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SEISMIC VULNERABILITY ASSESSMENT OF AN ITALIAN ANCIENT CHURCH ACCORDING TO CONVENTIONAL APPROACHES

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Abstract

Due to their architectural features, ancient masonry churches are typically prone to seismic damages. Therefore, the social and cultural relevance of such structures requires the assessment of their seismic vulnerability, that is influenced by great halls, lack of a proper connection between the walls, and floor diaphragms not sufficiently rigid to allow a proper distribution of the seismic actions.

In the present paper a case study is selected to assess the seismic vulnerability of a masonry church according to the conventional approach suggested by the Italian Guidelines on the evaluation and reduction of the seismic vulnerability of the Cultural Heritage. The Guidelines suggest a methodology characterized by increasing complexity of analysis. In detail, the first two levels of analysis are applied, assessing a qualitative analysis for evaluating the global seismic performance of the structure (LV1) and the local response of structural portions based on the macro-elements approach (LV2).

The obtained results highlight the influence of the sensitivity of the technician opinion in applying the proposed methodology, since it is not certain that the less accurate approach is associated with a higher safety level, although it should be associated with greater uncertainties. Such occurrence verifies especially when the efficiency of the seismic protection devices is overestimated, and the effectiveness of the masonry toothing is underestimated.

Keywords: Ancient Masonry Churches, Seismic Vulnerability, Structural Analysis Methods.

1 INTRODUCTION

The seismic risk mitigation of buildings having a great cultural importance, especially in seismic areas, is becoming more and more widespread cared for, to prevent losses of priceless cultural heritage and casualties. In this context, vulnerability assessment procedures and management plans to conserve the cultural heritage are being developed in Italy and Europe [1]-[3].

Existing masonry churches appear to be one of the most vulnerable monuments to earthquake. Their high seismic vulnerability is mainly related to the complex in-plan configurations and irregularities. The understanding of the church seismic response remains a considerable challenging task from an engineering point of view, full of open matters.

The Italian Guidelines on the evaluation and reduction of the seismic vulnerability of the Cultural Heritage suggest adopting growing complexity levels of analysis, depending on the promptness and accuracy with which the study must be performed as well as on the objective to be achieved. In accordance with this document, three distinct evaluation levels are indicated, requiring increasing information and refinement (in terms of geometrical and construction details, and materials characterization). The Level of Valuation 1 (indicated as LV1 method) evaluates the global seismic performance of the historical structures by means of a qualitative analysis and it is particularly useful for territorial evaluations [4]. The approach is based on the direct observation of the main features of the existing macro-elements, in the assignment of a score for the related vulnerability indicators, and in the definition of the vulnerability index as a weighted sum of the vulnerability indicators assigned to all possible local mechanisms that could occur in the structure, regardless of the probability of their contemporary activation. Therefore, the derived safety index results highly influenced by the expert judgement of the technician performing the analysis, other than by the buildings geometry and construction details, and it could be unconservative and not fully representative of the effective seismic vulnerability of the church [5]-[7]. The second method (LV2) is devoted to punctual analyses evaluating the local response of a certain portion of the structure. Finally, the LV3 method implies implementation of refined analytical and numerical models. In this context, the key issue is the understanding of the occurrence of a global behavior for the historic church or the activation of local mechanisms that independently develop under horizontal actions. In the first case, appropriate and advanced numerical tools have been proposed with the main aim to identify with accuracy the most vulnerable parts and define appropriate intervention strategies for a seismic vulnerability mitigation of monumental buildings [8]-[15].

The present work deals with the seismic vulnerability assessment of an existing masonry church according to the multi-level approach proposed by the Italian Guidelines [1]. Firstly, a high knowledge level is reached. At this aim, the support from laser scanning has been employed for the geometrical data acquisition and a deep historical analysis performed. A seismic assessment is performed through the LV1 method and compared with the results obtained by analyses of superior level. At this aim, a modal analysis is performed to evaluate which macroelements are more prone to the out-of-plane behavior. In this context, both the stiffening effects provided by the in-plane roof deformability as well as by the presence or absence of the arches supporting the vaulted roofs covering the church is considered.

2 DESCRIPTION OF THE CHURCH UNDER STUDY

The chosen case study is the Church “Natività di Maria Vergine”, located in Erchie, Italy, built and subjected to numerous structural transformations between the 1081 and the 1782. An extensive documentary research and several field surveys have provided an important preliminary knowledge of the church.

