in Autodesk Revit (see next sections).

Specific elements, such as the umbrella vault, were also surveyed from a set of images acquired with a calibrated camera. Fig. 2 shows the phases required to acquire the images and process the results for the umbrella vault. An image block of 35 images was acquired with a Nikon D700 and then processed with PhotoModeler. A dense point cloud was then extracted to obtain a 3D model of the vault with greater level of detail than that achievable from laser scanning. In addition, high resolution orthophotos were generated to document the conditions of the frescoes.

More details about the entire workflow for the survey are illustrated in [2].

Figure 2. The image acquisition and processing phases for the umbrella vault.

3.   From point clouds to BIM

Starting from laser scanning and photogrammetric data, a geometric reconstruction with a high level of detail can be achieved. However, BIM is much more than a simple interpolation to represents the external surfaces. BIM requires the objects to be parametric and consistent in their relationship with other objects.

The methodology for parametric BIM generation used for the castle is based on a preliminary separation between simple and complex shapes. In the case of simple objects, the tools available in most commercial software (Revit in this case) can be sufficient. The case of irregular objects (e.g. vaults) is much more complicated. Indeed, the modelling tools of commercial BIM packages are not adequate to represent the geometric level of detail encapsulated into laser point clouds. For this reason, the procedure described in [3] was used.

