COMPDYN 2025
10th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15-18 June 2025

SEISMIC VULNERABILITY OF WORSHIP BUILDINGS: THE CASE STUDY OF FLORENTINE CHURCHES

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Abstract

As is well known, the building heritage of countries bordering the Mediterranean basin is subjected to considerable seismic risk; among these countries, Italy also has one of the richest cultural heritages in the world. For this reason, a series of initiatives have been implemented in Italy in recent years, by interventions at both regulatory and research level, aimed at safeguarding constructions having historical and architectural significance. From a technical point of view, minimally invasive methods have been proposed in order to reduce seismic vulnerability while respecting the original characteristics of the structure; at the same time, a series of investigation methods have been developed, having often a speedy character given the vastness of buildings to be investigated. These methods allow analysing and comparing the data and vulnerability levels of similar structures, thus permitting compilation of a database that is the starting point for guiding decision-making processes and allocation of resources for the protection of historical buildings.
Among the various structural types, worship buildings have intrinsic characteristics that make them more vulnerable than other building types. Moreover, they often contain assets (statues, paintings, frescoes, etc.) of considerable cultural and artistic value. The proposed work presents the results of an investigation involving eighty-nine masonry churches in the city of Florence. The study takes into particular consideration the exposure of the investigated buildings, so providing indications to define possible intervention strategies and priorities, accounting both for the buildings structure and the value of goods housed within them.

Keywords: Worship Buildings, Seismic Vulnerability, Exposure, Empirical Methods.

1 INTRODUCTION

In recent decades, the Italian territory has been hit by seismic events that have increasingly pointed out vulnerability of masonry buildings, including those of historical and architectural significance. Umbria and Marche earthquake (1997), L'Aquila earthquake (2009), Emilia-Romagna earthquake (2012) and Central Italy earthquakes (2016-2017) are only the latest events causing significant damage to structures of the cultural heritage; among them, many churches have suffered damage mechanisms with partial or complete collapse [1]. Italy has an important heritage of ecclesiastical buildings, both in number and in cultural relevance, so it was necessary to activate a series of regulatory and technical initiatives for the protection of such important type of buildings.

Various approaches aimed at assessing seismic vulnerability of masonry buildings are available in literature, having different characteristics depending on the detail level and the field of application [2-8]. A classification of these methods is given by the Italian Guidelines for the Cultural Heritage [9]; according to this classification, three different evaluation levels are distinguished, characterized by an increasing degree of detail and accuracy:

- LV1 (first level of assessment): assessment of seismic vulnerability by qualitative analysis and simplified mechanical models, allowing to estimate a vulnerability index.
- LV2 (second level of assessment): assessment of seismic vulnerability based on local collapse mechanisms, performed by limit analysis of single macro-elements [10, 11].
- LV3 (third level of assessment): assessment of seismic vulnerability by global advanced analysis of the structure, based on linear or nonlinear numerical models [12]; they provide a high level of accuracy but require very detailed data and a high computational effort.

However, in recent times, procedures even more simplified than the LV1 level have been developed, also defined as speedy or empirical methods, since they are aimed at determining the level of risk on a large scale rather than addressing the individual building. These methods provide classification of buildings into types characterized by similar morphological and structural properties, with final evaluations based on the assignment of scores to each significant vulnerability parameter [2-8]. Often based on subjective evaluations, these approaches are useful for the seismic vulnerability assessment of historical heritage and territory mapping when a large number of buildings is involved, according to priority levels of intervention. Emphasis is also given to mixed empirical methodologies, based on initial analysis on a large scale, followed by more in-depth studies depending on the degree of assumed risk. Most studies, based on different levels of cataloging, have been developed concerning ordinary or historical buildings, isolated, in aggregate and on urban scale [13–15]. However, various methods based on the drafting of speedy filing for historical/monumental buildings have been recently developed, since they present special morphological-structural features requiring specific approaches. Religious buildings represent an example among all. This structural type, in fact, is characterized by peculiar and recurring constructive components such as apse, transept, vaults etc., which require a specific analysis strictly dedicated to this particular typology. As far as the Italian context is concerned, many studies have used well-established speedy schedules [16, 17], with the aim of creating an inventory of churches distribution on the territory, considering them from the vulnerability and seismic risk point of view. It is indeed very important to create a database that allows these data to be collected and used clearly and quickly by a large number of people in a multidisciplinary context. In recent years, several studies have been carried out on urban scale, in cities such as Florence [18], Lisbon [19], Vienna [20], etc., aimed at characterizing the building heritage using GIS (Geographic Information System) database; in this way, it was possible storing data in an efficient and practical way, in a functional and user-friendly environment.

