Structural characterization for the seismic protection of heritage churches

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Abstract. The high vulnerability of ancient masonry churches and their state of cultural heritage assets make their seismic protection a complex operation. Structural analysis offers valuable support, but requires a realistic modelling of the building structure. Acquiring a thorough knowledge of the building constructional characteristics is, therefore, fundamental and may be achieved combining information from different sources. Besides regular surveying operations and limited diagnostic tests, other tools are available to obtain a detailed picture of the situation. For the case of churches, that often are many centuries old and have evolved with several structural changes during their lifetime, a historical research aimed at the reconstruction of the different phases of the building transformation is extremely useful to point out its characteristics, and possibly its hidden criticalities. A different but equally useful contribution comes from the recently developed high-power software tools for 3D modelling, allowing to visualize the shape of the asset but also to understand in detail its geometry and its building process. The combination of these two very different means offers a deep insight of the building features. Three heritage churches in Italy testify here the positive results achieved by a synergic use of different knowledge sources, and in particular with crossing documental information and direct inspection supported by effective representation tools.

Keywords: heritage masonry churches, structural modeling, geometric representation, seismic vulnerability, construction history.

1 Introduction

The seismic protection of ancient masonry churches poses special problems due to their high vulnerability and their condition of cultural heritage assets [1]. Operations for improving their seismic response must satisfy restoration principles, and in general the concept of minimum effective interventions. To this purpose, structural analysis offers valuable support, but requires a realistic modelling of the building structure. Acquiring a thorough knowledge of the building constructional characteristics is, therefore, fundamental and may be achieved combining information from different contributions. Besides regular surveying operations and limited diagnostic tests, other tools are available, and increasingly used, to define a detailed picture of the situation. For the case of churches, that often date back to many centuries ago and have evolved with several structural changes during their lifetime, a historical research aimed at the reconstruction of the different phases of the building transformation is extremely useful to point out its characteristics, and possibly its hidden critical-

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ties. A second contribution comes from the recently developed high-power software tools for 3D modelling of surfaces, allowing to visualize the shape of the asset but also to deeply understand its form and its building process. Beyond the definition of a reliable model for structural analysis, the combination of these two very different means offers a deep insight of the building features. The passage from a complete geometric model to a model for numerical analysis requires identifying and reproducing the structural skeleton, usually resulting in a more synthetic representation. Some characteristics, or some traces of past events that affected the building, may not be easy, or even possible, to reproduce in numerical models. Yet, the enhanced knowledge of the asset resulting from their recognition may have important consequences, because awareness may make a sharper interpretation of the expected behavior possible. Operational decisions in terms of interventions or monitoring plans may be taken, in the presence of critical features affecting safety.

Case studies of heritage churches in Italy, described in the following, testify the positive results achieved by a synergic use of different knowledge sources, and in particular with crossing documental information and direct inspection supported by traditional survey techniques, rather than advanced ones [e.g., 2] elaborated with effective representation tools.

2 Case studies

The assessment of seismic vulnerability of heritage buildings needs to rely on procedures that take into account their specific features. To this purpose, the Italian Ministry of Cultural Heritage, MiBACT, has issued ad-hoc Guidelines [3] that comprise a sequence of steps that should lead to the best possible knowledge of the asset compatible with conservation principles. Research programs, some sponsored by the same Ministry, have been carried out to assess the feasibility and effectiveness of this path. In this perspective, for the churches examined here the general objective was an evaluation of the vulnerability level, or of the seismic capacity, which, however, is not the purpose of this work and will not be reported here. In the knowledge acquisition path that precedes numerical analyses, the three cases discussed in the following were selected because presented situations that could benefit from a combination of different investigation methods and tools.

