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COMPARATIVE SEISMIC ASSESSMENT OF A MEDIOEVAL MASONRY CHURCH IN SOUTHERN ITALY

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Keywords: Masonry Churches, Earthquake, Seismic Vulnerability Evaluation, Response Spectrum Analysis, Non-Linear Static Analysis (Pushover), Limit Analysis.

Abstract. *A comprehensive numerical investigation on a medieval masonry church in Calabria region (Southern Italy) is presented. The church has historical and architectural interest, being one of the first examples of Christian temples in the area. It exhibits a number of irregularities in plan and elevation, plus a visible state of degradation of the masonry material that make the investigation of its vulnerability under horizontal loads advisable, also in light of an expected short term and strong seismic event in the area.*

The safety assessment under horizontal loads is done using a variety of numerical analyses, ranging from Response Spectrum Analyses RSAs, non-linear static (pushover) and limit analyses (both on pre-assigned failure mechanisms and with FEs).

A refined full 3D plate and shell FE model is adopted, after detailed in situ inspection of the geometry and perusal of the historical documentation. Numerical results are obtained both by means of a noncommercial full 3D software developed by one of the authors (FE limit analysis), and a commercial code (Strand7®). Limit analyses with pre-assigned failure mechanisms, as per Italian guidelines for cultural heritage, are also performed, with evaluated collapse accelerations and associated mechanisms matching well with FE results.

As a matter of fact, a remarkable consistency among all the different procedures is found, meaning that even simplified approaches (like limit analysis with pre-assigned failure mechanisms) or RSA (typically not recommended because of the linearity hypothesis for masonry) can provide -if critically analyzed – useful hints on possible damage patterns and active failure mechanisms in case of a seismic event. In all cases, numerical computations proved to be valuable tools to predict the most probable behavior in case of an expected strong earthquake, suggesting the most suited way for an effective strengthening.

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1 INTRODUCTION

The evaluation of the seismic vulnerability of masonry churches is a key issue in the preservation of the cultural heritage [1]. A correct estimation of their load carrying capacity against horizontal loads should be therefore considered mandatory to guarantee their safeguard, allowing focusing restoration interventions on the base of quantitative information and on the expected structural behaviour in occasion of earthquakes. In the technical literature, several advanced numerical approaches are available for single case studies [2-8].

The seismic vulnerability of churches is generally high and it is mainly a consequence of the peculiar geometrical features (such as the presence of slender and long masonry walls, tympana and pinnacles), the low masonry tensile strength and the absence of enough stiff horizontal structural elements favoring the box behaviour. According to post-earthquake surveys, the typical way in which the ancient masonry churches fail is for the formation of partial collapse mechanisms activating well defined portions of the structures remaining roto-translating around cylindrical hinges [1].

In this paper a case study is critically examined, namely a Medieval small/medium masonry church located in Southern Italy. The church has historical and architectural interest, being one of the first examples of Christian temples in the area. It exhibits a number of irregularities in plan and elevation, plus a visible state of degradation of the masonry material that make the investigation of its vulnerability under horizontal loads advisable, also in light of an expected strong seismic event in the area.

The safety assessment under horizontal loads is done using a variety of numerical approaches [9-14], ranging from Response Spectrum Analyses RSAs, non-linear static (pushover) and limit analyses.

A refined full 3D plate and shell FE model is adopted, after detailed in situ inspection of the geometry and perusal of the historical documentation. Numerical results are obtained both by means of a noncommercial full 3D software developed by one of the authors (FE limit analysis) [7, 14-16], and commercial code (Strand7®). Limit analyses with pre-assigned failure mechanisms, as per Italian guidelines for cultural heritage [1], are also performed, with evaluated collapse accelerations and associated mechanisms matching well with FE results.

From a comparative analysis of the results obtained, a remarkable consistency among all the different procedures is experienced, meaning that even simplified approaches (like LA with pre-assigned failure mechanisms) or RSA (typically not recommended because of the linearity hypothesis for masonry) can provide -if critically analysed - useful hints on possible damage patterns and active failure mechanisms in case of a seismic event. In all cases, numerical computations proved to be valuable tools to predict the most probable behavior in case of an expected strong earthquake, suggesting the most suited way for an effective strengthening.