The study presented herein concerns an investigation carried out on a sample of eighty-nine masonry churches located in the municipality of Florence. The investigated churches have a data of first construction placed between the 11th and 14th centuries; however, most of them underwent significant modifications in later periods, so the current prevailing architectural style is Renaissance. The purpose of the study was to assess the risk level of the investigated sample by a smart procedure based on empirical methods that allow evaluating both vulnerability and exposure indicators.

2 SURVEY METHOD

In recent years, several studies have been developed on survey and analysis of damage suffered by churches due to severe seismic events, such as Umbria-Marche 1997 [21], L'Aquila 2009 [22], Emilia Romagna 2012 [23] and Central Italy [24]. These studies showed that the damage mechanisms affecting churches have recurring characteristics, despite the architectural uniqueness of each building.

The first phase of the proposed study provided a mapping of the investigated Florentine churches by creation of a database including their basic morphological characteristics, the period of construction and any transformations over the time. The database was implemented in GIS, in order to make this information available, in a clear and simple manner, to a vast number of users; in addition, the database can be used as a meaningful and objective tool in the development of decision-making processes and for the possible allocation of resources aimed at the maintenance and strengthening of this type of buildings. In a second phase, a risk level was assessed for each church through evaluation of vulnerability and exposure indicators, both obtained by speedy empirical methods. In particular, three approaches available in the literature were used: i) the "CARTIS Chiese Edificio" form [8, 21] to identify the morphological characteristics of the building; ii) the Italian Guidelines [9] to evaluate the vulnerability index; and iii) the exposure form proposed by Pirchio et al. [16]. The level of risk attributed to each church has been assessed by interpolating the obtained vulnerability and exposure indicators.

2.1 Morphological features

The CARTIS (typological and structural characterization) method is a procedure for classification of the built heritage from a qualitative point of view; it allows detecting typological and constructive characteristics, so as to have a reliable database of buildings for vulnerability assessments and thus for large-scale risk assessments. The methodology was first developed for ordinary buildings, to make up for the incompleteness of the data provided by ISTAT (National Institute of Statistics) [8]. In recent times, a methodology for ecclesiastical buildings (CARTIS Chiese) has also been developed, filling a gap relating to a very important segment of buildings belonging to the urban context of historic Italian cities. This method is based on two levels of filing:

- a first level (CARTIS Chiese card): it allows defining homogeneous municipal or supra-municipal compartments and/or areas from the point of view of morphological and construction characteristics (the prevalent structural typologies and the relative characteristics are identified), so highlighting the close dependence of these characteristics from the construction period and local building traditions;
- a second level (CARTIS Chiese Edificio form): it allows to gather more detailed information and validate the typologies defined in the first level [21, 22].

In this work, since we already had a well-defined perimeter on which to evaluate the ecclesiastical buildings, the CARTIS Chiese Edificio form was adopted as the data collection structure for each church. The use of such a data organization scheme was favored by the fact that the form compilation is based on the subdivision of churches into individual components or ‘macro-elements’, so as to maintain a correspondence with damage and vulnerability survey tools, such as the damage survey form provided by the Civil Protection Department (model A-DC). The database associated with the churches is constituted by sixty-six fields, taken from the input items in the CARTIS form that are most significant for this study.

The diagram in Figure 1 summarizes the route used for the subsequent analysis.

