MULTI-SCALE SEISMIC VULNERABILITY ASSESSMENT OF HISTORIC CENTRES: THE CASE STUDY OF POPOLI, ITALY

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Abstract: *Italian historic centres are notably highly vulnerable to earthquakes. The seismic vulnerability is an intrinsic property of the constructions that make up the building stock and depends on their ability to cope with the seismic demand, that depends on the structure and on the local seismic hazard. Characterising and quantifying at different scales the grade of vulnerability of historic cities is crucial for the definition of effective risk mitigation strategies and to optimize the allocation of limited resources by public administrations and civil protection departments. When dealing with historic centres, the expected damage and losses associated with earthquakes are difficult to quantify because of the cultural significance and values embodied in the constructions and monuments therein located. Moreover, the variety and complexity of historical buildings make the vulnerability assessment a challenging task, requiring the adoption of approaches driven by typological analyses and different levels of accuracy. The present work responds to this challenge by proposing a multi-scale method for analysing the seismic vulnerability of historic centres and deriving risk scenarios. The method combines and integrates established approaches and relies on the acquisition of specific input parameters aimed at feeding a dynamic digital system for the seismic risk management of historic centres in Southern Italy. The amount and level of the information details required for the vulnerability assessment depends on the scale of the study, mainly the territorial, urban, aggregate, and single building scale. The suitability of the method in the context of Italian historic centres is show cased through the case-study of the historic centre of Popoli, a medieval aggregate in the Abruzzi Region with an urban structure typical of many Italian heritage towns. Severely damaged by the 6.3 magnitude L'Aquila earthquake of April 6th, 2009, Popoli represents a pilot study given the large amount of information available in terms of documented and recorded earthquake-induced damage and seismic retrofitting interventions. The study if part of the research project "GENESIS: SEISMIC RISK MANAGEMENT FOR THE TOURISTIC VALORISATION OF THE HISTORICAL CENTRES OF SOUTHERN ITALY" financed by the Ministry of Education, University and Research (MIUR) through the PON Research and Innovation 2014 - 2020 and FSC. D.D.13/07/2017 n. 1735.*

1. Introduction

Earthquakes are among the most devastating natural hazards. Whilst historically floods, droughts and epidemics dominated disaster deaths, nowadays the highest death toll results from earthquakes (Ritchie and Rosado 2022). According to the Global Assessment Report on Disaster Risk Reduction (UNISDR 2017), the multi-hazard average loss that Italy could expect every year ranges between 5.001 and 14.000 million US$, to which earthquakes contribute for the most part. Despite the overall number of seismic events remain on average the same, the impact associated with such random phenomena is increasing exponentially. This is because the population living in earthquake prone regions has been rapidly growing and there are more people at risk.

The hazard event is not the sole driver of risk. Exposure and vulnerability of exposed elements play a major role. However, when population and economic resources are already exposed to potentially dangerous settings, the only determinant we can act upon to reduce the seismic risk is the physical vulnerability of the built environment. In fact, during earthquakes, the majority of deaths is caused by building collapse. The lower the capacity of the exposed building to cope with the seismic action, the greater its susceptibility to experience severe damage and kill people. This aspect is of paramount importance in the case of old historic centres, which are - almost by definition - highly vulnerable to natural and human-made hazards due to the presence of inherent structural deficiencies and lack of anti-seismic devices that sum up to degradation phenomena resulting from sporadic or ineffective conservation measures. By assessing the seismic vulnerability of risk-prone urban areas and by planning proactive and resilience-oriented targeted measures, it is possible to limit catastrophic effects and reduce potential losses during earthquakes.

Italy is rich in historic sites and vernacular expressions of traditional building techniques whose preservation depends on the identification and consequent mitigation of the major sources of vulnerability associated with the constructions. The latest seismic events (such as L'Aquila 2009, Emilia 2012 and Central Italy 2016) have harshly highlighted the high susceptibility to damage of Italian historic centres, emphasizing the need of quantifying their grade of vulnerability for the definition of cost-effective risk mitigation strategies at the large scale. Nonetheless, integrated seismic risk management tools accounting for the temporal and spatial dynamic nature of vulnerability and exposure at different scales and aimed to assist decision makers in the prioritization of retrofitting interventions are still not available in the Italian context of public administrations.

The GENESIS project - seismic risk manaGEmeNt for the touristic valorisation of thE hiStorIc centres of Southern italy - arises in response to this need. Thanks to the collaborations of about 20 beneficiaries among universities and industrial partners, the project intends to develop an open-source computational web-based platform to support the effective management and conscious use of built cultural heritage in Southern Italy. To analyse the seismic vulnerability of historic centres as well as derive risk scenarios and potential losses, the GENESIS approach will combine established parameter-driven assessment procedures resorting to different levels of information details. The acquired input data will be used to feed the dynamic digital system in order to be automatically processed at different levels of accuracy depending on the scale of the study, mainly the territorial, urban, compartment, and aggregate/building scale. The present work intends to provide an overview of the GENESIS multi-scale method for the seismic vulnerability assessment of Italian historic centres by discussing its practical application to the historic centre of Popoli, a medieval aggregate in the Abruzzi Region with an urban structure typical of many Italian heritage towns. Particularly, the paper will focus on the large-scale seismic vulnerability assessment of Popoli at the compartment level. It is noted that for the purpose of this study the compartment indicates a territorial area characterised by a stock of constructions made of few homogeneous classes of buildings presenting a relevant frequency in terms of construction age and building techniques and/or structural types (Cacace et al. 2018).