2 DESCRIPTION OF THE CASE STUDY

Gallicianò is located 620 m asl, on a rocky spur on the right bank of a torrent (Amendolea) inside Aspromonte.

The church of San Giovanni Battista, see FIGURE 1 and FIGURE 2, which is the object of the present structural investigation, is a single nave church, trapezoidal in plan divided into two main parts: the nave and the chancel which is accessed by crossing the triumphal arch. The nave is illuminated by three windows: one located on the western side, above the entrance portal and two on the south side. Two other windows along the north side of the nave appear to be buffered long time ago. A door on the south wall of the nave leads to the vestry. The chancel takes light from a window in the South side. The survey of the building along with the study of the available historical documents allow to affirm that this church dates from the late Middle Ages and the present structure is the result of transformations that altered the original masonry construction.

FIGURE 1:The case study used to benchmark the numerical procedure, Gallicianò church.

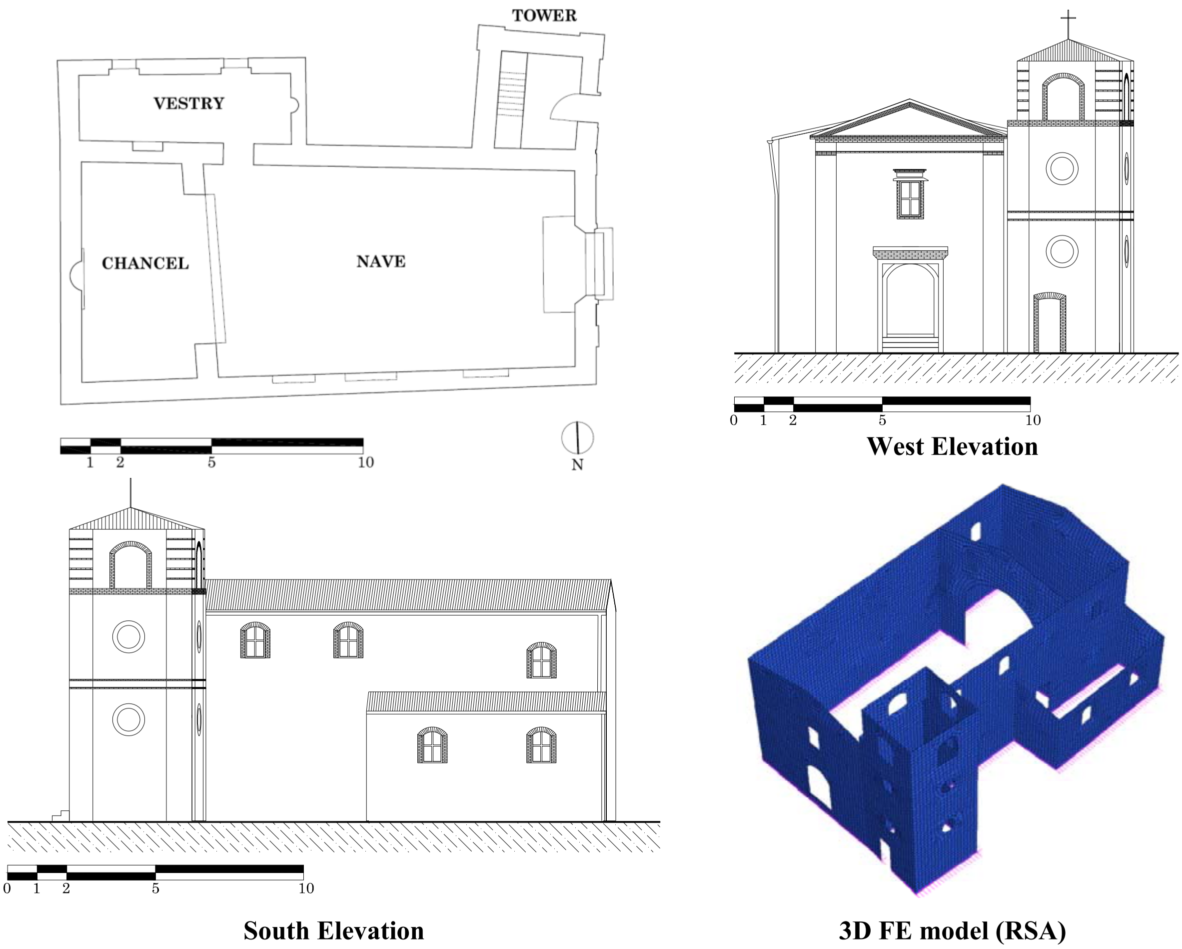


FIGURE 2: Plan, elevation views and 3D mesh of the church.

The main façade, for example, presents an articulated eighteenth century style composed by columns (having decorative function) and a tympanum characterized with typical frames. The church has continuous foundations realized with mixed stones which mainly consist of granites and schists bonded by a hydraulic mortar having poor mechanical properties.