This procedure was also used for the umbrella vault, for which the thickness was added as a parametric attribute. Pure modeling was carried out for the intrados captured by laser scanning, whereas the unknown thickness was parametrized to recreate the volumetric objects in a dynamic way. Unfortunately, the offset of a surface is not a trivial operation [4]. In fact, the normal direction has to be defined for each point of the surface. Changes in the curvature or geometric discontinuities can be a real challenge for an automatic offset, and lead to multiple object intrusions. This problem is still

partially unsolved [5], so the previous pure modeling step was repeated, trying to smooth the surface and simplifying the generative lines used to create the original surface.

Fig. 3 shows the results for the umbrella vault modeled from point clouds (top) and then turned into a parametric object in Revit. It is rather clear that the model with surfaces cannot be the final BIM, but just an intermediate step in the process to create a real BIM object with relationships to other objects. Fig. 3 (bottom) shows the result obtained for the entire tower, which combined the proposed approach for complex shapes with the "simple objects" (in terms of geometry) modelled with the tools available in Revit.
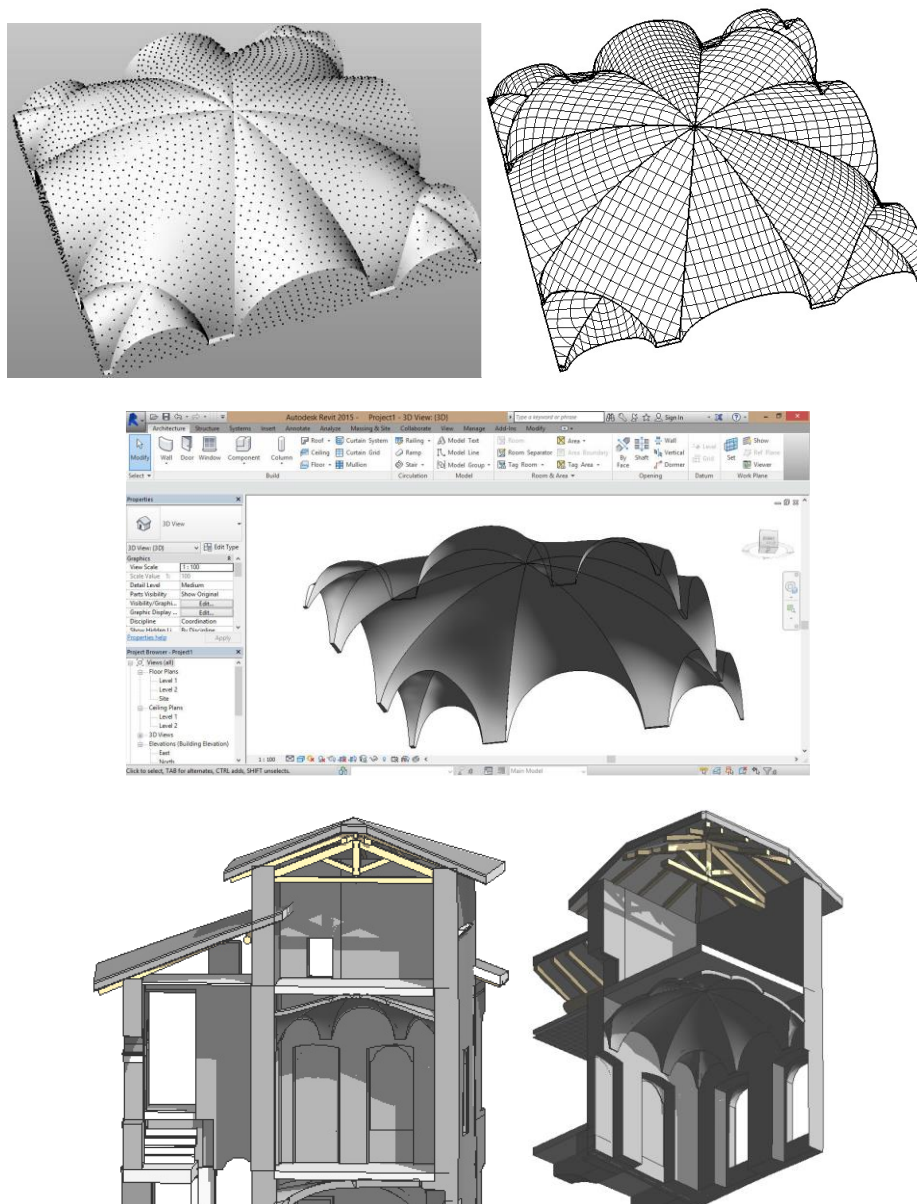