2.1 Architectural features

The church "Natività di Maria Vergine" was built in neoclassical style in Pietra Leccese, the typical stone of the area, and it is characterized by the presence of high vaulted ceilings, according with the typical local constructive techniques. The plan of the Church has a single, Latin-cross-shaped nave, marked by four chapels on each side. The chapels are delimited by round arches with structural function. A tympanum crows the transept, one meter higher than the rest of the church and characterised by square plan. The façade consists of two distinct levels, delimited by carved cornices and pillars with capitals in Ionic style. The tympanum takes the form of an anchor with a cross over the central arm and two pinnacles on the sides. The bell tower is articulated on four levels, two included in the body of the church. The structure, entirely made of tuff ashlars, has a total height of 26.50 m, a wall thickness of about 55 cm and good connections between the walls. There is also a small tower that contains the municipal clock, which rises about 6 meters from the roof of the church.

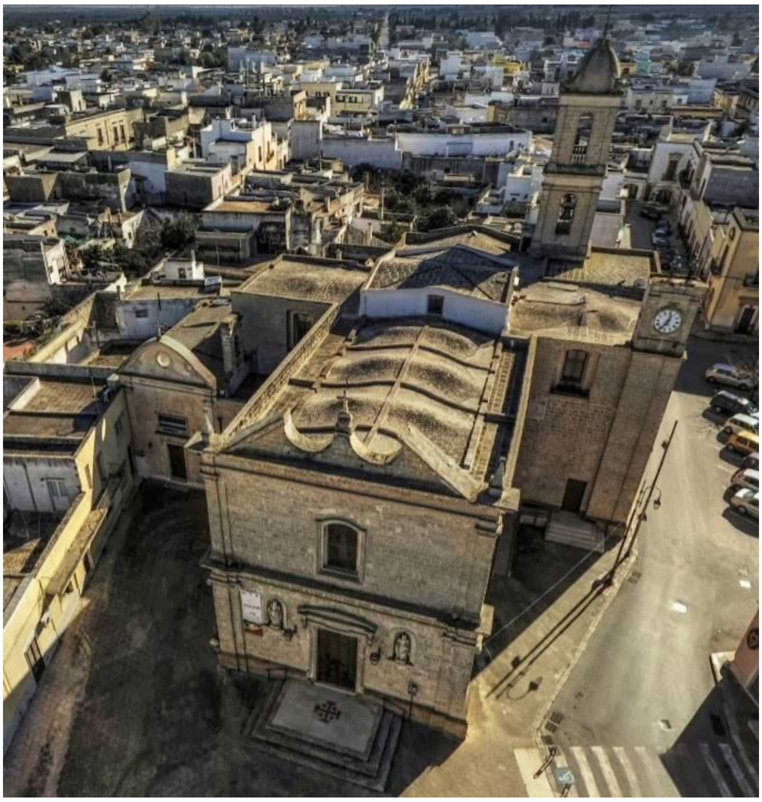


Figure 1: Aereofotogrammetric image of the church "Natività di Maria Vergine" (from Google Earth).

Figure 2: Vaulted ceilings: a) on the apse; b) on the transept; c) masonry arrangement (in the sacristy).

2.2 Historical phases of construction

Historical masonry churches are very complex structures, often developed thanks to subsequent modifications occurred over centuries [16]. As a result, it is thus important to carefully study the building construction process. The church “Natività di Maria Vergine” suffered various transformations over time. The first records of the building date back to 1080, when the presence of a little chapel was mentioned. The first certain information, however, is dated 1565. At this time the church was a simple structure with a rectangular plan, connected with a very small room used as sacristy. In 1603 the small church was enriched with 2 side chapels. The clock tower and belfry are dated 1689, while in 1706 the ancient rectangular structure was transformed in a Latin cross-shaped plant.

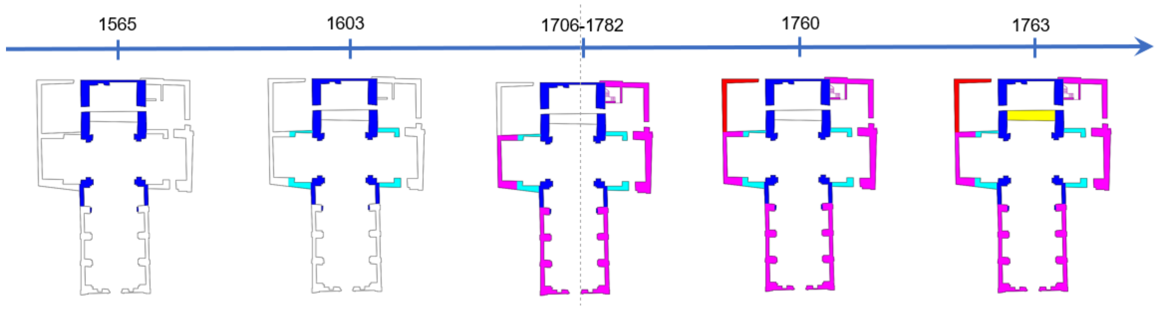


Figure 3: Constructive evolution of the case-study church.