2. Seismic vulnerability assessment of historic centres: the GENESIS approach

The GENESIS approach for the large-scale assessment of the seismic vulnerability of Italian historic centres relies on simplified empirical procedures based on *ex ante* typological analyses of individual buildings or relevant sets of constructions for which a similar structural behaviour is expected towards earthquake actions. Despite the great variety and complexity of historical buildings, when analysing groups of constructions in the context of urban centres, it is possible to find typological similarities and consistency in terms of structural systems, geometric features, building techniques and materials, that allow reducing the analysis of the entire building stock to a representative manageable number of archetypes. Most of the characteristics of these archetypes can be indeed parametrised and classified to derive typological vulnerability functions and estimate potential damage scenarios at the large scale.

In the GENESIS platform, the parameter-driven assessment of the buildings at the urban and compartment levels is conducted by applying the Vulnerability Index (VI) method calibrated by (Brando et al. 2017) on the basis of the damage scenarios observed in small historic centres of the inner Abruzzi region after 2009 L'Aquila earthquake. The *modus operandi* underlying this method consists in performing rapid building-by-building in situ inspections aimed at collecting information on a set of key geometric and structural parameters affecting the seismic vulnerability of the buildings. Each parameter P_k is then assessed according to a double score depending on its contribution to increasing or mitigating the building vulnerability, and it is associated with a weight (ρ_k) that accounts for its importance in ruling the seismic performance of the building. For each parameter, the weight is multiplied by the value obtained from the difference between fragility (v_{kf}) and protection (v_{kp}) scores, and the weighted sum of all parameters is then normalised with respect to their total weight, leading to a global vulnerability index of the building, as shown in Eq. (1). The results in terms of $i_{v,j}$ are finally used to compute the mean vulnerability index i_v of the investigated area and to obtain a vulnerability factor V (Eq. (2)) for the estimation of the mean damage grade μD (Eq. (3)), function of the expected earthquake intensity *I* and of the ductility factor *Q*, which accounts for the inelastic capacity of the buildings.

$$i_{v,j} = \frac{1}{6} \cdot \frac{\sum_{k=1}^{m} \rho_k \cdot \left(v_{kf,j} - v_{kp,j}\right)}{\sum_{k=1}^{m} \rho_k} + 0.5 \tag{1}$$

$$V = a + b \cdot i_v + c \cdot {i_v}^2 + d \cdot {i_v}^3 = 0.53 + 1.16 \cdot i_v - 4.00 \cdot {i_v}^2 + 4.21 \cdot {i_v}^3 \tag{2}$$

$$\mu_D = 2.5 \cdot \left[1 + tanh\left(\frac{I + 6.25 \cdot V - 13.1}{Q}\right)\right] \tag{3}$$

Table 1. Vulnerability parameters and associated weights according to the original VI method of (Brando et al. 2017).

Vulnerability Parameter	**Vulnerability type**	**ρ_k**
P_1	Position	1.5
P_2	Number of stories	1.5
P_3	1st mode mechanism	1.5
P_4	2nd mode mechanisms	1.0
P_5	Arches	1.0
P_6	Vaults	1.0
P_7	Slabs	1.0
P_8	Thrusting forces	0.8
P_9	Presence of added structures	0.5
P_{10}	Stairs	1.0
P_{11}	Irregularities	0.8
P_{12}	Non-structural elements	0.5
P_{13}	Site effects	1.5
P_{14}	Non-seismic external hazards	0.3

The original VI method considered fourteen parameters (Table 1), but successive studies conducted by the authors reduced this number down to eight parameters (Table 2) in order to exploit the information extractable from the CARTIS database, an inventory of structural typologies at the territorial scale developed by the Italian Plinius Study Centre (http://plinivs.it) and currently employed in many research activities funded by the Italian Civil Protection Department (Masi et al. 2021, Dolce et al. 2021, Angiolilli et al. 2023, Cianchino et al. 2024).

Table 2. Vulnerability parameters and associated weights according to the CARTIS-based VI method of (Brando et al. 2021).