At present the church has a provisional gabled roof (which may be considered totally flexible in the seismic analysis) with an inclination lower with respect to the outer edge of the tympanum and consists of corrugated metal sheet fixed on lightweight steel trusses.

3 NUMERICAL ANALYSES CONDUCTED

The numerical approaches utilized to evaluate the seismic vulnerability of the church are the following: 1) eigen-frequency elastic analyses, 2) pushover and 3) limit analyses (both with pre-assigned failure mechanisms and with FEs). All approaches provide –within the simplifications deriving from the hypotheses done on materials and load application- specific information on the behavior of the church under horizontal loads. In particular, all of them contribute in a correct estimation of the collapse acceleration and a prediction of the most vulnerable parts of the structure, which eventually would profit for a strengthening application.

Modal analyses may appear at a first glance unsuited for churches, because masonry does not behave elastically, even under very low horizontal forces. However, it has been shown in [10], that they can provide a preliminary insight into the activation of possible partial failure mechanisms.

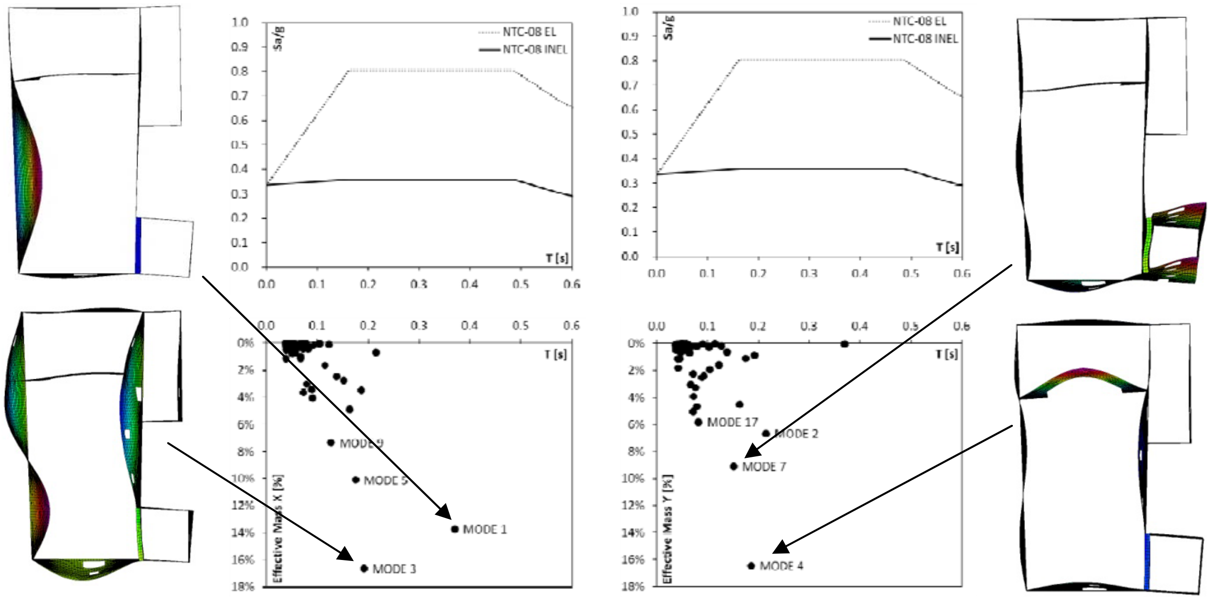
The application of limit analysis is certainly the most indicated, because very straightforward and coherent with the actual masonry behavior, but the reduction, as suggested by the Italian Guidelines on the Built Heritage [1], to 28 pre-assigned failure mechanisms could potentially lead to an overestimation of the load carrying capacity, without a sufficiently correct reproduction of the active failure mechanisms [7, 14].