2.3 Laser scanning and structural modelling

The coupling of three-dimensional terrestrial laser scanning (TLS) techniques and finite element analyses are becoming a frontier in the seismic vulnerability assessment procedures of masonry historical structures [17]-[18]. A TLS survey was performed to have a complete and detailed three-dimensional (3D) “geometrical model”, comprising both outer and inner parts of the Church, and the consequent detailed “structural model”. The FARO Focus 3D laser was used, providing a distance accuracy up to ±2 mm in a range from. 0.6 to 120 m. The data were recorded in the form of 3D point clouds (PCs) in a single reference system and elaborated with a specific software able to clean and optimize each single scan. The final geometric model is characterized by a scan size of 28.4 million points.

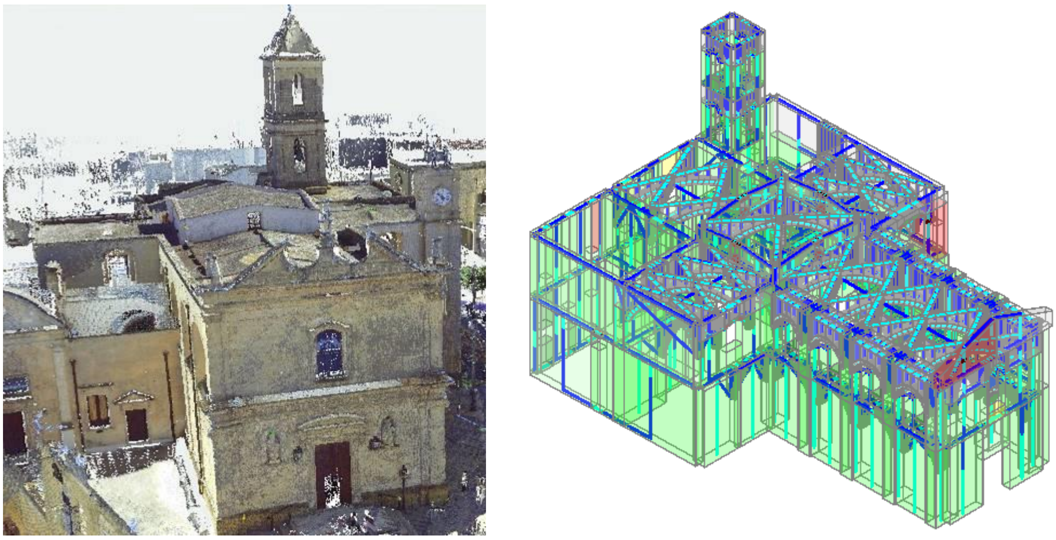


Figure 4: Case-study church modelling: a) Point Cloud (PC) from TLS; b) Structural model.

Basing on the information obtained directly from the TLS, a numerical model of the case-study was created in the commercial pushover analysis software Aedes PCM [19]. The structural model consists of masonry walls, modeled according to the equivalent frame approaches, and masonry arches simulated by means of the finite element block-joint model. Concerning the horizontal partitions, different modeling approaches have been adopted, to evaluate the influence of the deck's stiffness in the seismic response of the masonry church. In detail, the presence of the vaulted ceilings has been omitted or considered by adding stiffening arches, and the roof's stiffness has been varied considering the two limit conditions of in-plane infinitely rigid/deformable floor.

2.4 Modal Analysis

For an existing masonry church, the local mechanisms that can be activated during an earthquake are typically identified by means of a modal analysis. The adopted 3D models account for both the influence of the floor deformability and stiffening effects due to the presence of the arches. It is worth to note that the presence of the bell-tower is omitted in the models, since its seismic performance is characterized by a 3D shear/torsional behavior, instead of a kinematism. In this way, natural frequencies, mode shapes and effective modal masses will be related only to the macroelements for which the limit analysis theory can be applied to assess the seismic vulnerability of the church. The main results of the modal analyses performed according to the modelling strategies selected for this study are summarized in Table 1 concerning the First Mode. Moreover, the characteristics of the modal shape more exciting the longitudinal direction of the church (dir. Y) are indicated in Table 2. It is worth to note that the arches simulating the vaulted ceilings have a stiffening effect on the structure, emphasized if a deformable roof is considered. In facts, the arches link the structural portions and the modal masses excited increase. Therefore, the modelling strategies should be well calibrated to better identify the macroelements considered in the seismic vulnerability analysis.