Vulnerability Parameter	**Vulnerability type**	**$\rho k_{,AB}$**
$P_{1,AB}$	Masonry type	1.5
$P_{2,AB}$	Position	1.0
$P_{3,AB}$	Number of stories	1.5
$P_{4,AB}$	Age of construction	0.3
$P_{5,AB}$	Masonry quality	1.0
$P_{6,AB}$	Horizontal structures	1.0
$P_{7,AB}$	Thrusting forces	0.5
$P_{8,AB}$	Irregularities	0.5

Unlike the original method, the CARTIS-based VI procedure relies on the subdivision of urban centres into homogeneous areas (so-called compartments, e.g. the historical centre, the expansion area, etc.) and on the identification of a few representative classes of archetype buildings per each area (Brando et al. 2021). This classification is performed with the support of a local technician with proven experience in earthquake engineering, city planning and local construction practices, allowing to bypass time-consuming building-by-building surveys which are unpracticable for large urban areas. The reduced number of parameters available in CARTIS inevitably required the redefinition of the weight coefficients associated with each of them (Table 2) as well as the recalibration of the original formulation for the computation of a global vulnerability index of the CARTIS-derived archetype building (AB):

$$i_{v,AB} = \left(\frac{13}{60} \cdot \frac{\sum_{k=1}^{8} \rho_{k,AB} \cdot v_{kf,AB}}{\sum_{k=1}^{8} \rho_{k,AB}}\right) - \left(\frac{7}{60} \cdot \frac{\sum_{k=1}^{8} \rho_{k,AB} \cdot v_{kp,AB}}{\sum_{k=1}^{8} \rho_{k,AB}}\right) + 0.35 \tag{4}$$

The vulnerability indices of the *n* archetypes identified in each compartment are ultimately weighted by the number of buildings represented by each archetype to obtain a mean vulnerability index of the area and estimate therefrom the vulnerability factor V and the expected mean damage grade μD for a predefined seismic intensity *I* according to Eqs. (2) and (3).

Aiming at fostering a proactive identification of the vulnerable constructions of the selected case study for carrying out strategic interventions, in the present work, the parameter-driven seismic vulnerability assessment is performed by applying the CARTIS-based VI method. Yet, in order to evaluate the suitability and level of accuracy of different established approaches in the context of Italian historic centres, the results are compared with those obtained from the original VI method.

3. Case-study application

3.1. The historic centre of Popoli

Popoli is a small town of approximately 4700 inhabitants located in the centre of the Abruzzi region (Figure 1). It represents a classic example of medieval village, typical of the Italian cultural heritage. The first layout of the town developed in parallel to the historical path of Via Claudia Valeria, North-South direction (dashed red line in Figure 1), and, subsequently, the perpendicular-direction guidelines defined its typical orthogonal grid layout. The geographic location of this small village has made it over time a strategic hub in terms of connectivity with the major surrounding urban centres, namely L'Aquila, Sulmona and Pescara, as testified by the presence of significant fifteenth-century buildings located along the main thoroughfares. The rest of the settlement consists of clusters, often intertwined without specific urban planning rules. Due to the presence of carbonate formations in the inner part of the Abruzzi region, stone represents the main building material in this area.

Given the proximity to the Maiella massif in the Central Apennines, which are notoriously a seismic deforming region, the urban centre of Popoli is exposed to a high seismic risk. The most known seismic event experienced by the town was the 6.3 magnitude earthquake that occurred on April 6th, 2009, with epicentre near L'Aquila (Figure 1). The event caused a significant level of damage to the buildings, thus making the town an important area of investigation both in terms of observed earthquake-induced damage on traditional masonry structures and assessment of the effectiveness of previously implemented retrofitting interventions. As expected, most of structural damage concentrated in the historic centre, where buildings are characterized by an irregular stone masonry type typical of the local construction tradition but at the same time highly vulnerable.

In light of the above, Popoli was selected as a pilot case-study within the GENESIS project led by the University of Chieti-Pescara. The seismic vulnerability assessment of this urban centre is considered of utmost importance from the local administration, whose main objective is to optimise the allocation of public resources devoted to the reduction of the seismic risk of the city, particularly of the historic centre, i.e. the oldest and most vulnerable part (Figure 2). Hence, the present work focuses on the seismic vulnerability assessment of this historic compartment (approximately 165.000 m^2). As better described in the following, the large-scale analysis is conducted on the basis of onsite reconnaissance surveys, which have allowed for an initial screening of the main typological and structural characteristics of the buildings located within the investigated area.