As a matter of fact pushover and FE limit analysis remain certainly the most suited approaches to estimate the vulnerability of a church, but the computational effort required and the experience of the user in the field are key issues that should be taken into account with care.

4 DISCUSSION OF THE RESULTS

Modal analysis results are summarized in FIGURE 3, where meaningful vibration modes in transversal (left) and longitudinal (right) direction are also depicted. In addition, in the central-top part of the figures, the spectra (elastic and that scaled by the behaviour factor) are depicted, while, in the lower part, the modal participating mass ratios (M_{eff}), of the first meaningful modes, are plotted against the vibration period (T) and represented through a bullet.

Concerning the participating mass ratio of each vibration mode, a small contribution is usually observed, [10], therefore, in order to well describe the dynamic behavior of the structure, it was necessary to take into account several successive modes, obtaining a total participating mass ratio greater than 85% of the total mass, as prescribed by the Italian code. Even if the graph cannot be read easily, because of the great number of bullet points, it is very clear that almost all vibration modes are associated to low excited mass (less than 10%) but with peaks concentrated on the maximum acceleration of the spectrum.



Mode	1	Mode	3	Mode	4	Mode	7
T	0.370	T	0.192 s	T	0.186 s	T	0.151 s
Mass X	13.7 %	Mass X	16.6 %	Mass Y	16.4 %	Mass Y	9.1 %

FIGURE 3: Modal analysis results and modal deformed shapes.

Distribution of forces **G1**

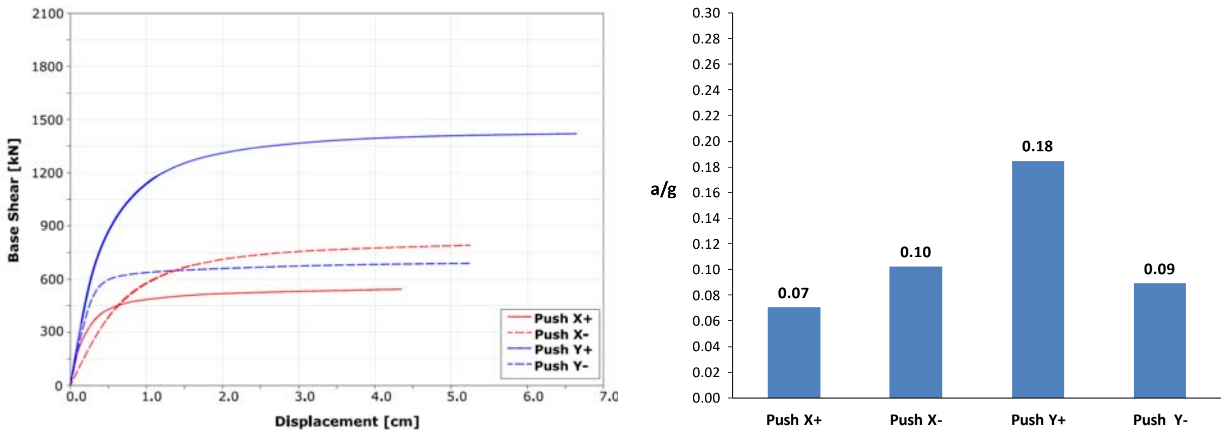


FIGURE 4: Pushover Force-Displacement of the control node capacity curves and normalized maximum base shear.