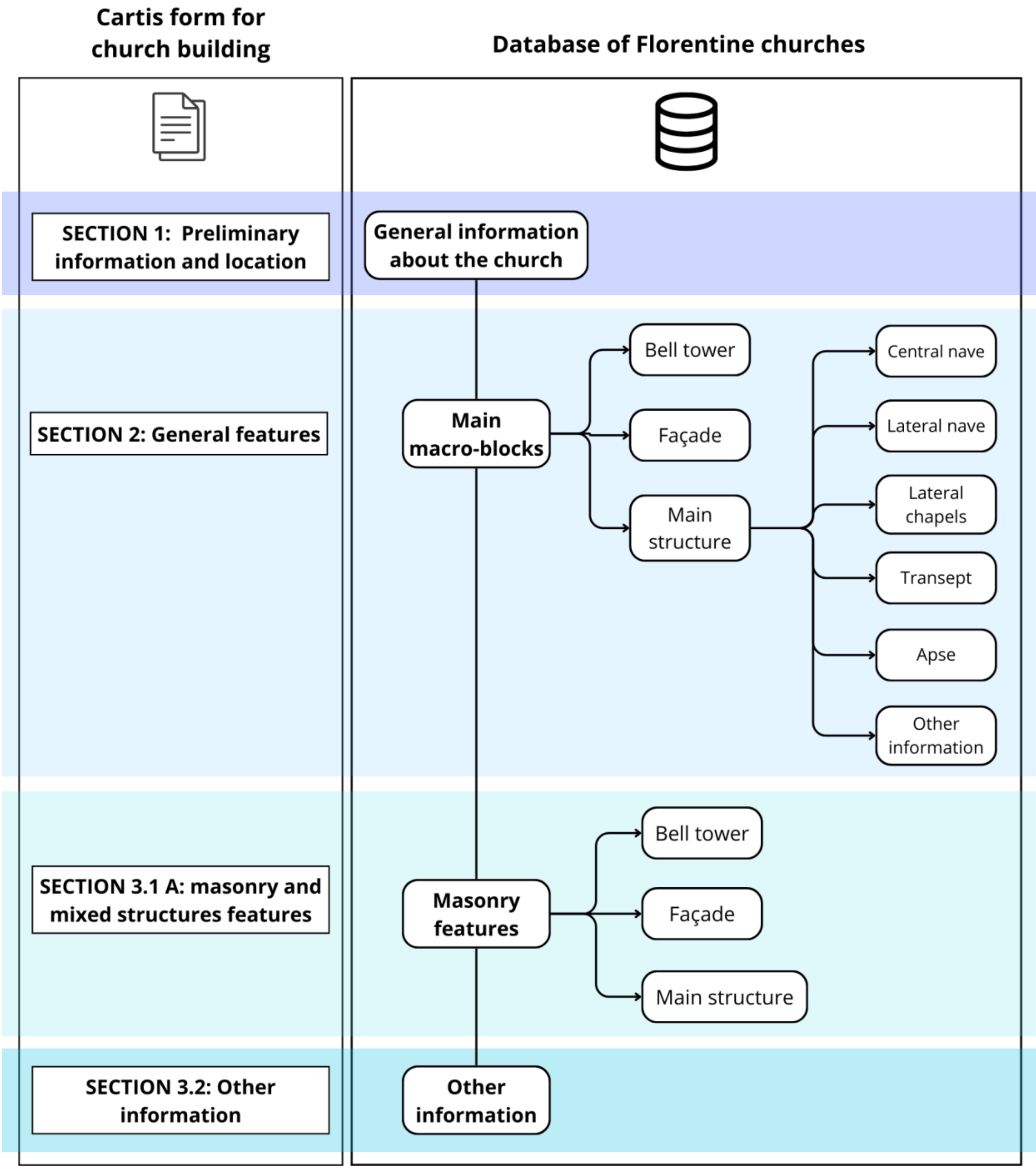

Figure 1: Creation of Florentine churches database by the CARTIS form for churches.

2.2 Vulnerability assessment

The Italian Guidelines for the seismic risk assessment and reduction of cultural heritage [9] and the Ministerial Decree of 2018 [23] provide the basic methodology to be followed to perform seismic verifications of buildings belonging to the cultural heritage [25, 26].

According to the first level of assessment LV1, evaluation of seismic behavior can be performed by dividing historical artifacts into four categories:

1. Palaces, villas and other structures with internal walls and intermediate horizons (a Palaces tab is provided);
2. Churches, worship buildings and other structures with large halls, without intermediate diaphragms (a Churches tab is provided);
3. Towers, bell towers and other structures with a mainly vertical development (a Towers tab is provided);
4. Masonry bridges, triumphal arches and other arched structures (Bridges - Arch tab is provided).