Figure 3. The point cloud used to generate the surface model of the umbrella vault (top). The creation of a parametric vault in Revit (middle) and the final model of the whole tower (bottom).

4. The finite element model

The objective of this section is to illustrate the procedure adopted to convert the complex shapes that characterize the building (mainly vaults and irregular walls) into a mesh for structural analysis. The software chosen was ©Midas FEA, because it deals with 3D elements. It also gives the possibility to import and mesh complex 3D geometry from existing models.

An accurate description of the distribution of masses and external forces is essential for both gravity and seismic analyses. Moreover, a good model of the structure should also provide a good description of the geometrical irregularities. Different works (e.g. [6]) have highlighted the importance of an accurate model based on photogrammetric or laser scanning technique as the first step for an accurate structural analysis of these types of structures. Given the complexity of the shape, it was decided to use tetrahedral elements. A mesh size of 0.2 m was set considering the thickness of the load-bearing walls, so that any wall would have at least 3-4 mesh elements along its thickness. Such choice was made to limit the number of elements (which otherwise could result to be unmanageable from a computational point of view) whilst still ensuring a good description of the stress distribution along the wall thickness.

The conversion of the BIM into a mesh for finite element analysis cannot be done directly in ©Midas. It was decided to use ©Rhinoceros and ©Inventor for specific operations, as illustrated in [2]. Then, a time-consuming adaptation of the model was carried out to obtain a mesh. Some operations were carried out for the openings, which were simplified. The imprecisions due to the ©Revit joining automatism were removed and corrected as well. The solids representing the different parts of the walls were joined together, toward the creation of a unique solid for the entire wall structure of the castle. Some of these operations were possible by using classical Boolean operations (union, subtraction and division), but a lot of time consuming work had to be done on the different surfaces forming the solids.
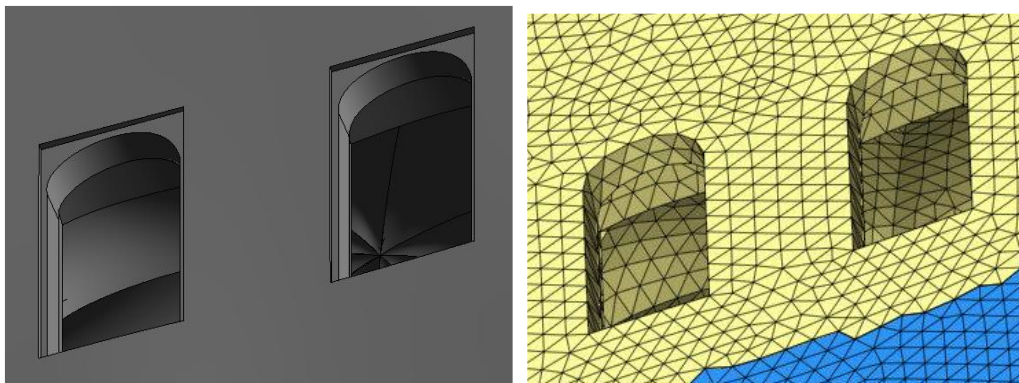

Figure 4. Simplification of the openings: model in ©Revit (a) and in ©Midas (b)

The vault required a significant amount of extra-work. In fact, the extrados had to be completely remodeled in ©Rhinoceros. The parametrization of the vault thickness obtained in ©Revit with the automatic offset had some errors (intersecting surfaces), that made it impossible to perform any Boolean operation to create a unique solid, so it was again necessary to adopt a pure modelling strategy. Some attempts were made using the automatic offset tool in ©Rhinoceros, that can deal with polysurfaces, but such approach works only with simple cases, while for the umbrella vault the offset surface generated had an inconsistent geometry with the wedge tips converging.
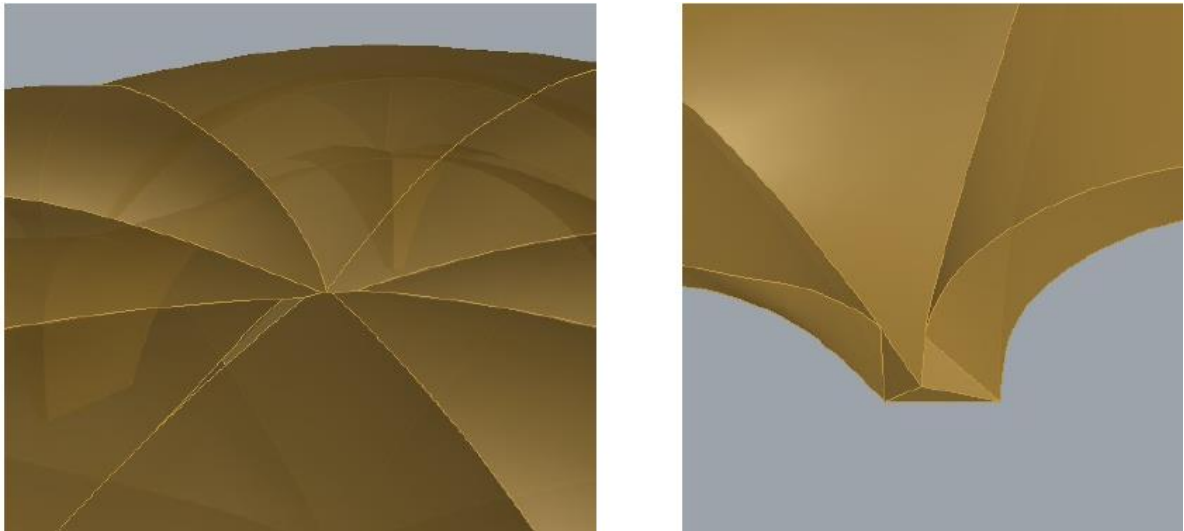
Figure 5. Problems related to the offset for the umbrella vault.