2.1 Dealing with irregularities

The church “Cattolica” of Stilo, Calabria, Southern Italy, is considered to date back to the 10th century and is one of the rare cases of byzantine churches in Italy. Located on a steep slope, fig. 1, it is partially supported by rock and partially by a landfill, but no sign of settlements are found, in spite of the long history of earthquakes in a highly seismic region. The dimensions are small, approximately 7.5 by 8 meters in plan. The four stone walls are covered by a system of 4 barrel vaults and 5 small cylindrical towers with semi-spherical vault (see fig. 2). The wall on the valley side includes three vaulted apses. In the interior, four stone columns support the vaults system. No substantial modifications of the structure appear to have occurred in its lifetime, beyond some remodeling of the entrance shape and similar interventions, until the beginning of the 20th century. At the time, the building was abandoned, having lost its original religious function, and had undergone decay. It was rediscovered by the archaeologist P. Orsi, who reconstructed its history and was responsible of its restoration, according to the principles of the time, basically bringing the building to the current state. Besides reconstituting the supposedly original façade, the main intervention with some structural significance concerned the roofs of the towers, where a concrete layer was cast. At present, the building, which is no more used as church but is a national monument, appears in a good state of conservation in its masonry parts, but two of the columns have been damaged and have a reduced cross-section; an inclination with respect to the vertical is present and for one of them a crack is evident.

In order to perform a seismic analysis, different kinds of information had to be gathered, in addition to what already available from the Ministry local office. Geotechnical investigations and an analysis of the site to select proper response spectra were carried out. Walls are built with bricks, approximately 30x18x8 cm, on the outer side, and mainly with stone blocks of similar size inside the church. The mortar layers are 5 cm thick. Diagnostic non-destructive tests on masonry were performed to supplement information on walls constitution and material properties. The most critical elements seemed to be the columns that had a significant structural role in vertical load bearing and that could trigger dangerous situations in seismic conditions. In order to develop a detailed three-dimensional model of the building, one important issue was the definition of the roof structure including composition of the vaults and towers, given the restrictions and the difficulties in diagnostics and direct inspection [4]. The documental sources by Orsi on his interventions and all the subsequent ones proved fundamental to this purpose. A trustworthy reconstruction was possible . The operation of building the geometric model, developed in [5], required a detailed understanding of the interrelation of components particularly for the vault system, which is not fully regular, and allowed to appreciate the global organization of the structure, yielding as well a reliable description of self-weights (fig. 3). From the geometric model, a finite element model for numerical analyses was derived. The important role of columns was confirmed and quantified in the analyses for vertical loads (fig. 4) and for seismic action. Even if the results in terms of stresses were within an allowable range, the degradation of these elements indicated the need for further investigation.

Figure 1. The “Cattolica” and its location on the mountain side

Figure 2. The system of towers and vaults

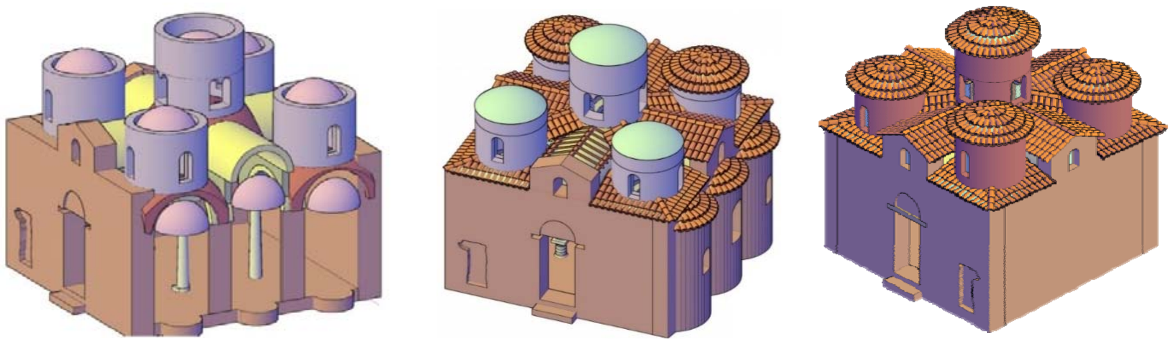

Figure 3. Phases of construction of the architectural model [4]