The Churches tab assumes twenty-eight damage mechanisms associated with the macro-elements constituting a church. The seismic behaviour of the whole structure is represented by a vulnerability index *VI*, ranging between 0 and 1, obtained through an appropriate combination of scores deriving from the vulnerability indicators (V_{ki}), any aseismic devices (V_{kp}) and the weight attributed to each mechanism considered (ρ_k), as follows (eq. 1):

$$VI = \frac{1}{6}\frac{\sum_{k=1}^{28}\rho_k\left(V_{ki}-V_{kp}\right)}{\sum_{k=1}^{28}\rho_k}+\frac{1}{2} \quad (1)$$

Concerning the seismic hazard, since the churches are all located within the city of Florence, a subsoil category B, 3rd class of use, peak ground accelerations (PGA) respectively equal to 0.065 g for the Damage Limit State (T_R=75 years) and 0.151 g for the Life Safety Limit State (T_R=712 years) have been assumed.

2.3 Exposure assessment

In general terms, exposure is the measure of the quantity and quality of assets exposed to seismic events; it also expresses the value of what can be lost due to a disastrous event. This parameter represents one of the key factors, together with vulnerability and hazard, for the definition of seismic risk; human, economic and cultural values are therefore expressed through this parameter. The greater the exposure of an area, the more severe the hypothetical consequences of an earthquake may be. For these reasons, seismic risk mitigation is not only about improving or adapting buildings, but also about planning strategies protecting people and cultural heritage. A significant part of this study was dedicated to the assessment of the exposure in terms of cultural value, thus focusing on quantifying the historical, artistic and architectural value of the churches under investigation. An attempt was made to provide a measure as objective as possible of the cultural value of the assets, so as to include in the analysis not only the assessment of vulnerability, but also the potential losses in terms of historical-artistic heritage. In this regard, there are few studies in the literature that, within the analysis of seismic risk, also take into account exposure; in most cases, exposure is considered only on urban scale, giving greater importance to human and economic risk and much less to cultural risk [27–29]. The study provided by Pirchio et al [16] considers various declinations of the concept of seismic exposure, including that in terms of the historical and cultural heritage of worship buildings. For this reason, it was decided to adopt the same evaluation criteria, i.e. to draw up a scoring system that takes various aesthetic and decorative aspects of churches into consideration. A table including five parameters was drawn up; they are:

- Façade ornaments: quantity and quality of sculptural, pictorial and architectural decorations are assessed (score from 0 to 10);
- Vaults and any frescoes on them: the artistic value of frescoes and decorated wooden ceilings is considered (score from 0 to 5);
- Interior decorations: the presence of frescoed walls, stuccoes or mosaics is assessed, also emphasizing the importance of wall decorations (score from 0 to 10);
- Number of paintings: it is carried out through a census (score from 0 to 5);
- Presence of works by recognized masters: one third of the total score is assigned to this parameter, to emphasize importance of works of considerable value within the buildings (score from 0 to 15).

Each of the above parameters was assigned a weight p_k whose sum allows to define, for each church, an exposure index EI; this index was then normalized, on a scale from 0 to 1, dividing it by the maximum obtainable score (45 points) (eq. 2):

$$EI = \sum_{k=1}^{5} p_k / 45 \tag{2}$$

2.4 Risk assessment

Once the vulnerability and exposure indices have been determined, as shown in the previous paragraphs, a matrix correlating these two parameters was drawn up (Figure 2).

The matrix is organized into five rows and five columns, each corresponding to equal intervals of both indices (indices ranging from 0 to 1). Three different risk levels were then assumed: low risk (green), representing buildings with medium-low vulnerability and exposure values; medium risk (yellow), identifying intermediate situations, where at least one of the two indices is significant; and finally high risk (red), identifying the most critical conditions, where both vulnerability and exposure assume high values.

		Exposure Index				
		0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1
Vulnerability Index	0 - 0.2	LOW	LOW	LOW	MEDIUM	MEDIUM
	0.2 - 0.4	LOW	LOW	MEDIUM	MEDIUM	MEDIUM
	0.4 - 0.6	LOW	MEDIUM	MEDIUM	MEDIUM	HIGH
	0.6 - 0.8	MEDIUM	MEDIUM	MEDIUM	HIGH	HIGH
	0.8 - 1	MEDIUM	MEDIUM	HIGH	HIGH	HIGH

Figure 2: Risk matrix.

It is therefore evident that seismic risk does not depend on a single parameter but on the fundamental contribution of different parameters composing it; once the hazard is fixed, the risk can still be significant despite a low vulnerability, and vice versa. In addition, the importance of the exposure parameter for a construction type such as churches must be underlined. As expected, this type of constructions is characterized by significant risk values; on the one hand because of the high cultural value of the assets preserved and, on the other, because of the intrinsic vulnerability due to their morphological and structural characteristics. For this reason, considering both indices allows for a more complete and accurate assessment of the risk level, enabling identification of churches having a higher priority in terms of conservation and intervention. Furthermore, this methodology allows optimization of resources and planning of more effective prevention strategies, so reducing the impact of seismic events on buildings of great cultural value.