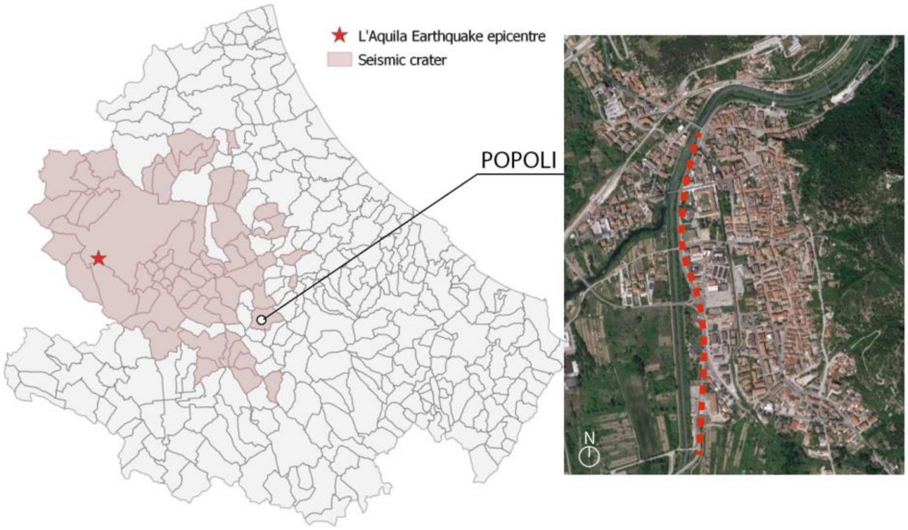


Figure 1. Localization of the municipality of Popoli in the Abruzzi region and overview of the urban settlement.

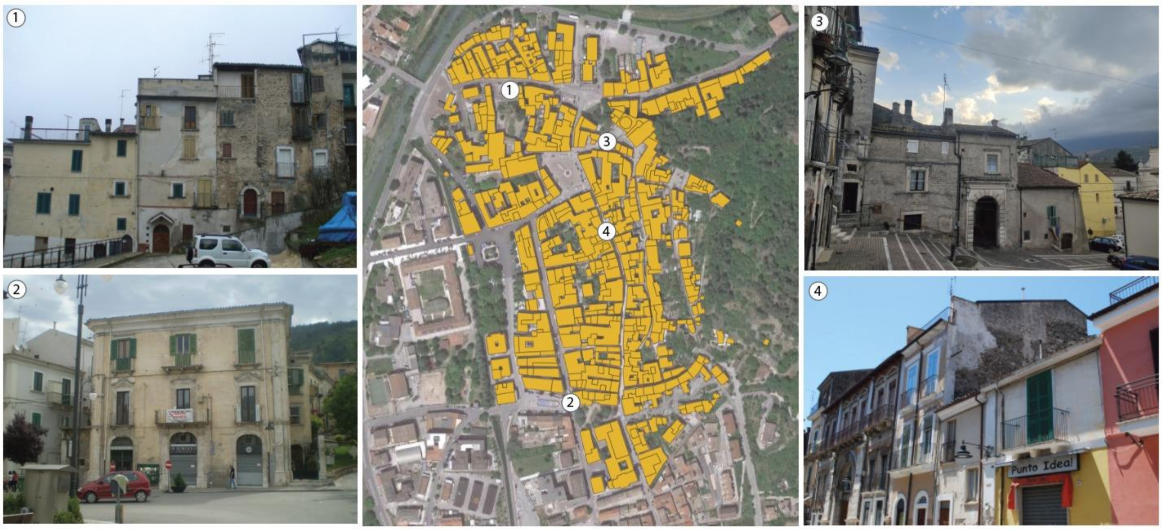


Figure 2. The historic compartment of Popoli and typical building features.

3.2. Identification of archetype buildings

In order to identify the common features of the building stock and derive a reduced number of representative archetypes, the buildings of the study area were evaluated according to the data collected through the CARTIS survey form (Zuccaro et al. 2023), following the procedure outlined in Section 2 and detailed in (Brando et al. 2021). Thanks to a rapid onsite inspection activity and to the support of local technicians with an in-depth knowledge of the building features and construction techniques of the area, eight Archetype Buildings (ABs) were identified. Moreover, by disaggregating the CARTIS information through splitting percentages, it was possible to understand the main characteristics of this reduced set of building typologies representative of the historic centre. As shown in the tree diagram of Figure 3, the buildings belonging to the historic compartment are all irregular masonry structures in aggregate built before 1860, of which 50% are two-storey buildings and the other half consists of three-storey buildings. In what concerns the masonry quality, hence the presence or absence of adequate wall-to-wall and floor-to-wall connections, it is found that about 65% of the buildings has tie rods, while the remaining 35% lacks them. Floor slabs are assumed as deformable, being generally composed of steel beams with brick arches. As for the roofing system, two main typologies are observed: light roofs consisting of timber truss elements (about 40% of the buildings) and heavy roofs made of reinforced concrete (remaining 60%). Overall, the buildings tend to be regular both in plan and elevation (100%). As clarified in Section 2, the CARTIS-based VI method does not rely on building-by-building surveys, but each

CARTIS-derived archetype represents a specific number of buildings, thus the results obtained for single archetypes will be extended to the buildings falling in the same typological class to perform the vulnerability study.