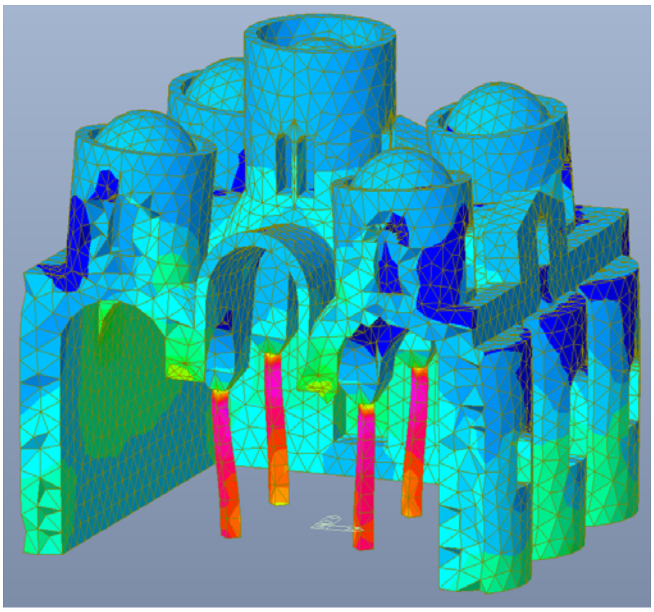

Figure 4. Deformed shape and stress ranges described graphically for vertical loads: the role of the columns that reach an acceptable but significant compression level is highlighted by the red color.

A thorough reconstruction of the damaged columns geometry, in terms of misalignment and of reduction of cross sections at various levels was performed, while ultrasonic tests allowed to quantify the depth and profile of the crack. Figure 5 shows the column that presents the more extended damage. Once more, documental analysis indicated that damage was not recent even if the time of its occurrence and the causes were unknown. This quantitative information was then included in the numerical model, resulting in a more precise evaluation of the stress state, which was still acceptable, but with significantly reduced margins. Structural analyses in this and in the following cases were performed with [6].

