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APPLICATION OF HYBRID QUANTITATIVE-QUALITATIVE MODEL FOR SEISMIC VULNERABILITY OF HISTORIC CENTERS

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Abstract

Seismic vulnerability assessment of historic centers has been a subject of extensive research in the last years. Indeed, historic centers, constituted mainly by masonry buildings, and often with poor anti-seismic characteristics, represent a particularly fragile asset of the Italian built environment. For this reason, it is necessary to have at disposal models for assessment of seismic vulnerability of such objects.
This study presents the application of a hybrid quantitative-qualitative model for evaluating seismic vulnerability of masonry buildings. The model is particularly suitable, due to its computational efficiency and the number of parameters required, to an application to urban scale, also for assisting the risk management chain in the decision-making process.
The model has been implemented as a Python package and integrated efficiently in the open-source GIS software Quantum GIS. As a show case, the developed tool is applied to a case study city center, Fiumefreddo Bruzio, located in the Calabria region, in the southern Italy.

Keywords: Seismic risk, simplified vulnerability assessment, masonry existing buildings, historic centers, data-lake based algorithms.

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1 INTRODUCTION

Historic centers in Italy represent a significant cultural and architectural heritage, yet they are particularly vulnerable to seismic events due to their construction typologies, age, and general lack of seismic design. These areas are predominantly composed of unreinforced masonry buildings characterized by irregular configurations, variable construction quality, complex and heterogeneous transformation phases and limited structural interventions over time. The assessment and mitigation of their seismic vulnerability is thus a priority for national and regional risk reduction strategies. This is crucial especially for the zones in Central and Southern Italy with medium-high seismic hazard.

Seismic vulnerability assessment at urban scale requires methodologies that are both accurate and scalable. Traditional analytical approaches, although rigorous, are often infeasible for large datasets due to their computational demands and the detailed input requirements. Conversely, purely qualitative methods may lack resolution and consistency needed for prioritizing interventions. To address this gap, hybrid approaches combining simplified mechanical models with qualitative indicators have been proposed, allowing for a balance between accuracy and applicability to large urban areas.

Within this framework, the GENESIS project – Seismic Risk Management for the Touristic Valorisation of the Historical Centers of Southern Italy – has developed a multidisciplinary platform integrating geomatics, structural engineering, and risk modeling, [1]. A key component of the project is the development of geo-referenced data-lake, and computational tools capable of supporting large-scale vulnerability assessment. As part of this initiative, the present study proposes and applies a hybrid quantitative-qualitative methodology for the seismic vulnerability assessment of masonry buildings.

The proposed model is based on the seismic vulnerability assessment method proposed by Ferretti et al. [2], originally developed and validated for both reinforced concrete and masonry typologies. It is based on the estimation of the capacity peak ground acceleration (PGA_c) through a simplified mechanical model, corrected by a set of qualitative parameters reflecting construction quality and structural configuration.

A first model development specifically suited for existing datasets for the case of reinforced concrete existing built heritage, as performed by the authors in [3] for different territorial scales showing some promising results, even if focusing on aggregated data on urban compartments and not data on single buildings. This work extends the idea focusing on masonry buildings and adopting the geospatial datasets collected within the GENESIS platform. The proposed method has been implemented in a Python-based tool integrated into QGIS.

To demonstrate the applicability and reliability of the method, a case study is presented for the historic center of Fiumefreddo Bruzio, located in the Calabria region. Approximately 40 masonry buildings are analyzed using geometric and typological information retrieved from the GENESIS platform. The results are compared against more detailed assessments by means of complete geometric surveys on a subset of buildings to evaluate the accuracy and robustness of the proposed approach.

This paper aims to contribute to the development of scalable and reliable tools for urban-scale seismic vulnerability assessment of historic masonry building stocks, in support of preventive planning, risk management, and emergency response strategies.

2 HYBRID QUANTITATIVE-QUALITATIVE MODEL FOR EVALUATING SEISMIC VULNERABILITY

The seismic vulnerability assessment model proposed in this study is developed through the combination of the simplified quantitative-qualitative method proposed by Ferretti et al. [2]

with data available in the GENESIS platform [1], tailored for application to masonry building typologies.