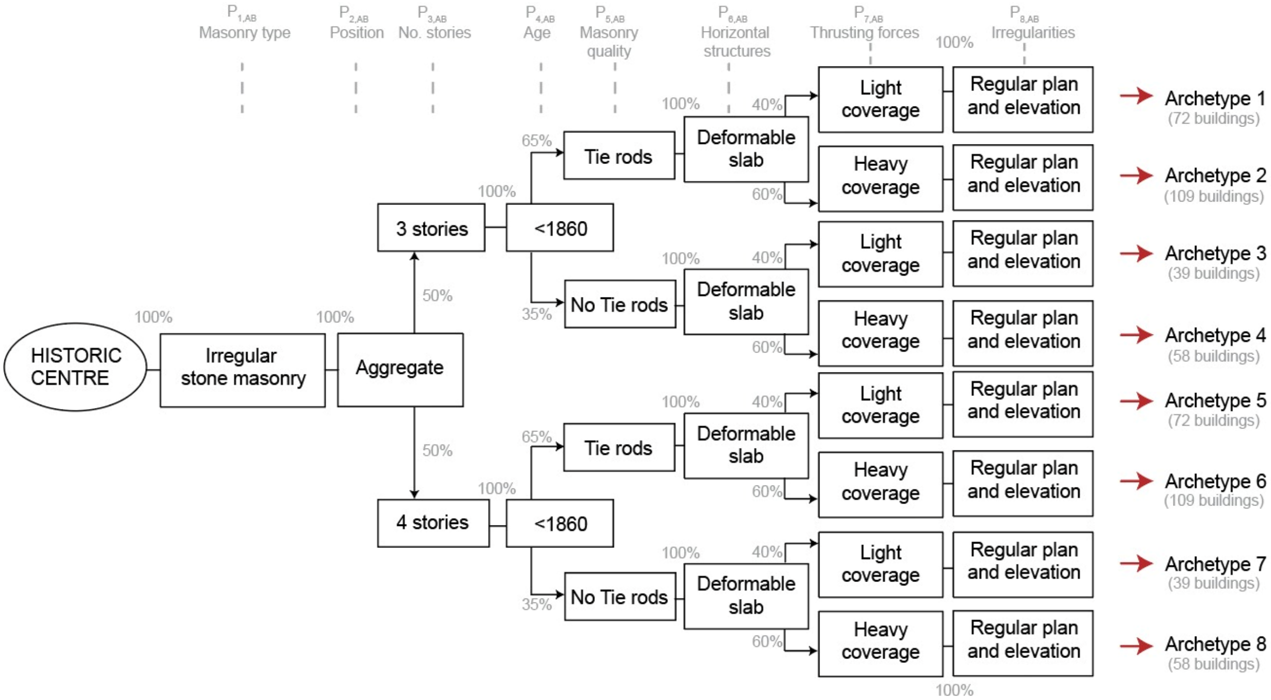


Figure 3. Identification of the CARTIS-derived archetype buildings in the historic centre of Popoli.

4. Vulnerability analysis results

4.1. Parameter-driven assessment

Once the archetypes were identified, their characteristics were parametrised and classified following the CARTIS-based VI method in order to estimate their vulnerability index according to Eq. (4). To this end, for each archetype, the eight vulnerability parameters $P_{k,AB}$ in Table 2 were first assessed by applying a protection ($v_{kp,AB}$) or a fragility ($v_{kf,AB}$) score in the range [0-3] depending on their contribution to reducing or increasing the building vulnerability, and then associated with a weight (ρ_k) ranging from 0.3 for the parameter with the least influence on the seismic performance of the archetype to 1.5 for the most influential parameter. The main criteria driving the vulnerability assessment of the different parameters are resumed below:

- P1 - Type of masonry. This parameter is among the ones that most affect the overall behaviour of the building under seismic actions, hence its high weight ($\rho_k = 1.5$). The vulnerability of this parameter is influenced by the arrangement and quality of the structural resisting system (e.g. rubble vs regular stonemasonry, monolithic vs multi-leaf walls, presence/absence of horizontal courses, etc.), aspects that are easily detectable in the case of fair-face masonry elements. Protection factors able to counteract the vulnerability associated with this parameter include the presence of tie rods.
- P2 - Position. The relative position of a building in the urban mesh and its interaction with other buildings play an important role in terms of seismic vulnerability (ρ_k=1.0), especially in the presence of aggregates. Indeed, unlike isolated buildings, aggregates can show substantial differences in their behaviour under seismic loading depending on their planar layout. For instance, extreme/corner cells cannot rely on the stabilizing effect provided by adjacent buildings like inner cells, being more prone to rotation and translation mechanisms. The presence of misaligned façades and staggered floors between building cells also represents a vulnerability source. To assess these aspects, information on the presence and type of buildings connections are fundamental.
- P3 - Number of stories. This is the parameter that most influences the seismic response of a building together with the masonry type (P1), in fact they are given the same weight (ρ_k=1.5). It is well known that buildings with a higher number of storeys are more likely to experience severe and spread damage

during earthquakes. As the number of floors increases, the overall aspect ratio of the building changes and the forces induced by horizontal thrusts become more influential.

