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Large-scale seismic vulnerability assessment of masonry buildings through a simplified methodology

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Abstract

Assessing the seismic vulnerability of existing building stocks is crucial for risk mitigation, especially in countries, like Italy, where historic masonry structures are prevalent and vulnerable to seismic events. This paper proposes a procedure for evaluating the seismic vulnerability of residential masonry buildings to support risk mitigation strategies at the territorial scale. The procedure relies on first-level data collection forms to characterize the building stock and applies an analytical simplified methodology that requires limited effort and knowledge of the structure. The vulnerability assessment is conducted by correlating the structural capacity, expressed in terms of Peak Ground Acceleration with key structural and geometric parameters. Based on these correlations, response surfaces are calibrated and fragility curves are derived through Monte Carlo simulations, enabling the evaluation of the overall vulnerability of the building stock in a given territory. In the paper, the procedure is applied to the municipality of Maranello (Italy): after a validation of the analytical simplified methodology, performed through a comparison with results of pushover analyses on selected masonry buildings, fragility curves are derived for masonry typologies considered representative of the building stock. Within the municipality, homogeneous territorial areas, called Sectors, are identified and, based on the presence of the different building types in these areas, typological fragility curves are combined to evaluate the seismic vulnerability of entire Sectors. The study highlights the effectiveness of the procedure in supporting stakeholders and decision-makers in prioritizing interventions to reduce seismic risk at municipal, regional and national levels.

Keywords Seismic vulnerability assessment · Unreinforced masonry buildings · CARTIS project · Typological fragility curves · Risk prediction

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1 Introduction

Seismic events represent very dangerous and destructive events that could affect buildings, with significant physical, economic and social impacts. This is particularly relevant in countries that have historically experienced a high seismic activity, like Italy. Over the past century, the country faced numerous major earthquakes, several of which reaching magnitudes M_w greater than 6.5, including significant recent events, e.g., 2009 L'Aquila, 2012 Emilia and 2016 Central Italy (DPC 2018; Swiss Reinsurance Company 2019). These events did not only cause massive losses of lives but also entailed enormous costs, with over 180 billion euros spent in emergency management and recovery over the past 50 years (Di Ludovico et al. 2021; Dolce et al. 2021; Masi et al. 2021; Praticò et al. 2022). Furthermore, damage to the Italian cultural heritage and indirect losses to the economy have further compounded these challenges. From the perspective of seismic risk reduction and considering disaster risk management, it is essential to focus on reducing the vulnerability of the existing building stock, particularly in urban areas.

Seismic risk is a function of three components: hazard, exposure and vulnerability (Pitilakis et al. 2014). Hazard refers to the likelihood of a seismic event occurring at a specific location, exposure reflects the nature and extent of assets at risk, and vulnerability quantifies how susceptible these assets are to damage. While seismic hazard and exposure can be defined at the national level, as it is done in many countries around the world, the assessment of vulnerability - especially at a large scale - remains a challenging task. More specifically, the vulnerability of buildings, particularly those constructed with unreinforced masonry, is a key factor in seismic risk evaluations. In fact, these buildings tend to exhibit poor seismic performances, leading to significant losses, as observed in past earthquakes (D'Ayala and Paganoni 2011; Di Ludovico, 2023; Javed et al. 2006; Penna et al. 2014).

In order to assess the seismic vulnerability of buildings at a large scale, several methods for the derivation of fragility curves can be adopted. In the literature, they are conventionally classified into four categories: (i) empirical methods, based on observations of actual damage and post-seismic surveys (Del Gaudio et al. 2019; Ferlito et al. 2013; Ioannou et al. 2021; Polese et al. 2020; Rota et al. 2008; Zuccaro and Cacace 2015); (ii) judgement-based methods, directly estimated by experts, or based on vulnerability-index models that make use of an expert judgment (ATC-13 1985; Milutinovic and Trendafiloski 2003; Mouroux and Le Brun 2006); (iii) analytical methods, based on the results of static or dynamic analyses on structural models (Borzi et al. 2008; Calvi 1999; Ferretti et al. 2023; Pitilakis et al. 2014; Rota et al. 2010; Shabani et al. 2021); (iv) hybrid methods, which can combine any of the above-mentioned techniques, in order to compensate for their respective weaknesses (Kappos et al. 2006; Sandoli et al. 2021). In general, it is not possible to state that one method is better than the others, as they all have advantages and disadvantages. The selection of one of these methodologies usually depends on accuracy of the obtainable results, the computational effort and also on the amount of information and resources required to achieve the objective of the seismic risk assessment. Besides, frequently, the complexity of the problem and the lack of available information imply different uncertainties, both aleatory and epistemic, e.g., intrinsic uncertainty in basic random variables; model form uncertainty; statistical uncertainty in estimating parameters (Buratti et al. 2017; D'Amico et al., 2019; Pitilakis et al. 2014; Shinozuka et al. 2000).