Pushover analyses are carried out assuming for masonry an elasto-plastic behavior with Mohr Coulomb failure criterion and with the mechanical properties of TABLE 1, and applying both G2 (constant) and G1 (inverse triangular) distributions along longitudinal (Y) and transversal (X) directions. The obtained capacity curves are depicted in FIGURE 4. Only G1 distribution results are shown, being the less conservative. As it always occurs in practical design for churches, G2 distribution provides more conservative results.

In FIGURE 4 we also reported using histograms the horizontal acceleration normalized against gravity acceleration, i.e. the a_g/g associated with the activation of a failure mechanism in the church.

Material	w	f_m	τ_0	E	G	ν	ε_0
	[kN/m^3]	[MPa]	[MPa]	[MPa]	[MPa]		[%]
Masonry Material	19	1.0	0.02	870	290	0.25	0.35
Note: multiplication factors applied: presence of rows of bricks to align stones (1.3) and good transversal interconnection (1.5)							

TABLE 1: Mechanical properties used to model the church.

In FIGURE 5 the deformed shapes near collapse provided by pushover analyses, with indication of the location of control points and the corresponding pushover curves (on the right) are also represented to give an idea of the active failure mechanisms and the amount of displacement reached by the different nodes monitored during the analyses. Only X- and Y- load cases are shown for the sake of conciseness, but it is interesting to notice that failure mechanisms are always local, a peculiar behavior for such kind of structures [2-13]. Similar results are found by the authors for the seismic load applied along the positive directions of the geometric axes (i.e. X+ and Y+).