For this reason, it was necessary to extract the borders and isocurves of each wedge, to fix them, and to remodel each extrados wedge. At the beginning, the vault was kept separated from the rest of the model. After considering the difficulties encountered when trying to obtain a compatible mesh in these zones, it has been decided to include it in the whole solid.
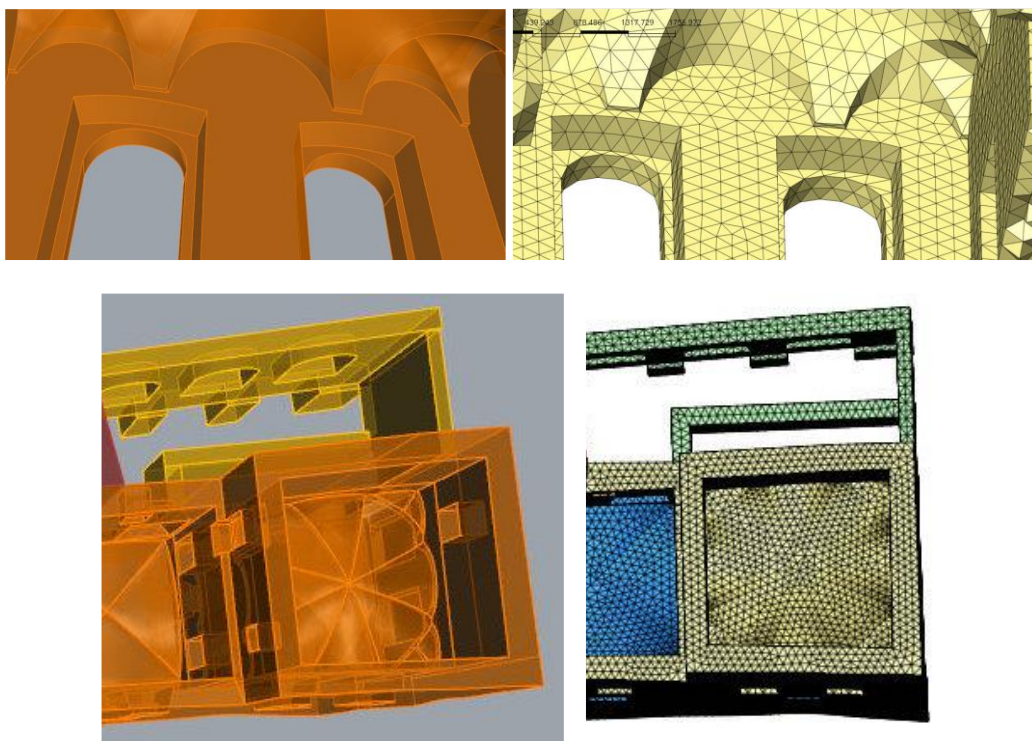

Figure 6. Some images of the original model and the final mesh in Midas.

5. The Finite Element Analysis

Once the model was successfully meshed, the geometrical basis for a structural analysis was set. The next step included the setting of boundary conditions, material properties, and loads as a function of the type of analysis. In this work, it was decided to run a linear elastic analysis under self-weight. This is a fundamental step before any other more sophisticate analysis: it allows to adjust the boundary conditions and to check the model to detect any error, because strange stress or deformation patterns can easily be detected under self-weight only. It can be run many times (limited CPU cost), correcting errors or resetting boundary conditions. Moreover, the obtained stress values can be directly compared with single-flat jack measurements.