This model has been implemented as a Python package and integrated efficiently in the opensource GIS software Quantum GIS.

The data retrievable from the GENESIS platform are derived directly from the forms or from the geo-referenced polygons representing individual buildings. Figure 1 shows an example of data available in the GENESIS platform for an historical center showing the polygons of the buildings and an extract of one accurate GENESIS form for the specific building highlighted.

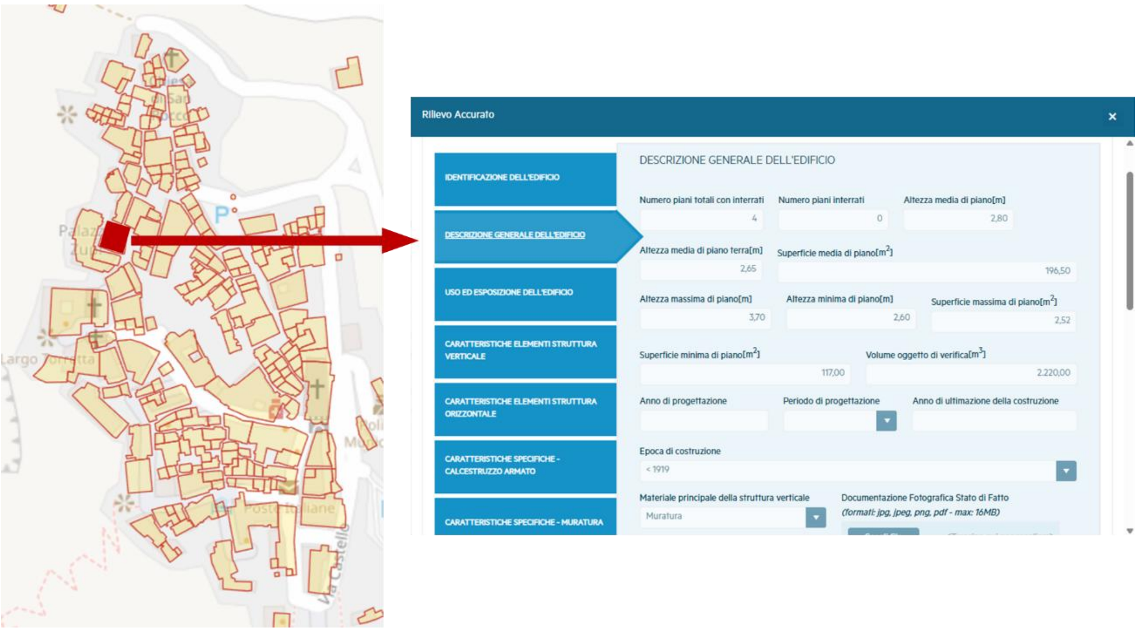

Figure 1: An extract of a map from the platform, including polygons representing the buildings and an extract of a form for one specific building

As described in [2], the assessment method allows estimating the building's collapse capacity in terms of peak ground acceleration (PGA_C) through an analytical evaluation of the shear resistance of masonry piers, corrected by qualitative parameters that reflect the structural configuration and construction quality.

The structural system is idealized as having rigid diaphragms. For each floor i, the effective resisting area is computed in both principal directions (x and y):

$$A_{x,i} = \sum_{j=1}^{N_{w,x,i}} A_{x,i,j} \tag{1}$$

$$A_{y,i} = \sum_{j=1}^{N_{w,y,i}} A_{y,i,j} \tag{2}$$

where $A_{x,i,j}$ and $A_{y,i,j}$ are the effective areas of the j-th masonry pier along the x and y direction respectively; $N_{w,x,i}$ and $N_{w,y,i}$ are the number of piers in the x and y direction respectively. The minimum of the two defines the weakest direction for each floor i:

$$A_{min,i} = \min(A_{x,i};\ A_{y,i}) \tag{3}$$

The average vertical compressive stress acting on the masonry walls at floor i can be calculated as:

$$\sigma_{0,i} = \frac{\sum_{k=\mathrm{i}}^{\mathrm{N}} W_k}{A_{x,i} + A_{y,i}} \tag{4}$$

where W_k and N are respectively the total vertical load from the k-th floor above floor i and the total number of floors.