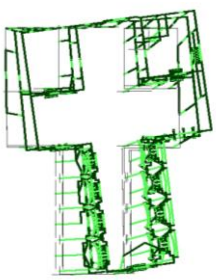
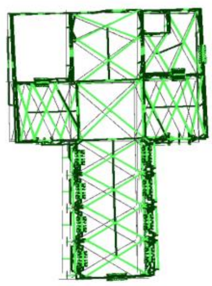
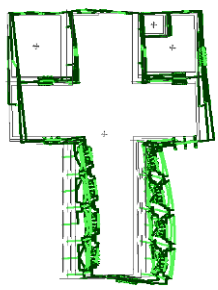
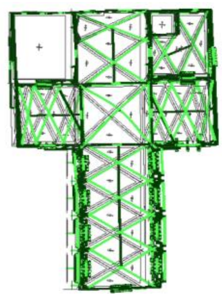
	Model 1	**Model 2**	**Model 3**	**Model 4**
Roof	Infinitely Stiff	Infinitely Stiff	Deformable	Deformable
Arches	Disregarded	Modelled	Disregarded	Modelled
Main Period	0.184 sec	0.187 sec	0.204 sec	0.201 sec
Modal Mass dir. X	75.0%	79.8%	69.8%	81.6%
Modal Mass dir. Y	4.5%	4.4%	0.0%	1.7%
Modal Deformation				

Table 1: Main characteristics of the first mode according to different modelling strategies.

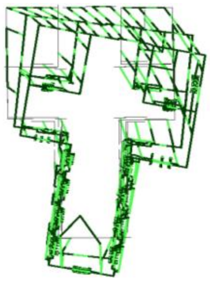
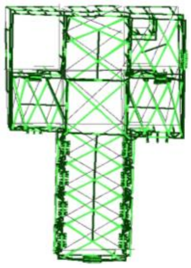
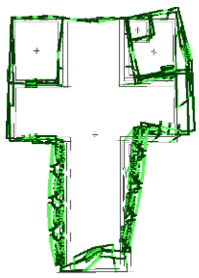
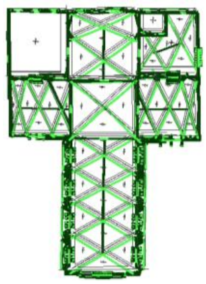
		Model 1	**Model 2**	**Model 3**	**Model 4**
Roof		Infinitely Stiff	Infinitely Stiff	Deformable	Deformable
Arches		Disregarded	Modelled	Disregarded	Modelled
Mode		3	2	2	3
Period		0.125 sec	0.134 sec	0.163 sec	0.144 sec
dir. Y	Modal Mass	58.5%	71.2%	24.8%	66.3%
	Total Excited Mass	66.0%	75.5%	24.8%	71.2%
dir. X	Modal Mass	11.3%	10.3%	3.4%	3.4%
	Total Excited Mass	88.5%	90.1%	73.2%	86.5%
Modal Deformation					

Table 2: Main characteristics of the modal shape most exciting the longitudinal direction according to different modelling strategies.

According to the results, the first mode, although even characterized by a torsional component, develops mainly in the transversal direction, while the modal masses excited longitudinally are less. On a practical point of view, this means that the typical most vulnerable macroelements, that are the façade and its tympanum [20]-[22], as well as the thin wall of the apse, should be less vulnerable to a seismic action. On the contrary, the transverse walls of the nave and of the sacristy should be more prone to an earthquake damage.

3 APPLICATION OF *LV1* METHOD

The simplified model outlined by the Italian Guidelines [1] is adopted for the seismic vulnerability assessment of the building at a territorial level (LV1). The approach assumes that the seismic vulnerability i_v is defined by assuming the contemporary activation of 28 possible collapse mechanisms [7], combined according to the relationship:

$$i_v = \frac{1}{6} \cdot \frac{\sum_{k=1}^{28} \rho_k \cdot \left(v_{ki} - v_{kp} \right)}{\sum_{k=1}^{28} \rho_k} + \frac{1}{2} \qquad (1)$$

where v_{ki} is the indicator of vulnerability attributed to the k-th mechanism associated to a specific macro-element, v_{kp} is the indicator of vulnerability assigned to the seismic protection devices of the same mechanism, and ρ_k is the weight of each collapse mechanism.

For the considered case study, a total of 21 mechanisms are considered due to the lack of elements like nartex (M4), colonnade (M7), aisles (M9), lantern (M15), chapels (M22/M23).