3 THE CASE STUDY

A detailed description of the investigated churches is provided below, followed by results in terms of risk obtained by the procedure described in the previous paragraph.

3.1 Sample description

Eighty-nine masonry churches in the municipality of Florence were analyzed (Figure 3), located both in the historical center (identified as per the UNESCO area delimitation) and in peripheral areas, so as to investigate as large a sample as possible. In particular, about 69% of churches are located within the historical center, while the remaining 31% are outside. For each church, first of all, morphological characteristics were identified in order to obtain a typological and historical classification of the whole sample. A relevant data, in this regard, is the percentage distribution of the plan configuration (Figure 4); it can be observed that only three churches are located in an isolated position, while most of them is classified as an aggregate building. Concerning the age of construction, most churches were built between the 11th and 14th centuries, although the prevailing architectural style is Renaissance; in fact many churches, even though belonging to earlier periods, underwent significant modifications at later times. Most of the churches (45%) have a medium-small size plan area (300-999 sq. m.), while only a few, and in exceptional cases, have very large plan area (for instance, the churches of Santa Maria Novella and Santo Spirito). As regards the plan configuration, 63% have a simple rectangular shape, 22% have an “immissa” Latin cross plan, while structures with a central plan or a “commissa” Latin cross plan are less frequent.

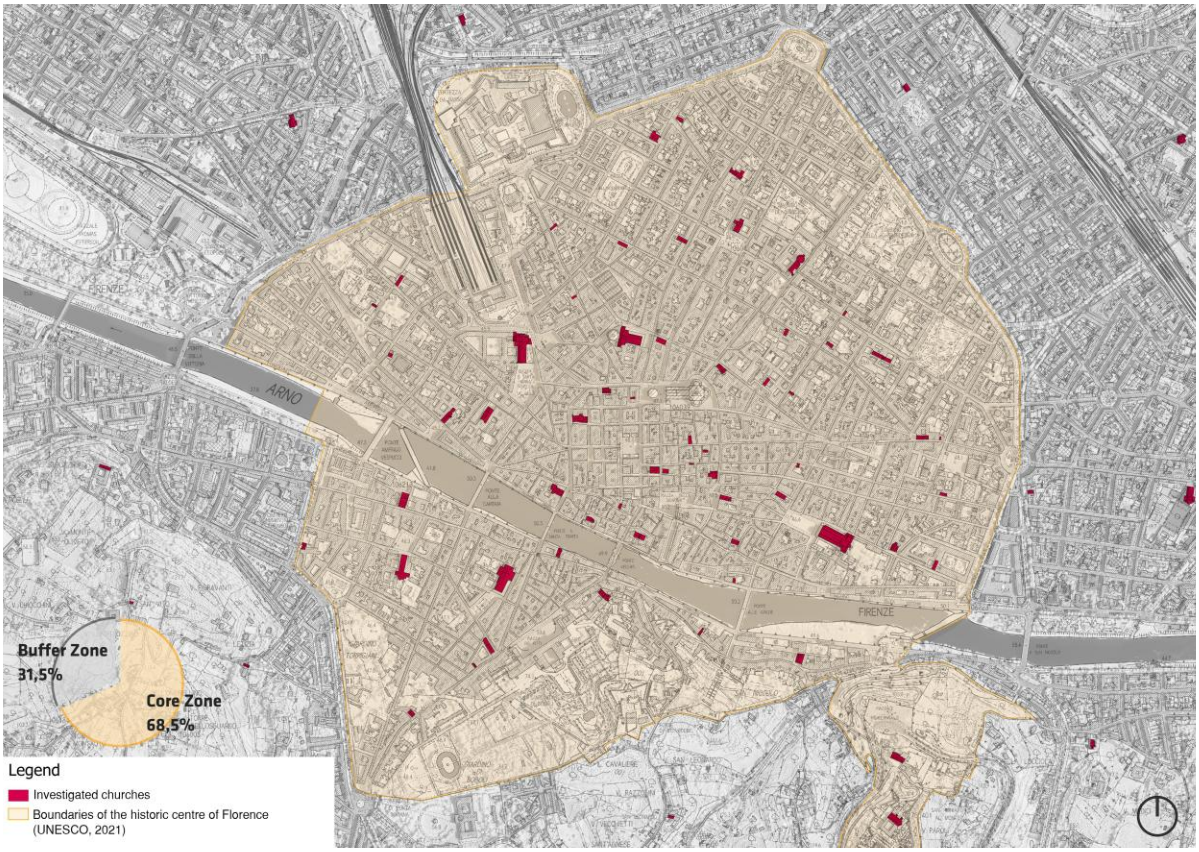

Figure 3: Map of Florence with the investigated churches in the UNESCO Core Zone and the Buffer Zone.