- P4 - Age of construction. For the great part of masonry buildings located in minor historic centres, this parameter – as compared to the others – does not have much influence in terms of global seismic behaviour (ρ_k=0.3). Indeed, all historic buildings are vulnerable almost by definition since they were not built according to modern anti-seismic engineering criteria. Still, dating back to the construction period can help understand the building methods and techniques adopted at the time in which the building was conceived.
- P5 - Masonry quality. The vulnerability of this parameter is related to all those factors that influence the development of the 1st and 2nd mode collapse mechanisms, such as the aspect ratio of the resisting elements, the arrangement and quality of the masonry fabric as well as the lack of connections between walls. For example, slender or multi-leaf walls not adequately connected can result prone to out-of-plane collapse risk. The presence of transverse connections between leaves or tie rods between orthogonal walls can allow mitigating potential vulnerabilities. Being complementary to P1, P5 is given a weight ρ_k equal to 1.0.
- P6 - Horizontal structures. The type of horizontal diaphragm (deformable, semi-rigid, or rigid), the presence of vaulted systems as well as the effectiveness of wall-to-floor connections can sensibly affect the seismic response of a building. Flexible floors do not ensure in-plane stiffness and absence of membrane deformation in the presence of lateral seismic forces, exposing the walls to out-of-plane collapses. On the other side, excessively stiff floors can be often detrimental for masonry buildings. All these factors may significantly affect the overall stability of a structure during earthquakes, hence a weight ρ_k equal to 1.0 is assigned to parameter P6.
- P7- Thrusting forces. This parameter takes into account the type and quality of the roofing system, with particular reference to its impulsive nature and materials. Historic roofs may come in many different forms and styles. Generally, pitched roofs tend to thrust out at eaves level due to the weight applied through roof coverings, finishes and imposed or live loads. The developed thrust must be constrained, with the most efficient form being to use trusses or to introduce ties at eaves level across the building. Indeed, adequate roof-to-wall connections can contribute reducing the fragility associated with the presence of impulsive roofs. In most cases, thrusting forces can lead to localized damage, but they do not threaten the global structural stability of a building. Therefore, a weight ρ_k equal to 0.5 is assumed. It is also worth noting that in large-scale assessments based on simplified and rapid survey procedures, evaluating this vulnerability source is not straightforward as roofing systems are often not accessible nor visible through external inspections.
- P8 – Irregularities. This parameter takes into account possible in-plan eccentricities with respect to the symmetry axes of the building as well as in-height irregularities that can cause variations in the stiffness distribution, leading to potential torsional effects under earthquake loading. Irregularities can cause significant local damage due to stress concentration, but it is unlikely the occurrence of global collapse mechanisms. In the light of these considerations, P8 is also associated with a weight ρ_k =0.5.

It is worth noting that the weight coefficients used in the parameter-driven vulnerability assessment were derived from (Brando et al. 2021). For the sake of completeness, Table 3 reports, for each archetype building, the protection *(*$v_{kp,AB}$*)* and fragility *(*$v_{kf,AB}$*)* scores attributed to each of the 8 parameters based on direct observation and engineering judgment.

Table 3. Scores assigned to the protection and fragility factors for each archetype.