In the context of updating seismic risk assessments for the Italian residential building stock, several fragility and vulnerability models were developed by research groups affiliated with the ReLUIS (Network of university laboratories for seismic engineering) and EUCENTRE (European Centre for Training and Research in Earthquake Engineering) competence centres, under the coordination of the Italian Department of Civil Protection (DPC). These models, presented in works such as Donà et al. (2021), Lagomarsino et al. (2021), Rosti et al. (2021) and Zuccaro et al. (2021), were implemented within the I.R.MA (Italian Risk MAps) platform Borzi et al. (2021), following the methodological framework described by Dolce et al. (2021). The platform leverages the OpenQuake enginePagani et al. (2024) for seismic risk computations. A comprehensive evaluation and comparison of the implemented fragility models is provided by (da Porto et al. 2021), who assessed their predictive performance in estimating damage, economic losses, building usability, and casualties.

Given the complexity and diversity of the existing building stock in Italy, particularly regarding masonry construction, large-scale vulnerability assessments are necessary for effective risk mitigation. The scientific community has made substantial progress in understanding seismic risks and developing advanced engineering solutions. Nevertheless, despite significant advancements in seismic engineering, large-scale vulnerability assessments still encounter substantial challenges. These include accounting for diverse construction methods, materials, and varying structural conditions across the building stock.

To address these challenges, multi-level approaches to vulnerability assessment are often employed (Ferreira et al. 2019; Mazumder et al. 2021). This approach ranges from quick on-site surveys and visual inspections (first-level assessments) to more detailed structural analyses (second- and third-level assessments). First-level assessments provide a rapid, qualitative understanding of the building characteristics, helping identify structures that warrant more in-depth analyses. Second- and third-level assessments, involving detailed mechanical models and computational methods, offer deeper insights into the seismic performance of individual buildings or groups of buildings. Additional contributions in this field include the work of (Aguado et al. 2018), who propose a large-scale seismic vulnerability assessment method for masonry façades in historic city centers, and (Barbat et al. 2010), who present a comprehensive multi-level framework for evaluating seismic risk in urban areas, integrating physical vulnerability, social fragility, and resilience. These references strengthen the discussion on hierarchical approaches applied to residential masonry buildings.

This study presents a procedure for assessing the seismic vulnerability of building stocks at the territorial scale through the derivation of typological fragility curves. The approach builds upon a simplified vulnerability assessment methodology initially developed by Mazzotti et al. (2013) and recently updated by Ferretti et al. (2024), which provides insights into the safety of existing buildings with minimal resource requirements. To demonstrate its applicability, the methodology is implemented in Maranello, a municipality in the Modena district of the Emilia-Romagna region, Italy. The required data for assessing the vulnerability of residential masonry buildings were collected using the CARTIS form (Zuccaro et al. 2015, 2023), a regional-scale building inventory tool endorsed by the Italian Department of Civil Protection, which is based on the identification of structural typologies within specific areas of the municipality (called “Sectors”), which have to be defined considering the historical evolution of the city over time. By focusing on masonry building typologies, the study aims to enhance the precision and cost-efficiency of seismic risk mitigation strategies, addressing the vulnerabilities of structures most susceptible to earthquake damage.