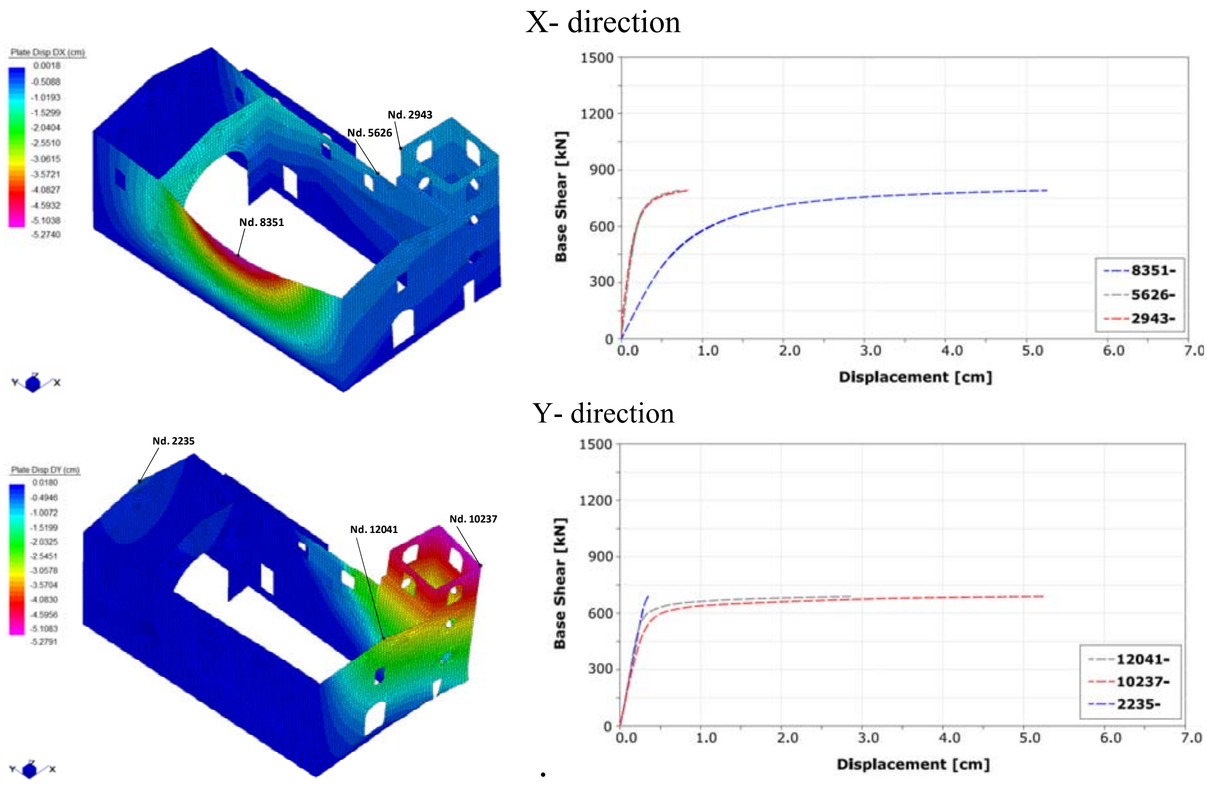


FIGURE 5: Deformed shapes at collapse from pushover analyses with indication of the control points and pushover curves (on the right), G1 distributions.

Some analyses according to Italian Guidelines for the Built Heritage specifics [1], i.e. using the kinematic theorem of limit analysis on 28 possible pre-assigned failure mechanisms, are also performed.

Collapse multipliers found through the application of the upper bound theorem of limit analysis on the mechanisms depicted in FIGURE 6 are summarized in FIGURE 7. From an overall analysis of LA results, a quite satisfactory agreement with global pushover is worth noting, with almost the same out-of-plane mechanisms active and similar collapse accelerations.

The four failure mechanisms in FIGURE 8 are finally found using a sophisticated FE limit analyses approach by one of the authors [7, 8, 14], applying G1 horizontal loads along the longitudinal and transversal directions. As can be noted, the most vulnerable elements are again the façade and lateral walls, all exhibiting rather low collapse multipliers. The longitudinal direction exhibits relatively higher collapse multipliers, but still too low if compared with the PGA assumed by the Italian Code for spectral analysis.

Summarizing, all limit analyses results address a high seismic vulnerability and are again in good agreement with both pushover and pre-assigned failure mechanisms predictions.