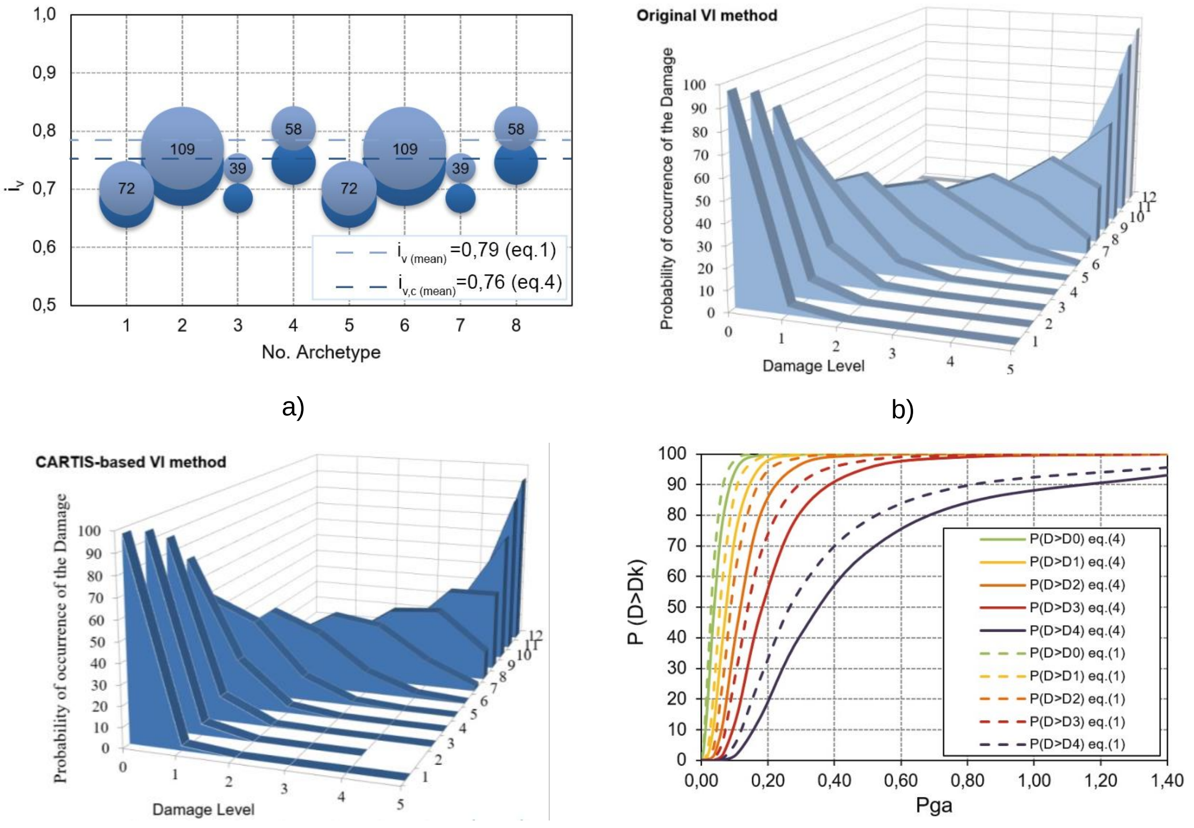
Vulnerability Parameter	**AB1**		**AB2**		**AB3**		**AB4**		**AB5**		**AB6**		**AB7**		**AB8**	
	v_{kp}	v_{kf}	v_{kp}	v_{kf}	v_{kp}	v_{kf}	v_{kp}	v_{kf}	v_{kp}	v_{kf}	v_{kp}	v_{kf}	v_{kp}	v_{kf}	v_{kp}	v_{kf}
$P_{1,AB}$	2	3	2	3	0	3	0	3	2	3	2	3	0	3	0	3
$P_{2,AB}$	0	2	0	2	0	2	0	2	0	2	0	2	0	2	0	2
$P_{3,AB}$	0	1.5	0	1.5	0	1.5	0	1,5	0	1.5	0	1.5	0	1.5	0	1.5
$P_{4,AB}$	0	2	0	2	0	2	0	2	0	2	0	2	0	2	0	2
$P_{5,AB}$	2	1	0	1	2	1	0	1	2	1	0	1	2	1	0	1
$P_{6,AB}$	0	3	0	3	0	1.5	0	1.5	0	3	0	3	0	1.5	0	1.5
$P_{7,AB}$	0	3	0	1	0	3	0	1	0	3	0	1	0	3	0	1
$P_{8,AB}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

4.2. VIs comparison

The vulnerability assessment of the parameters yielded the estimation of a vulnerability index $i_{v,AB}$ for each archetype building of the historic compartment (Eq. (4)). In order to obtain a mean vulnerability index of the entire area for the computation of the expected mean damage grade μ_D, the individual indices were weighted according to the number of buildings $n_{j,AB}$ represented by each archetype:

$$i_{v,C} = \frac{\sum_{m=1}^{8} n_{j,AB} \cdot i_{v,AB}}{\sum_{m=1}^{8} n_{j,AB}} \tag{5}$$

The results in terms of individual (single archetype) and average (all archetypes) vulnerability indices for the historic compartment are presented in Figure 4A along with those obtained by applying the original formulation. To guarantee a consistent comparison, only the information - and consequently the parameters – in common with those extractable from the CARTIS database were considered in Eq. (1). As it can be observed, the two vulnerability assessment methods lead to comparable results. However, with respect to the CARTIS-based approach, the original formulation yields a slightly higher vulnerability index for each archetype, which results into a slightly higher average vulnerability of the study area (0.79 vs 0.76) and into marginally different mean damage grades. This minor difference can also be perceived by looking at the plots in Figure 4B and Figure 4C, where the Damage Probability Matrices (DPMs) resulting from the well-known binomial probability distribution are shown for both methods. It follows that the corresponding fragility curves representing the probability of exceeding a given damage level D$_k$ defined according to EMS-98 (Grünthal 1998) for a predefined seismic intensity, e.g peak ground acceleration (PGA), do not feature a perfect match (Figure 4D). Indeed, the original VI method tends to overestimate the damage as the PGA increases.



a) b)

c) d)

Figure 4. Vulnerability analysis results: comparison between CARTIS-based and original VI method in terms of a) vulnerability indices of the identified archetypes, b) - c) damage probably matrices, and d) fragility curves.