2 A procedure for the large-scale seismic vulnerability assessment

This paper outlines a comprehensive procedure for the large-scale vulnerability assessment of residential masonry buildings, covering all stages of analysis, from data collection to the derivation of typological fragility curves. Considering the time and cost limitations required when assessing extensive building stocks, the approach incorporates a rapid vulnerability assessment methodology specifically for masonry buildings. This is achieved through a simplified analytical framework aimed at evaluating the safety of existing structures with minimal resource expenditure. The results are used to define Response Surfaces, which subsequently serve as inputs to derive overall fragility curves for the investigated area through Monte Carlo simulations. The main steps of the procedure are:

- Data collection and survey framework for the subdivision of the municipality into Sectors;
- Vulnerability assessment of typological buildings through a simplified analytical methodology;
- Derivation of typological fragility curves;
- Derivation of fragility curves for Sectors.

The final result can serve as valuable tools for stakeholders and decision-makers, enabling the prioritization of interventions at national, regional and municipal levels within the framework of seismic risk management. Furthermore, the methodology facilitates a preliminary identification of recurrent vulnerabilities on a large scale, supporting the strategic planning of necessary interventions to effectively mitigate seismic risk.

2.1 Data collection and survey framework

The vulnerability assessment begins with the collection of building inventory data using the CARTIS (CARatterizzazione TIpologico-Strutturale dei comparti urbani costituiti da edifici ordinari – Typological-structural characterization of Italian ordinary buildings in urban areas) survey form. Developed by the Plinius Centre of the University of Naples “Federico II” within the framework of the ReLUIS project, funded by the Italian Department of Civil Protection, the CARTIS form has been specifically designed to characterize the built environment of municipalities, with a focus on masonry and reinforced concrete residential buildings (Zuccaro et al. 2015, 2023).

The form incorporates a systematic interview-based approach, relying on technicians with experience on the building construction practice and its evolution in the specific urban area to be investigated. Although developed for a different purpose, the CARTIS form is coherent, for what concerns terminology and taxonomic definitions, with the AeDES form (Baggio et al. 2009), used by the Italian Civil Protection Department for the damage survey in the aftermath of an earthquake.

To date, the CARTIS form has been applied to approximately 4% of Italian municipalities, and the resulting data have been integrated into an online platform to facilitate consultation (Brando et al. 2021; Polese et al. 2019, 2020). The flexibility of the survey allows its application at various territorial scales, ranging from municipal compartments to district, provincial and regional levels.

The CARTIS form is divided into four sections, each focusing on a distinct aspect of the building stock within a municipality:

- Section 0: this section involves collecting preliminary documentation, such as urban regulations, historical records, GIS maps, and aerial/satellite imagery. The goal is to divide the municipality into homogenous Sectors, characterized by buildings sharing similar construction periods and typological features.
- Section 1: this section focuses on identifying the structural typologies characterizing each Sector, with unique codes assigned to each one. Up to eight prevalent building typologies can be identified for each sector: masonry buildings are categorized as MUR (e.g., MUR 1, MUR 2, etc.), and reinforced concrete buildings as CAR (e.g., CAR 1, CAR 2, etc.).
- Section 2: this section is dedicated to the identification of the main characteristics of the typologies under examination, e.g., number of storeys, average floor height, age of construction, main use, etc.
- Section 3: this section is divided into two parts – one for masonry (Part A) and one for reinforced concrete (Part B) buildings – and collects information about structural and non-structural details. As an example, for typical masonry buildings belonging to a Sector, it is necessary to identify the type of masonry (i.e., regular or not regular), the number of wall leaves and the quality of their connection by means of passing-through stones or bricks, the presence or absence of an inner weak core within the wall thickness. Other details include wall thickness at different storeys, distance between walls, the type of slabs and vaults, the presence of reinforced concrete elements, of iron ties and buttresses, and mortar type and quality. A checklist of potential fragility factors is also provided to support engineering evaluations during the vulnerability analysis.

At the end of the survey process, with the help of the expert technician, the interviewer critically assesses the reliability of the collected data and compares them with preliminary findings. If inconsistencies arise, additional interviews are conducted to improve accuracy. Through a historical and analysis of the territory, the CARTIS survey facilitates the division of municipalities into Sectors, each associated with recurring building typologies and their structural characteristics. This provides a robust and useful basis to characterize the exposed assets for subsequent seismic vulnerability assessments.