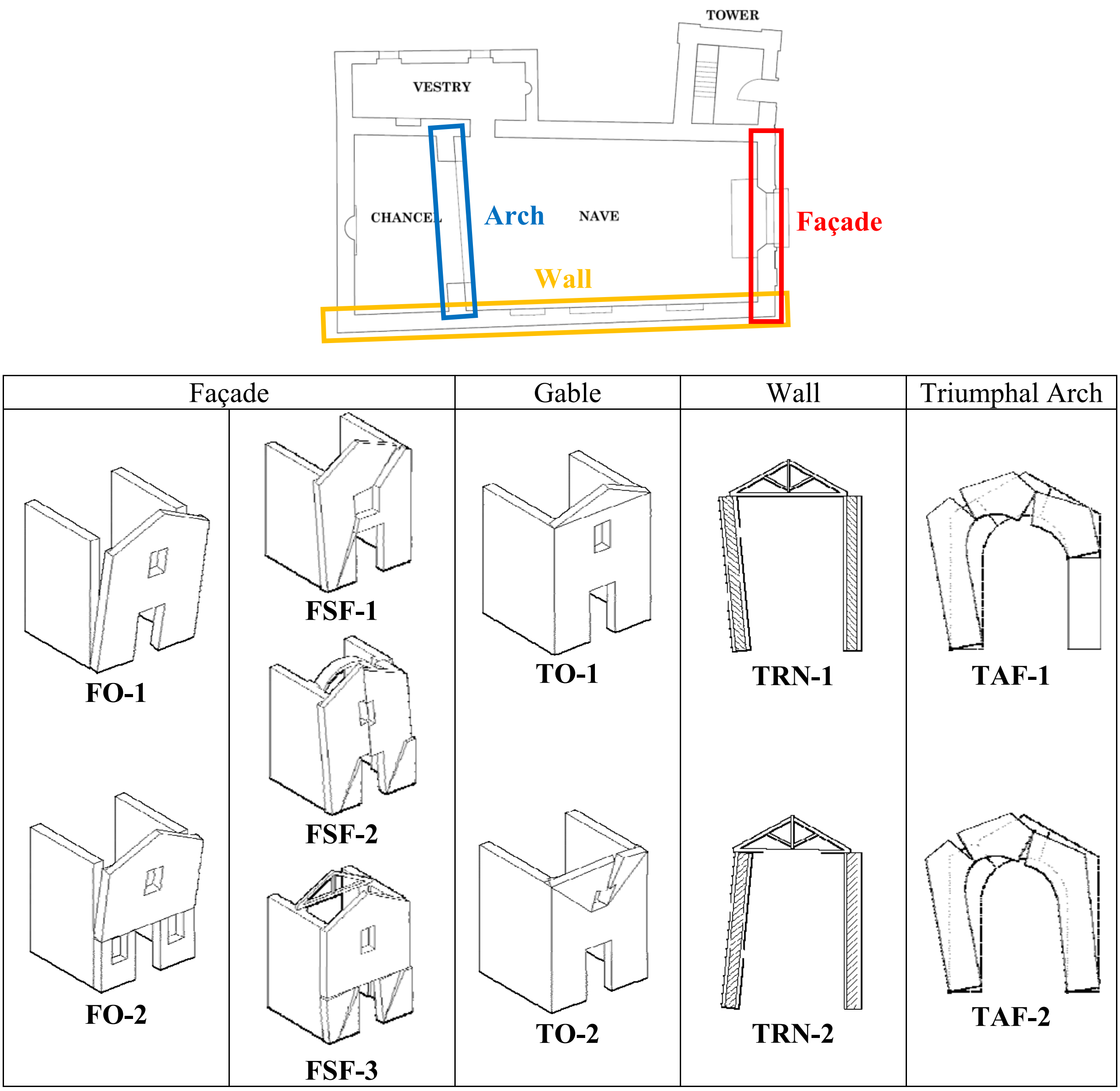


FIGURE 6: Macro elements and failure modes (indicated by Italian Guidelines for Built Heritage) analyzed for the church under investigation. **FO** ≡ Façade Overturning; **FSF** ≡ Façade Shear Failure; **TO** ≡ Tympanum Overturning; **TRN** ≡ Transversal Response of the Nave; **TAF** ≡ Triumphal Arch in-plane Failure.

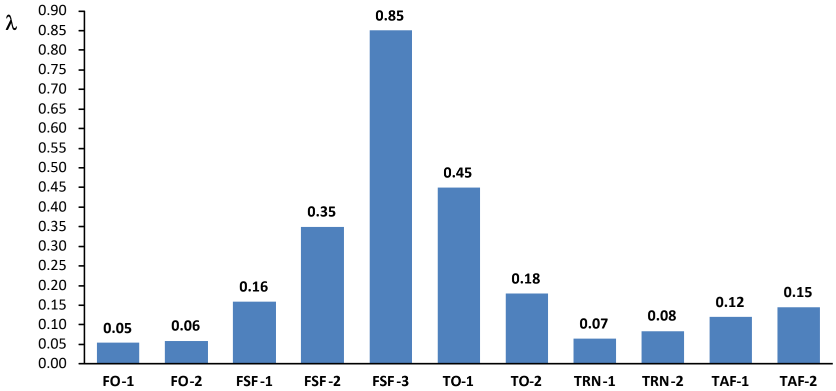
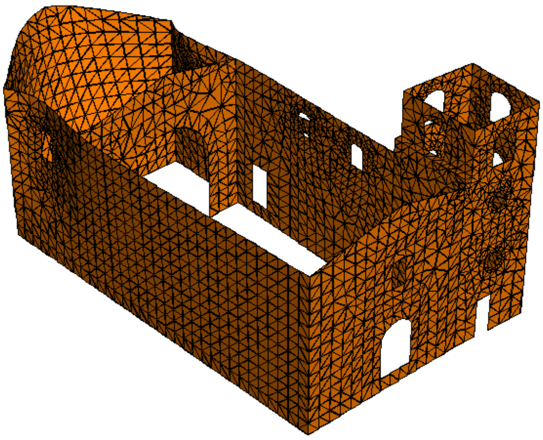
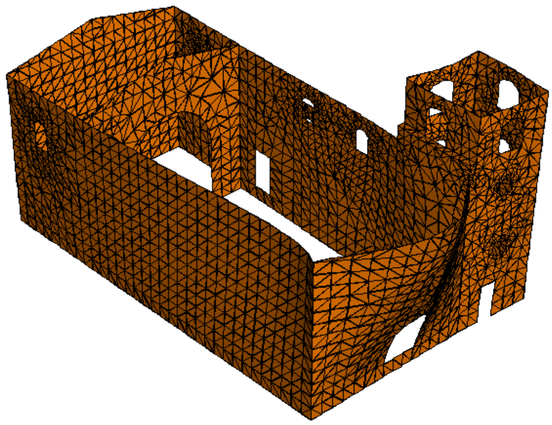