As regards the presence and characteristics of the macro-elements, the following was found:

- only 46% of the churches have one or more bell towers;
- 81% of the churches have a single nave;
- 53% of the churches have side chapels;
- 74% of the churches have no transept and/or an apse with a regular rectilinear layout;
- only 38% of the churches have domes, most of which with a circular base set on spandrels;
- 85% of churches have vaulted systems, 40% of which with a structural function; the prevalent type (31%) is cross vaults, followed at 25% by barrel vaults.

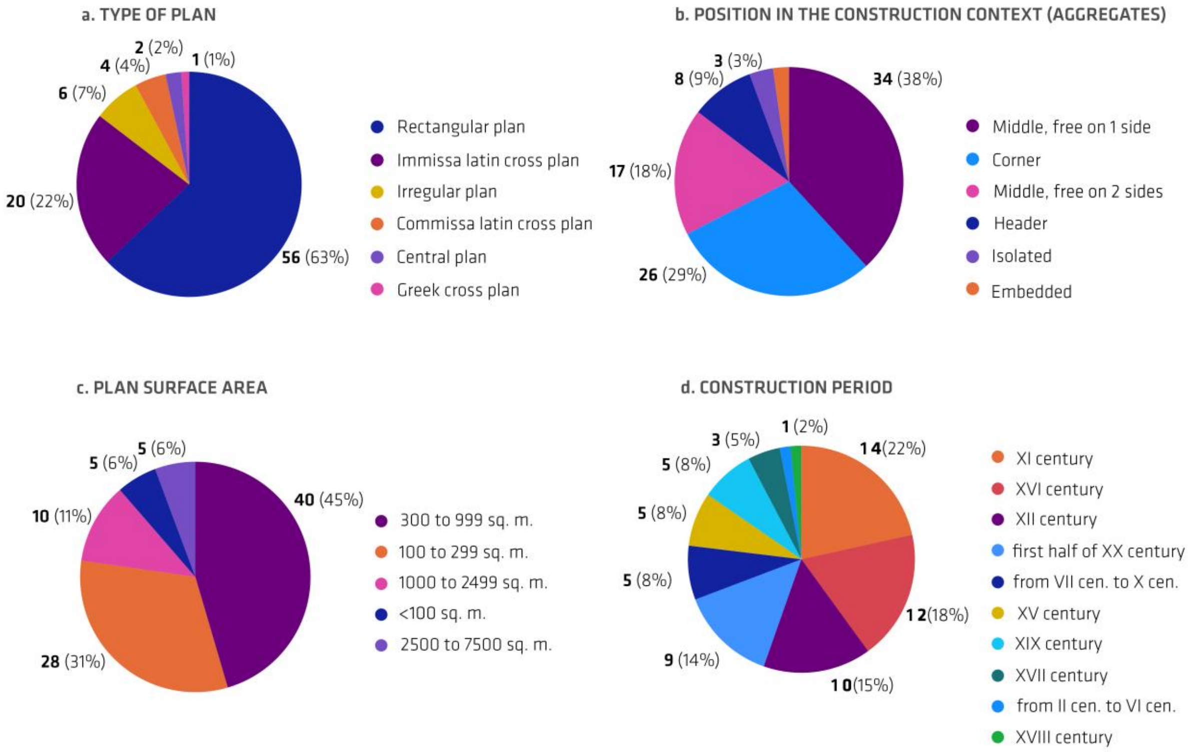

Figure 4: Main characteristics of the church sample: a) Type of plan; b) Position in the construction context; c) Plan surface area; d) Construction period.

3.2 Results and discussion

The results of the investigation, concerning the sample of eighty-nine Florentine churches, are summarized in the diagram in Figure 5. From the diagram, it is evident that the vulnerability index shows a lower variability than the exposure one. This result could be expected, due to the typology of buildings and the two examined parameters: vulnerability, which depends largely on the morphological-structural characteristics, and exposure which instead depends on the socio-cultural value attributed to each building, with consequent risk on assets and human life.