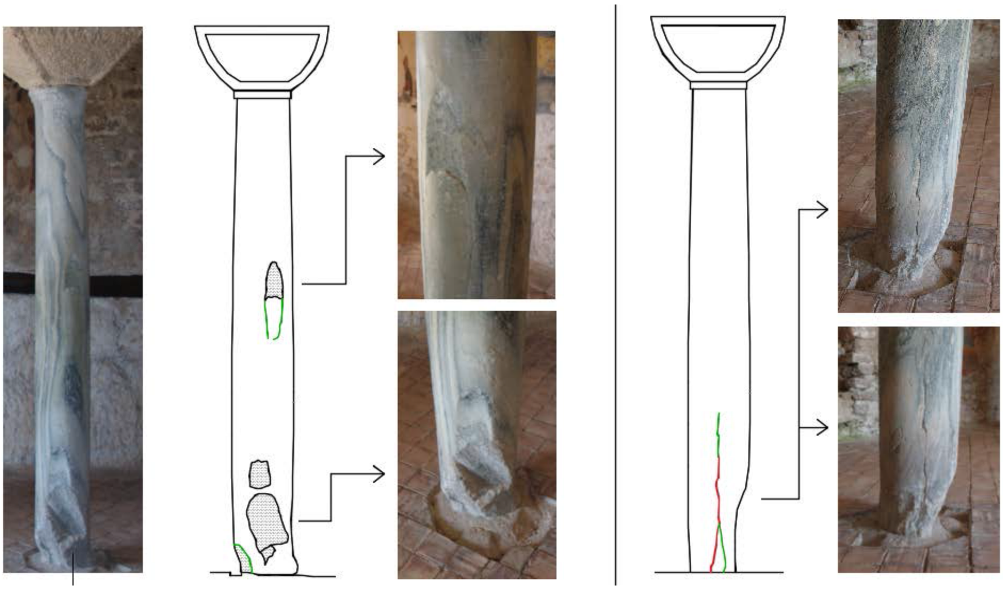

Figure 5. Description of column damage

2.2 Assessing structural modifications

The abbey of Viboldone, near Milano in Northern Italy, most likely founded in 1176, is a heritage asset of major importance for being beautifully frescoed but also for the role that it played in the life of the surrounding territory. The current building, in brick masonry, is a three-nave church, where naves are covered by a gothic cross vault system; the rectangular based bell tower is above the apse, while a simple sacristy is at the end of the naves, on the left side. Dimensions are grossly 37 by 15 meters in plan (fig. 6) [7].

In this fortunate case, the documentation on the history of the building is very rich, as different archives collect documents that refer to the abbey from its first construction times. Modifications that were performed on the structure for various reasons could be reconstructed from these documents that registered them in various forms, ranging from bills of the constructors to diocesan reports, for its entire lifetime.

Following the historical analysis, its development started as a small church, as shown in fig. 6, corresponding to the current apse area. The church was extended in the years 1220-30 forming the three naves, for three bays (fig. 7). An additional bay bringing the church to the current length was added around a century later, when very likely also the bell tower was completed, while the sacristy arrived between the 15th and 16th century. Besides these major additions, many other works have been performed, for maintenance and repair, as small modifications for reasons of use, or for strengthening. This long history of modifications and interventions points out the importance of collecting documental knowledge for understanding or for correctly foreseeing the structural behavior. Given the clear sequence of additions, this case is a good candidate for a step analysis in which parts, and loads, are progressively added [8]. In any case, an indication may be derived for checking and keeping under control the areas of possible discontinuity and other critical situations. From the point of view of modeling, the relative ease of modifying geometry made the development of full or partial models for numerical testing of various conditions possible. Among other analyses, the modal one has also shown areas of local deformability that could give rise to local damage; the first two modes concerned the bell tower. In the third, as from the figure, a typical lateral nave deformation is highlighted by the red color.

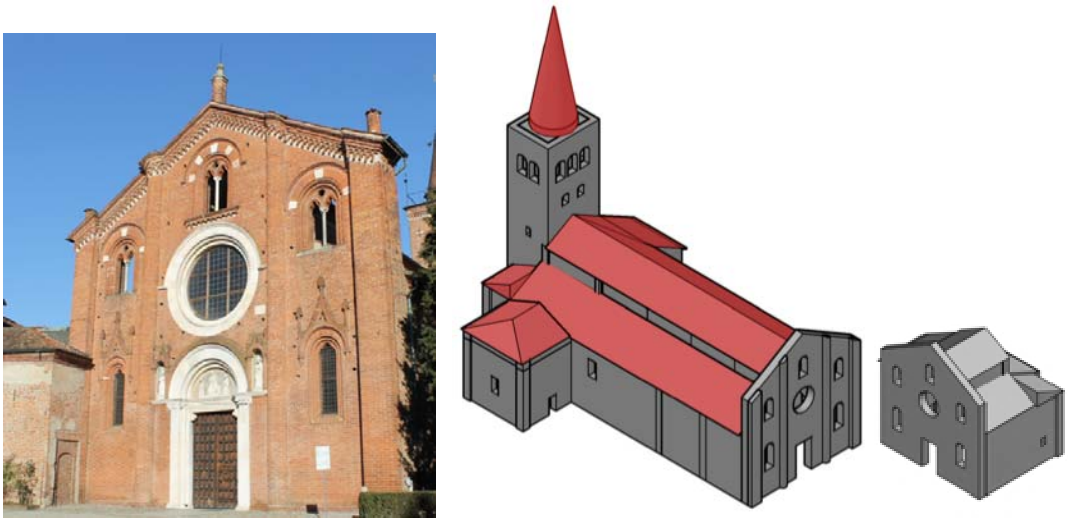

Figure 6. From left, the romanesque façade of the Viboldone abbey, the current building, and the original one [5].