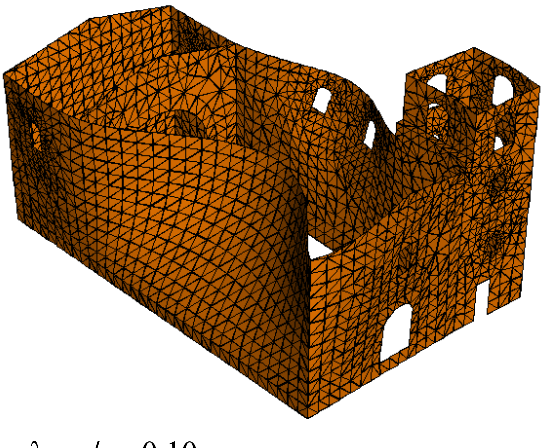
FIGURE 7: Collapse multipliers $\lambda=a_g/g$ for in-plane and out-of-plane mechanisms associated with the failure of the different macro-elements.



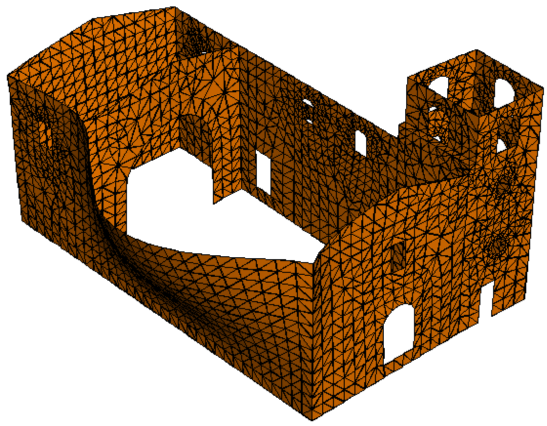
Y+ $\lambda=\mathbf{a_g/g}=0.13$



Y- $\lambda=\mathbf{a_g/g}= 0.11$



X+ $\lambda=\mathbf{a_g/g}= 0.10$



X- $\lambda=\mathbf{a_g/g}= 0.08$

FIGURE 8: Deformed shapes from FE limit analyses and corresponding ag/g=lam collapse values

5 CONCLUSIONS

- In the present paper, a seismic vulnerability assessment on a Medieval masonry church located in Southern Italy, conducted by means of different numerical approaches, has been presented.
- The numerical approaches used are Modal Analyses, non-linear static (pushover) and limit analyses (both on pre-assigned failure mechanisms and with FEs). A refined full 3D plate and shell FE model is adopted, coherent with the in-situ investigations conducted.
- A remarkable consistency among all the different procedures is found, meaning that even simplified approaches (like limit analysis with pre-assigned failure mechanisms) or EAs (typically not recommended because of the linearity hypothesis for masonry) can provide -if critically analyzed- useful hints on possible damage patterns and active failure mechanisms in case of a seismic event.
- Numerical computations proved to be valuable tools to predict the most probable behavior in case of an expected strong earthquake, suggesting the most suited way for an effective strengthening.

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