The values of the vulnerability index vary between 0.37 and 0.62, with an average value of 0.49. The most frequent vulnerability factors of the analyzed churches were the presence of large sail vaults at the top of the façade, the presence of large openings in the façade or in the side walls and, inside the building, the presence of vaults and large-span arches with inadequately counteracted thrusts. However, aseismic devices such as chains on the counter-façade, in correspondence with vaults and triumphal arches, were often detected.

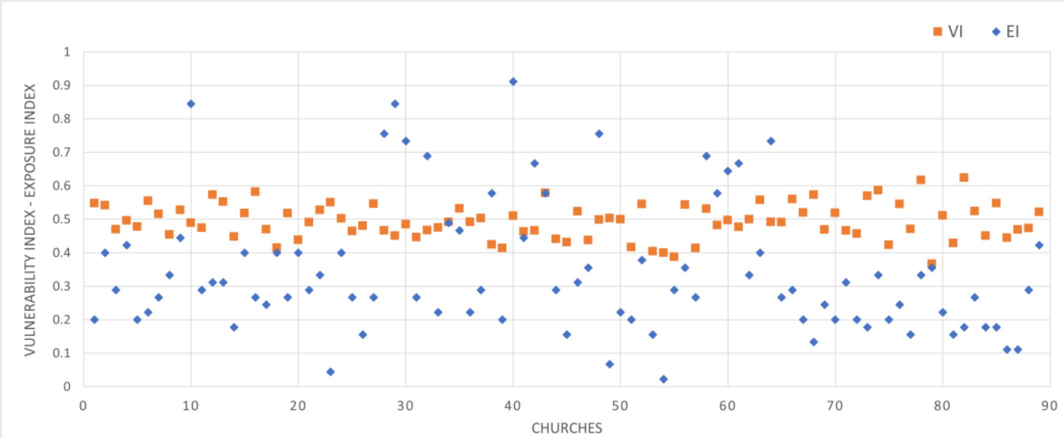

Figure 5: Comparison between Vulnerability Index and Exposure Index for the Florentine churches sample.

A further recurring factor, which plays a seismic protection role, is the position of the church in a wider construction context, defined as a structural aggregate. This condition, characterized by the presence of adjacent structural bodies, is useful in counteracting overturning mechanisms and in limiting in-plane mechanisms.

As regards the exposure index, more spread values were detected, as they range from a minimum of 0.05 to a maximum of 0.91, with an average value of 0.34. The lowest value of 0.05 was found on a minor church that was recently deconsecrated, while the highest value of 0.91was found for the basilica of Santa Maria Novella.