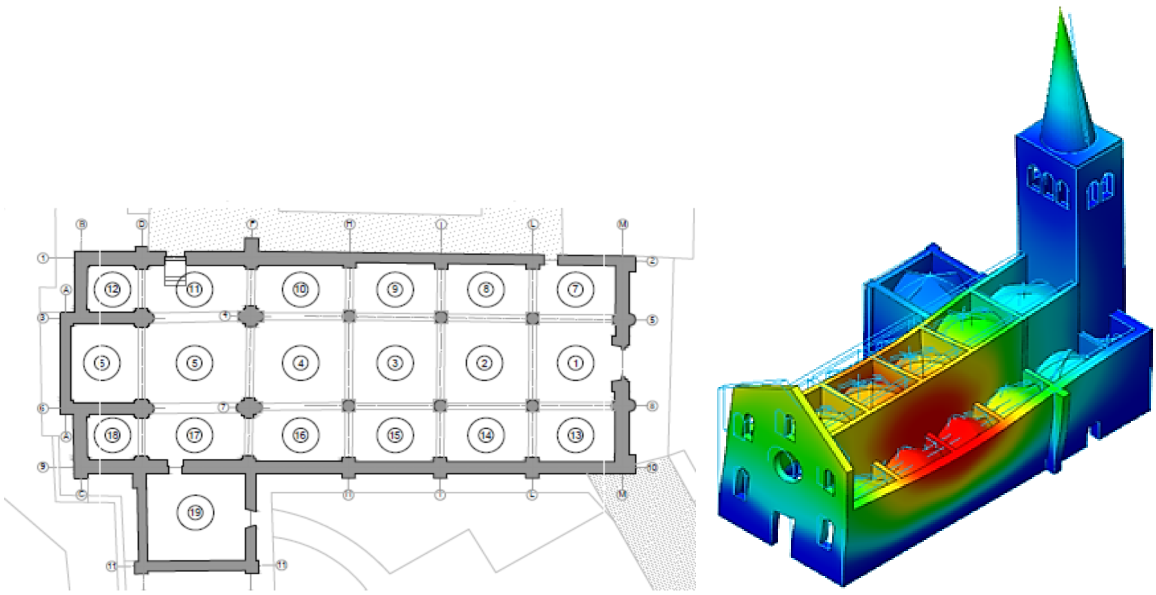

Figure 7. Left: building layout; numbered circles indicate the vaulted areas; the last bay on the right hand side, with the current entrance, was added in the 14th century; Right: third modal shape [5].

2.3 Managing complexity

The church of S. Mary of the Valley in Messina, Sicily, in fig. 8, in spite of an apparent external simplicity, is a case of very complex geometry, partially due to layers of modifications and additions [9].

The church, already cited in a document of year 1168, is an example of Norman architecture. The area is characterized by high seismicity, although the very strong event of 1908 with epicenter only 17 km away did not produce but local damage to the church.

The history of this building, which had suffered periods of decay, has been restored, and is now closed to the public, may be reconstructed with fair precision in general and with very good detail for the last century. It comprises a series of interventions, for modification or reconstruction of parts, and most recently for strengthening of elements and foundations. The result is a situation where the original complex geometry has been further complicated by new or modified parts and by the presence of different materials. The walls alternate local stone with lines of bricks, columns and arches are in stone blocks, vaults in bricks.

In this case, the use of vector graphics tools to produce a consistent architectural model is by one side very demanding and by the other a powerful and almost indispensable tool for understanding the building in its complexity.

Passage to a model for a global numerical analysis is not straightforward. The art of eliminating non-structural parts, which still maintain their masses, managing different thicknesses and complex intersections, must bring to a structurally significant model that must result manageable in analyses. Figure 9 shows part of the geometric model, performed according to [10], and of the finite element one, for which beam and plate elements have been used . In the geometric model, colors are used for differentiating elements and materials. Starting from the current model, versions representing the church in different historical periods, before some interventions were performed, could be reproduced and analyzed, giving an assessment of the consequences of some interventions as well as attempting to interpret the causes of the development of some observed local damage.