The two well known shear failure criteria, namely Turnsek and Cacovic [4] criterium (indicated with TC) together with Mann and Müller [5] criterion (indicated with MM), have been considered, permitting to define the shear strength for each floor i:

$$V_{r,i}^{TC} = A_{min,i} \cdot \frac{1.5\tau_{0d}}{b} \sqrt{1 + \frac{\sigma_{0,i}}{1.5\tau_{0d}}} \tag{5}$$

$$V_{r,i}^{MM} = \frac{A_{min,i}}{b} \left(\frac{f_{v0d}}{1 + \mu\varphi} + \frac{\mu}{1 + \mu\varphi} \sigma_{0,i} \right) \tag{6}$$

where τ_{0d} is the design shear strength for diagonal cracking failure, f_{v0d} is the design shear strength for sliding failure, b is a shape factor ranging from 1 to 1.5 respectively for squat and slender masonry piers, μ is the friction coefficient of masonry and φ is a coefficient related to the masonry pattern. The choice between TC and MM failure criteria depends generally on the masonry typology under investigation: for irregular masonry types the TC criterion is generally considered, while MM criterion is considered for regular masonry typologies for which the typical stair-stepped path through the masonry joints is activated in the diagonal cracking mechanism. In this study the values of masonry mechanical properties are derived by Italian standards depending on the masonry typology masonry typology (**Errore. L'origine riferimento non è stata trovata.**, [6]).

The lateral seismic demand is calculated using a linear static approach with a unitary base acceleration:

$$F_i = W \frac{z_i \cdot W_i}{\sum_{j=1}^{\mathrm{N}} z_j \cdot W_j} \tag{7}$$

$$V_{s,i} = \sum_{k=\mathrm{i}}^{\mathrm{N}} F_k \tag{8}$$

where F_i is the lateral force applied at floor i, z_i represents the height of i-th floor from the base, W_i is the weight of i-th floor and $V_{s,i}$ is the total shear demand at i-th floor, and W the total weight of the building. The capacity-to-demand ration can then be written as:

$$\alpha_i = \frac{V_{r,i}}{V_{s,i}} \tag{9}$$

and the spectral acceleration capacity can be defined as:

$$S_a = \min(\alpha_i) \cdot g \tag{10}$$

which corresponds to the attainment of the failure of the weakest floor.

The analytical shear capacity is corrected by a reduction coefficient C_{rid} to account for non-ideal structural features not captured by simplified mechanics. This coefficient is based on ten qualitative parameters drawn from the GNDT Level II form [8]. Each parameter is assigned a vulnerability class (A–D), associated score p_k and weight w_k. The correction factor is computed as:

$$C_{rid} = \prod_{k=1}^{10} \left(1 - \alpha \cdot \frac{p_k \cdot w_k}{\sum_{j=1}^{10} p_{j,D} \cdot w_{j,D}} \right) \tag{11}$$

where α is a calibration constant, $p_{j,D}$ and $w_{j,D}$ are respectively the scores and weights for the j-th parameter in the worst case (i.e. class D). The ten qualitative parameters considered with the associated values of $p_{j,D}$ and $w_{j,D}$ are reported schematically in the first four columns of Table 1. In the model proposed in this study these parameters are explicitly correlated to data retrievable from GENESIS platform. The last column of the Table maps each parameter to the corresponding data within the platform, which are used for its evaluation.

The corrected capacity spectral acceleration is therefore:

$$S_{a,c} = S_a \cdot C_{rid} \tag{12}$$

The capacity PGA, PGA_c, is obtained by converting the corrected spectral acceleration according to the following:

$$PGA_c = \frac{S_{a,c}}{\alpha_{PM} \cdot \alpha_{AD} \cdot \alpha_{DT} \cdot \alpha_{DUC}^{-1}} \tag{13}$$

where α_{PM} is the modal participation factor, assumed equal to 1 for one-story buildings and 0.8 otherwise, α_{AD} is the spectral amplification factor, assumed equal 2.5, α_{DT} is a parameter accounting for the dissipative behavior of the structure that for masonry buildings is assumed equal to 0.8 or 1 depending on the relevance of dissipative contribution of non-structural element; α_{DUC} is a ductility factore accounting for the ductility resources of the structure, assumed in [2] as 2.0 by means of comparison with non-linear static analysis on a set of case-study buildings.