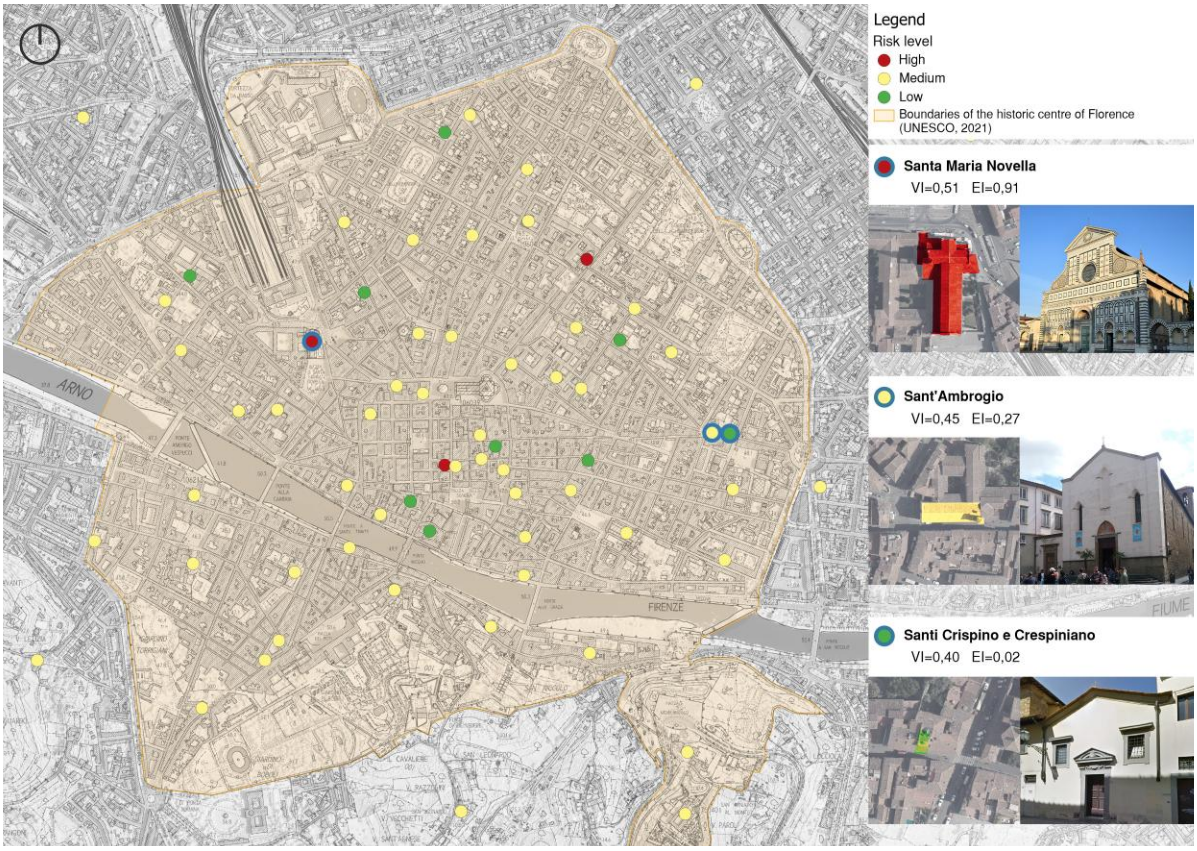

Figure 6: Map of the historic center of Florence showing the risk level of investigated churches.

By cross-referencing the values of the risk matrix in Figure 2, it emerges that 78% of the sample is characterized by a medium risk level, while the remaining 22% is divided into 19% low-risk churches and 3% high-risk churches. The greater variability of the exposure index determines a change in priority if compared to a ranking based on vulnerability; churches currently used for non-religious functions (libraries, exhibition or conference rooms) are at the bottom of the priority ranking, while large basilicas and Renaissance or Baroque churches are at the top of the ranking (see Figure 6).

4 CONCLUSIONS

Inclusion of artistic and decorative assets in the seismic risk assessment of churches represents an innovative and more comprehensive approach compared to traditional methodologies that focus mainly on structural vulnerability. The exposure index thus assessed allows identifying churches with a greater cultural value so providing, at the same time, a scientific basis for planning more targeted conservation and risk mitigation strategies.

The present investigation, carried out on a sample of eighty-nine masonry churches in the city of Florence, has highlighted that the variation of seismic vulnerability is lower than that of exposure. In particular, the vulnerability indices assessed through the proposed methodology were found to be between 0.37 and 0.62, with an average value of 0.49. The most critical vulnerability factors, connected to possible collapse mechanisms, were the presence of large sail vaults, large openings in the walls and vaulted structures or arches with inadequately contrasted thrusts. However, the presence of aseismic devices such as chains in the counter-facades and the position of many churches within structural aggregates compensated, in many cases, the identified vulnerability factors, so helping to reduce probability of activating overturning mechanisms and improving the overall structural stability.

The exposure factor pointed out more dispersed values, with indices ranging from 0.05, in the case of a church of low cultural interest, to 0.91 for the basilica of Santa Maria Novella, with an average value of 0.34. The obtained risk matrix showed that 78% of the sample is characterized by a medium risk level; 19% of churches present a low risk level while only 3% are characterized by a high risk level. Therefore, the investigation showed how the exposure significantly affects the priority of intervention, establishing a hierarchical scale among buildings and leading to a reclassification of churches based on their socio-cultural value. Churches used as libraries or exhibition rooms occupy lower positions in the priority ranking, while large basilicas and Renaissance or Baroque churches remain at the top of the ranking, confirming the need for targeted strategies for the protection and conservation of the architectural heritage of an important city such as Florence.

In conclusion, the developed investigation has highlighted how, in a context of significant cultural importance such as the Florentine one, it is essential to obtain evaluations of the historical heritage other than those of a strictly constructive and typological nature; this allows for a more objective assessment of the building heritage, in order to achieve more precise evaluations in terms of social, economic and cultural losses.

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