This outcome was somehow expected because of the differences between the two formulations in terms of coefficients, base vulnerability and weights assigned to the parameters (see Tables 1 and 2). As specified in Section 2, the original formulation was calibrated accounting for fourteen parameters while the CARTIS-based method only considers eight parameters, and they are not exactly a subset of the former. The greater uncertainty deriving from the reduction of the vulnerability parameters considered in the assessment was taken into account by (Brando et al. 2021) through a recalibration of their respective weights. Yet, the recalibrated values ($\rho_{k,AB}$) do not differ much from those defined in the original method (ρ_k) and, altogether, they equally contribute to the overall stability of the structure under earthquake actions; in fact, as shown in Table 4, their influence in the vulnerability evaluation ($i_{v,j}$ (ρ_k) vs $i^*_{v,j}$ ($\rho_{k,AB}$)) is negligible.

Beyond the number of parameters themselves, what most affects the results is the coefficient associated with the "Base Vulnerability" (BV) of the buildings, set as 0.5 in the original method (Eq. (1)) and 0.35 in the CARTIS-based method (Eq. (4)). This implies a vulnerability (relative) percentage difference (Δ) ranging between 3% and 8% depending on the archetype. In order to reduce these discrepancies, the BV in Eq. (1) was iteratively changed till the difference between the vulnerability indices estimated from both methods was minimized and contained within 3% (see Δ_{min} in Table 4). This was achieved for a value of BV equal to 0.46, which is lower than the corresponding value considered in the original formulation but higher than the one accounted in the CARTIS-based approach. The latter (BV = 0.35) was defined by (Brando et al. 2021) during the recalibration process of the original formulation aiming not to overestimating the seismic vulnerability of the buildings in the investigated municipality, i.e. Grottazzolina (Marche Region). Yet, it must be stressed that the buildings of Grottazzolina featured a different masonry type (brick masonry) as compared to the buildings located in the historic centres of the inner Abruzzi through which the original VI method (Eq. (1)) was calibrated (irregular stone masonry). Despite a certain grade of variability, most of the constructions of the historic centre of Popoli exhibits typological similarities with the buildings of the municipalities considered for the validation of the original VI method. This explains why the new value defined for the BV approaches more the value of the original method.

Regardless of the number of vulnerability sources taken into account, it is possible to adapt the VI method proposed by (Brando et al. 2017) and initially calibrated on the basis of a building-by-building survey, also to assess the seismic vulnerability of a reduced set of representative constructions provided that typological similarities exist between the buildings of the study area and those with respect to which the method was calibrated.

Table 4. Vulnerability indices comparison: CARTIS-based versus original method.

Archetype Building	**$i_{v,AB}$ ($\rho_{k,AB}$)**	**$i_{v,j}$ (ρ_k)**	**$i^*_{v,j}$ ($\rho_{k,AB}$)**	**Δ [%] ($i_{v,AB} – i^*_{v,j}$)**	**$i^*_{v,j}$ (BV=0.46)**	**Δ_{min} [%] ($i_{v,AB} – i^*_{v,j}$)**
#1	0.68	0.70	0.70	3%	0.66	3%
#2	0.74	0.77	0.77	4%	0.73	2%
#3	0.68	0.74	0.73	8%	0.70	2%
#4	0.75	0.80	0.80	8%	0.77	3%
#5	0.68	0.70	0.70	3%	0.66	3%
#6	0.74	0.77	0.77	4%	0.73	2%
#7	0.68	0.74	0.73	8%	0.70	2%
#8	0.75	0.80	0.80	8%	0.77	3%
Weighted i_v	0.76	0.79	0.79	4%	0.76	0%

5. Conclusions

Predictive strategies for the evaluation of the seismic vulnerability of historic urban areas are crucial to assist public bodies and policy makers in prioritizing retrofitting actions and allocating financial resources across territorial areas in order to mitigate the risk associated with random and unpredictable events, such as earthquakes. In the Italian context, up to date, dynamic and accessible supporting tools for multi-scale risk management are not yet available to local public administrations. Financed by the Ministry of Education, University and Research (MIUR), the GENESIS project - seismic risk manaGEmeNt for the touristic valorisation of thE hiStorIc centres of Southern italy – is trying to fill in this gap by developing an open-source computational web-based platform integrating established vulnerability models and risk assessment procedures at different scales and levels of interest. This work provided a first insight into the GENESIS multi-scale method for the seismic vulnerability assessment of Italian historic centres through a demonstrative case-study located within the seismic crater of 2009. The analyses were conducted at the compartment level by extracting the necessary input data from the CARTIS database and following two well-known approaches. It is concluded that:

- Regardless of the number of vulnerability sources taken into account, both archetype-based and building-by-building VI-based methods are proven suitable for large-scale evaluations, but adjustments of the weights and base vulnerabilities might be needed depending on the building characteristics;
- As compared to building-by-building methods, vulnerability assessment approaches based on *ex ante* typological analyses of relevant sets of constructions (archetypes) allow providing a rapid vulnerability screening of the investigated area with minimal effort, being far more convenient in the case of extensive urban centres;
- By implementing different types of vulnerability models, the GENESIS platform will allow performing vulnerability studies at different scales and with increasing levels of accuracy depending on the amount of collected information.

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