The ratio PGA_c/PGA_d, named also safety index or $S.I.$, being PGA_d the demand peak ground acceleration, represents the vulnerability of the building with values approaching 0 for more vulnerable buildings.

In both the expeditious and accurate GENESIS survey forms, there is no direct information on the effective resisting areas in the two principal directions, $A_{x,i}$ and $A_{y,i}$. Therefore, in this study, such information is inferred using the geometric data of each building's polygon, as obtained from cadastral maps.

To estimate the effective resisting areas in the x and y directions, $A_{x,i}$ and $A_{y,i}$, a *rotating calipers* algorithm is applied to each polygon representing a building. The process begins by determining the convex hull of the polygon. Then, for each edge of the convex hull, the polygon is rotated such that the edge aligns with the x-axis, and the corresponding bounding box is computed. Among all the bounding boxes generated from each edge, the one with the minimum area is retained and rotated back to match the original orientation of the polygon—thus obtaining the *minimum oriented bounding box*.

From this bounding box, the length l and height h of the polygon are derived. These values, combined with information from the GENESIS survey – such as the average distance between walls d_{av}, the average wall thickness t_{av}, and the opening ratio o – allow for an estimation of the effective resisting masonry areas in the two principal directions using the following expressions:

$$A_{x,i} = \text{ceil}\left(\frac{l}{d_{av}} + 1\right) \cdot t_{av} \cdot (1 - o) \tag{14}$$

$$A_{y,i} = \text{ceil}\left(\frac{h}{d_{av}} + 1\right) \cdot t_{av} \cdot (1 - o) \tag{15}$$

Figure 2 shows an example extracted from a historic urban center where it is possible to observe both the original buildings polygons present in GENESIS platform (obtained from cadastral maps) and the corresponding *minimum rotated bounding boxes*.

Figure 2: Zoom on a portion of a historic urban center: view of the polygons representing buildings from cadastral maps (dark purple) and corresponding minimum oriented bounding boxes (light purple).

3 CASE STUDY

In this study, the proposed model is applied to a set of about 40 buildings of the historical center of Fiumefreddo Bruzio, located in the Calabria region, where the building stock is primarily composed of masonry structures.

The seismic input acting at the base of the buildings is evaluated in accordance with the Italian building code **Errore. L'origine riferimento non è stata trovata.**, considering a reference period of 50 years. Assuming soil type B [9], the Peak Ground Acceleration (PGA) obtained for a return period Tr=475yrs (life safety limit state) is 0.231 g.

In compliance with Italian building code **Errore. L'origine riferimento non è stata trovata.**, the masonry mechanical properties used for shear resistance calculations are reduced by a confidence factor (FC) of 1.35, accounting for the low level of knowledge achieved, and by a partial safety factor for masonry γ_m equal to 2.

The 36 buildings to which the model is applied are ranging from one to four stories and constitute a homogeneous sample, consisting of "Natural stone of various types and shapes" masonry. No interventions aimed at increasing the masonry resistance were detected.