2.2 Vulnerability assessment through a simplified analytical methodology

The adopted simplified methodology, developed in previous research (Ferretti et al. 2024; Mazzotti et al. 2013), is designed to be applied at the scale of individual buildings, enabling a rapid assessment of the seismic vulnerability of the analysed structures. This approach is especially useful for extensive building inventories, where limited time and resources require efficient yet reliable evaluation methods. It offers essential information on the seismic safety of structures while reducing the effort needed for assessment. The methodology is schematically reported in Fig. 1 and synthetically described below; interested readers may refer to the cited works for further information.

Depending on the material of the structure, i.e., masonry or reinforced concrete, two different procedures should be followed to evaluate the structural capacity. In the following, reference will be made only to masonry structures, given the objective of the present research. The simplified methodology is organized through the following steps (Fig. 1):

- Collection of technical information, in order to obtain a plausible picture of the current state of the building and to reach a specific knowledge level;
- Estimation of the resistant capacity of the structural system, in terms of Peak Ground Acceleration (PGA_c), corresponding to the Life Safety Limit State. Even if several intensity measures can be adopted for vulnerability assessment, e.g., spectral accelerations (Eads et al. 2015; Luco and Cornell 2007), or PGVs (Yakut et al. 2012), in the present study, the choice of PGA as the intensity measure was related to the adoption of a mechanical model to assess the vulnerability of the structure, requiring forces and, consequently, accelerations.

In more detail, the evaluation of PGA_c is performed, floor-by-floor, by assuming a strong spandrels-weak piers condition; in this way, the capacity of the construction can be computed considering the in-plane shear strength of the masonry piers on each floor, in x- and y-directions. By evaluating both the resisting shear force and the acting shear force at each floor, the latter calculated through a seismic linear static analysis of the structure subjected to an equivalent static force distribution considering a reference acceleration equal to 1g, it is possible to identify the weakest floor of the construction, i.e., the one characterized by the lowest ratio between the resisting and acting shear forces. This ratio corresponds to the spectral acceleration, a conventional value to express the building capacity, which can be then converted into the corresponding PGA_c value considering modal participation factor, spectral amplification factor, dissipative behaviour of the structure and a ductility factor. To bridge the theoretical calculation framework, based on the mentioned assumptions, with the actual conditions of the building, a reduction coefficient (C_{rid}) is used, allowing expert judgment to identify potential structural vulnerabilities and critical issues

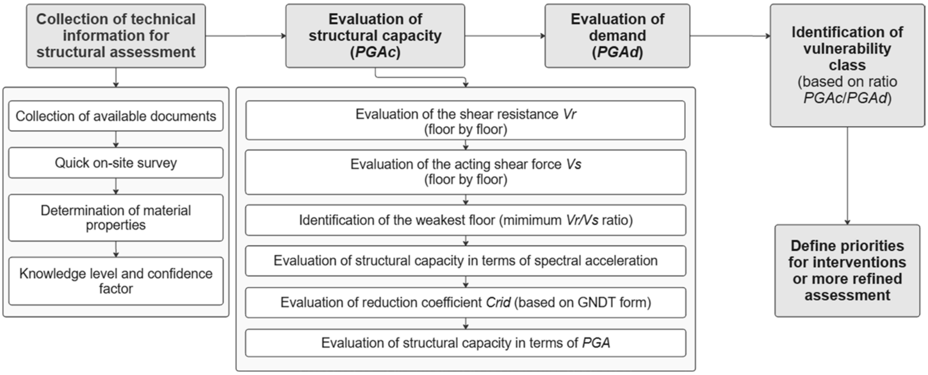


Fig. 1 Scheme of the simplified analytical methodology for vulnerability assessment of existing buildings

not explicitly addressed in the theoretical capacity calculations. This process, grounded in well-established methodologies, e.g., GNDT II Level form (Italian Group for Protection against Earthquakes) (Regione Toscana 2003), ensures a thorough and reliable evaluation of the building's seismic performance. In particular, the reduction coefficient C_{rid}, which multiplies the conventional capacity of the building, is calculated based on the evaluation of ten different parameters, contained in the GNDT II Level form and related to some structural characteristics of the building (e.g., typology and quality of the resisting system, regularity in plan and in elevation, type of horizontal structural elements, connection between orthogonal walls, presence of vulnerable non-structural elements, state of damage of the building). For each parameter, based on the on-site survey, a vulnerability class and a relative weight are associated, which are combined to calculate the reduction coefficient, which has typically a value bounded between 0.6 and 1, as reported in (Ferretti et al. 2024).