3 Conclusions

Antique masonry churches are particularly prone to seismic damage, due to their constructional characteristics; as cultural heritage assets, they are subject to limitations both in terms of diagnostics and of interventions. Yet, an accurate use of other knowledge sources and analytical tools may overcome these limitations and produce very effective results.

An extended archive research as base for reconstructing the structure evolution is fundamental in buildings with a long life; representation of geometry developing three-dimensional models with vector graphics, even based on data collected with accurate but standard surveys, becomes a very powerful mean to deeply understand the structure composition and its possible behavior. For three significant cases these tools have been used synergically, demonstrating their effectiveness in complex situations.

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Figure 8. The Norman church

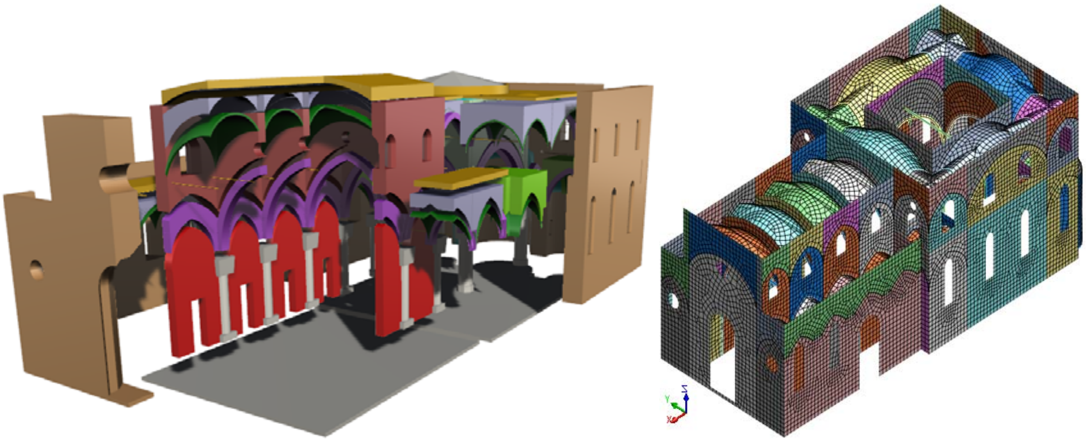

Figure 9. The geometric model and the finite element one [7].

5 References

[1] Lagomarsino, S., Podestà, S. (2004a). Seismic vulnerability of ancient churches: part 1. Damage assessment and emergency planning, Earthquake Spectra, 20(2), 377-394.
[2] Manzo, A., Chesi, C. (2018) Building techniques and structural damage of historical constructions detected through the point cloud survey, Proceedings, SAHC 2018.
[3] DPCM 26.02.2011, Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale con riferimento alle norme tecniche per le costruzioni, G.U. 26.02. 2011 n.47, Roma, 2011.
[4] Spigarolo, F. (2015) Valutazione della sicurezza sismica dei beni culturali: la Cattolica di Stilo, Master Thesis, M.A. Parisi supervisor, Politecnico di Milano.
[5] AUTOCAD, vs. 2016.
[6] Midas Gen, vs. 2015.
[7] Balestrini, F., Cazzaniga, G. (2016) Evoluzione storica, caratterizzazione strutturale e risposta sismica: l'abbazia di Viboldone, Master Thesis, M.A. Parisi supervisor, Politecnico di Milano.
[8] Elyamani, A., Roca, P., Caselles, O., Clapesc, J. (2017) Seismic safety assessment of historical structures using updated numerical models: The case of Mallorca cathedral in Spain, Engineering Failure Analysis 74, 54–79.
[9] Fleres, R. (2017) La vulnerabilità sismica degli edifici monumentali, Master Thesis, M.A. Parisi supervisor, Politecnico di Milano.
[10] RHINOCEROS Manual, Version 5.0, 2014.