Once defined i_v, the ground accelerations corresponding to the damage limit state (DSL) and the life-safety limit state (LSLS) are evaluated following the formulations proposed in [1]:

$$a_{DLS}S = 0.025 \cdot 1.8^{2.75-3.44 i_v} \tag{2}$$

$$a_{LSLS}S = 0.025 \cdot 1.8^{5.1-3.44 i_v} \tag{3}$$

Depending on the score attributed to the vulnerability or efficiency of the single macro-element, the obtained vulnerability index varies between 0.54 and 0.74, corresponding to a ground acceleration varying between 0.028 g and 0.042 g for the damage limit state (DLS) and between 0.113 g and 0.168 g for the collapse condition (LSLS).

4 APPLICATION OF *LV2* METHOD

The LV2 approach is adopted to assess the collapse ground acceleration of the most vulnerable macroelements, selected according to both the study of the evolution of the church's phases of construction and the modal analysis results. For the present case study, both the simple and the composite overturning are considered, depending on the stage of construction of the considered structural element within the building and its connection with the surrounding elements. The analysis is carried out by means of the Limit Analysis approach, in which, once evaluated the collapse load of the considered macroelement (α_0), the seismic spectral acceleration is estimated according to the following relationship, descending from the standard modal analysis principles:

$$a_0^* = \frac{\alpha_0 g}{e^* FC} \tag{4}$$

being *FC* the confidence factor (equal to 1.18 for the considered case), e^* the participating mass fraction of the considered kinematism, and *g* the gravity acceleration.

A synthesis of the obtained results is summarized in Table 3. The most critical structural portion concerns the thin walls of apse and of the sacristy with acceleration of 0.128 g and 0.130 g, respectively, corresponding to vulnerability indexes varying between 0.86 and 0.90 depending on the adopted modelling approach. Considering all others macroelements, the LV2 approach reveals the safety against the reference seismic actions, since the collapse occurs for acceleration values variable between 0.156 g and 0.398 g against an expected PGA of 0.099 g coupled to a spectral acceleration plateau of 0.170 g at periods in the range 0.287-0.861 sec.

It is worth to note that the demarcation line between the safety and the collapse occurrence is signed by only two parameters, that should be defined according to the expert judgment of the technician: the confidence factor to apply in the analysis and the chosen dimensions of the transversal wedge. The first parameter depends on the knowledge level of the structure, and it can be significantly reduced increasing the details of the performed cognitive analysis. The latter is very difficult to assess, since it is related to the effectiveness of the connection between two orthogonal walls, therefore the masonry toothing. Wedge angles lower than 30° should be considered depending on the effective masonry friction angle. To obviously safeguard the human lives, the presence of a transversal wedge can be omitted, resulting in the lower collapse acceleration values.

Macroelement	**Localization**	**Mechanism**	**Collapse Acceleration**	**Design Acceleration**			
				Model 1	Model 2	Model 3	Model 4
Façade		Simple Overturning	0.156 g				
		Composite Overturning	0.398 g				
Gable		Simple Overturning	0.260 g				
Nave		Simple Overturning	0.336 g	0.144 g	0.145 g	0.149 g	0.149 g
Transept		Simple Overturning	0.212 g				
Apse		Simple Overturning	0.128 g				
Sacristy		Composite Overturning	0.130 g				

Table 3: Synthesis of the linear kinematic analysis performed (LV2 approach).

Finally, another parameter worth of note to assess the seismic vulnerability of a macroelement is the strength reduction factor to apply in order to evaluate the reference seismic demand. In this work the conventional value q=2 was adopted according to the indication of the

Italian building Code [23]. However, it should be noted that this value could be unconservative in the case of the two-side rocking dynamic performance, occurring in the gable, or excessively conservative in the other cases, in which the one-side behavior occurs for the presence of retaining structural elements [24]-[25].

5 CONCLUSION

The performed study represents a matter of reflection for the seismic vulnerability assessment of an existing masonry church. In the work an existing church is considered as a case study and its seismic vulnerability is assessed according to the two different approaches suggested by the Italian Guidelines on the evaluation and reduction of the seismic risk of Cultural Heritage. In detail, both the simplified approach for assessing the seismic vulnerability at a territorial level (LV1) and the one considering the local response of the most vulnerable macroelements (LV2) are applied. The performed analysis highlight that the LV2 methodology provides seismic safety factors than can be higher or lower than those evaluated according to LV1 approach, strongly depending on the knowledge of the structure, as well as on the sensitivity of the technician in giving a score to the vulnerability of each macroelement.

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