N.	Parameter Description	Class A-D	Weight w_k	Data from GENESIS platform
1	Structural system typology and organization	0-5-20-45	1.50	Period of construction and/or of significant structural intervention; presence and effectiveness of masonry wall connections with corner bonding; presence of tie rods or ring beams.
2	Quality of the structural system	0-5-25-45	0.25	Type and arrangement of masonry (with reference to NTC2018)
4	Foundations and site conditions	0-5-25-45	0.75	Subsoil category; site topography; presence of foundations at different levels
5	Horizontal structures (floor systems)	0-5-15-45	Variable*	Characteristics of horizontal structural elements (Typology of horizontal diaphragms; presence of vaults); presence of effective connections to vertical walls (with floor ring beams, corner stones and tie rods nailed, welded or grouted to beams, etc.)
6	Plan configuration	0-5-25-45	0.50	Regularity in plan
7	Elevation configuration	0-5-25-45	Variable**	Regularity in elevation
8	Maximum spacing between load-bearing walls	0-5-25-45	0.25	Maximum spacing between walls d_{aw}, average wall thickness t_{aw}, average wall spacing-to-thickness ratio
9	Roof type and behavior	0-15-25-45	Variable***	Roof type, shape and material; presence and effectiveness of connections between roof and vertical elements
10	Non-structural elements	0-0-25-45	0.25	Presence of vulnerable non-structural elements; state of preservation
11	Damage condition	0-5-25-45	1.00	Overall state of preservation, of horizontal structures and of vertical structures

* Horizontal structures: $w_5 = \min\left(\frac{50}{\alpha_0}; 1\right)$ where α_0 is the percentage of rigid floor slabs properly connected to the walls

** Elevation configuration: $w_7 = 0.5$ if irregularities are limited to portico openings at the ground floor; otherwise $w_7 = 1.0$

*** Roof type and behavior: $w_9 = 0.5 + \alpha_1 + \alpha_2$, where $\alpha_1 = 0.25$ if the roof is heavy (i.e. $\geq 2kN/m^2$) or made of reinforced concrete and $\alpha_2 = 0.25$ if the perimeter-to-support-length ratio is ≥ 2.0

Table 1: Qualitative parameters considered in C_{rid} (from GNDT Level II) and their correspondence with data present in GENESIS platform

Figure 3: Panoramic view of the Fiumefreddo Bruzio village

The results of the seismic vulnerability analyses lead to safety indices $S.I.$ (i.e. PGA_c/PGA_d), varying between 0.18 and 0.44. Figure 4 depicts a map of the historic center of Fiumefreddo Bruzio classifying the analyzed buildings according to their $S.I.$ values allowing so an immediate assessment of the vulnerability level associated with each building.

Figure 4: Results in terms of $S.I.$ for the analysed buildings in Fiumefreddo Bruzio,

As an in-depth comparison and validation, for the six buildings highlighted by red circles in Figure 4, a more accurate application of the model is considered using the information derived from a geometric survey conducted also inside buildings. In particular, geometric parameters (e.g. effective areas of masonry piers along the x and y direction, $A_{x,i,j}$ and $A_{y,i,j}$, and maximum wall spacing-to-thickness ratio for each level) are derived from the building floor plan drawings at various levels. The six buildings were selected in order to cover a wide range of floor areas (ranging from 52 m^2 to 575 m^2), number of stories (from two to four) and geometric configurations, from the most regular and compact to the most irregular. This variety ensures the representativeness of the analyzed sample and enables a comparative analysis between the results obtained with the proposed method and those derived from the more accurate approach. Results presented in Table 2 show a quite limited difference with maximum values of about 20% in two cases.

	S.I. Proposed model	S.I. Accurate model	Relative-difference [%]
n. 165	0.26	0.23	11.6%
n. 193	0.32	0.35	-7.0%
n. 202	0.40	0.33	20.1%
n. 207	0.32	0.30	6.9%
n. 220	0.29	0.24	22.7%
n. 272	0.18	0.17	5.3%

Table 2: Comparison between the proposed model and a more accurate application of the model for a sample of six buildings

4 CONCLUSIONS

This study presented a hybrid quantitative-qualitative methodology for the seismic vulnerability assessment of masonry buildings at the urban scale, integrated within the GENESIS platform and implemented in a GIS-based tool. By combining simplified mechanical modeling with qualitative indicators derived from georeferenced surveys, the model enables an efficient and scalable evaluation of building safety indices. Its application to the historic center of a case study demonstrated the tool's effectiveness in identifying vulnerability across a heterogeneous building stock. The comparison with more detailed analyses confirmed the reliability of the approach, supporting its potential use in territorial risk management and prioritization of mitigation actions.

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