The reader is referred to [2] for more details about setting of material properties, loads and boundary conditions. This section will illustrate only some results obtained from the simulations run on the model described in the previous paragraph. Shown in Fig. 7 is the distribution of first principal stress. One interesting behavior can be found in correspondence of two openings (partially infilled) which weakens the wall itself right where the load from the vault is transferred to the walls. Here it is possible to notice a zone of tensile stress concentration exactly in correspondence of two repaired cracks.
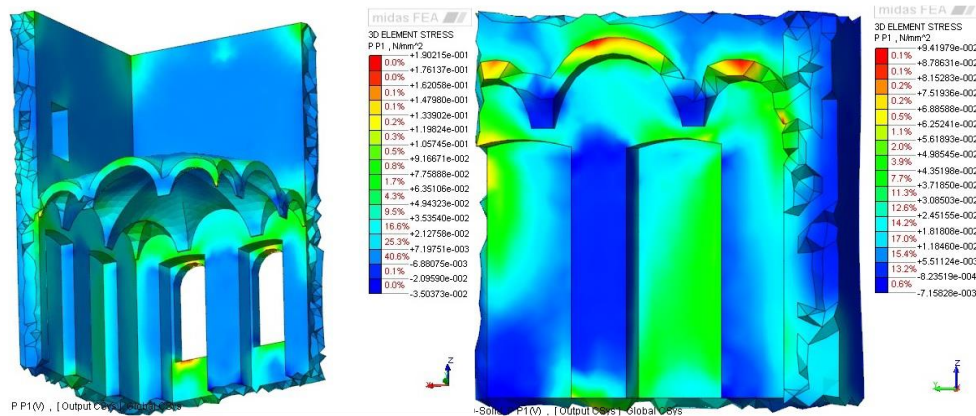

Figure 7. Simulation results (first principal stress) for room with the umbrella vault.

Some interesting results ware also observed by applying the live load provided by the Italian regulation (NTC, 2008) for the category C3 of spaces susceptible to crowding ($q_k = 5$ kN/m^2). Fig. 8 shows the difference with and without live load (the same scale for the color bar is set to highlight the differences). A significant increase of the tensile stresses is visible (almost doubled in the most critical zones), especially in the corner lunettes. A comparison of these results with photographs confirm that these areas have several cracks, which were repaired during previous restoration works.
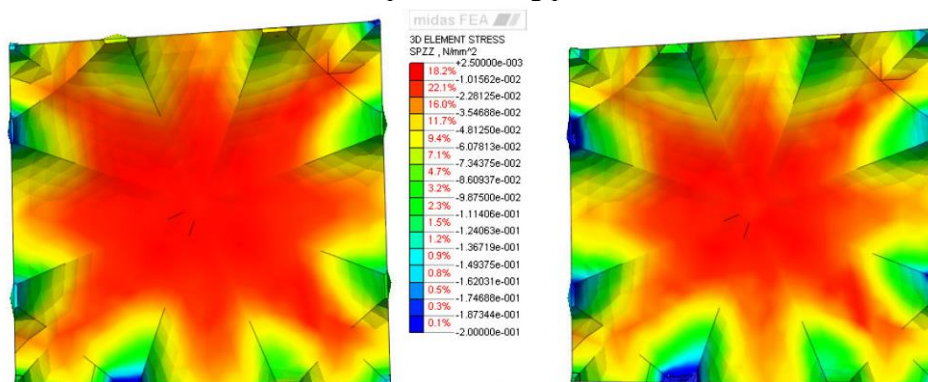

Figure 8. Vertical stress with (left) and without (right) live load on the umbrella vault.

6. Conclusions

This paper ha presented the workflow to generate a detailed BIM of an historical building from a laser scanning and photogrammetric survey. The BIM was then converted into an accurate 3D finite element model.

This approach can be useful for studying the structural behavior of historical buildings, especially when they present large geometric irregularities. In particular, an accurate geometric model can be a valid tool to understand the behavior of particular elements such as vaults or irregular walls. At the end we can state that the proposed approach can be an effective possibility, notwithstanding several difficulties and limitations found. Defining the entire workflow and the procedures during the different steps was quite problematic. However, after resolving the previous limitations, guidelines for operators can be prepared. We think that the effort required to transform a BIM into a compatible model for structural analysis can be acceptable.

The advantages in terms of quantity and level of detail of information that can be provided by such model advanced model is another aspect that requires further work. It would be interesting to compare the results given by this method with a more simplified model, to be able to quantify pros and cons for this approach.

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