About the material properties needed to assess the structural capacity, if it is not possible to carry out in-situ testing, they can be deduced from Standards of the time of construction or consulting literature indications. Specifically, it is possible to refer to the strength values reported in the Italian Building Code (Ministero delle Infrastrutture e dei Trasporti 2018, 2019), as well as to recommendations of regional authorities based on specific typological studies. In addition, appropriate confidence factors must be selected, according to the knowledge level, following CEN (1998). The seismic vulnerability is then quantified as the ratio between the capacity (PGA_c) and the demand (PGA_d), evaluated with respect to the Life Safety Limit State. Typically, PGA_d can be assumed constant for all buildings within small municipalities (MIT, 2018, 2019).

A key aspect of the analysis introduced in this paper is the distinction between the 'weak' and the 'strong' direction of each building, corresponding to its two principal axes. This distinction, which is not typically included in the standard version of the methodology, has been specifically incorporated into the present study to account for the orientation of the seismic action relative to the building's directions. Indeed, typically, one direction shows a higher PGA_c, reflecting the geometric configuration and load-bearing characteristics of the structure. This differentiation between directions is fundamental and it is retained in the calculation of the PGA_c/PGA_d ratio, as further detailed in the subsequent Sections.

2.3 Derivation of typological fragility curves

The seismic vulnerability of different masonry typologies is assessed through a systematic approach involving response surface calibration, probabilistic simulation and fragility analysis. Response Surfaces (RSs) are first defined for each typology, using significant structural parameters such as material properties and geometric configurations, and calibrated based on the structural capacity of individual buildings. The Monte Carlo method is then employed to generate fragility curves that account for the variability in these parameters, ensuring a robust probabilistic representation of seismic vulnerability. This fragility analysis considers the range of seismic capacities derived for the weakest and strongest directions of the buildings, enabling the evaluation of the probability of reaching the Life Safety (LS) limit state for each typology. Finally, the Shinozuka approach(Shinozuka et al. 2000) is applied to combine the fragility curves of individual typologies, based on their distribution across the Sectors identified earlier.

2.3.1 Definition of response surface

Data collection and vulnerability analysis are conducted for a set of selected buildings belonging to specific typologies, resulting in the determination of PGA_c values. Considering the correlation of the capacity with specific geometrical and mechanical properties, the Response Surface (RS) is used to extend the available data for defining the fragility curves of the prevailing masonry types in the municipality. The RS method is based on the definition of a statistical model expressing a structural response parameter (PGA_c in the present case) as a function of a set of variables. The RS is typically based on a polynomial function, and the method is extensively used in many applications in different research fields (Box 1987; Khuri et al., 2018; Rajashekhar et al., 1993; Searle et al. 1992). For the development of typological fragility curves, data from representative buildings of each typology must be collected.

Response Surface models are here used to identify relationships between the PGA_c, obtained for the buildings on which the simplified vulnerability assessment methodology is applied, and the most significant mechanical and geometric characteristics. To determine a unique correlation function, a multiple linear regression model is applied, where the variable $y = PGA_c$ is the 'response variable', dependent on the 'independent or predictor variables' x_i. Correlation functions of different complexity can be adopted, depending on the number of data available for each typology and which model provides the best fitting. In this work, given the parameters on which the evaluation of PGA_c is performed, the considered independent variables x_i are the load-bearing area of the walls in the direction of seismic action divided by the total plan surface of the building, and the masonry shear strength. To prevent the prediction of negative structural capacity values, log-normal distributions are adopted from the independent variables with the natural logarithm of PGA_c used as the response parameter.

Therefore, the following general function is used for the RS evaluation:

$$ln\,(y) \;=\; \beta_{0} + \beta_{1} \cdot ln\,(x_1) + \beta_{2} \cdot ln\,(x_2) + \beta_{3} \cdot ln\,(x_1) \cdot ln\,(x_2) + \epsilon \tag{1}$$

where:

- x_1 and x_2 are the independent variables;
- β_{i} are the regression coefficients;
- ϵ is the zero-mean normal error.

The purpose of a multiple linear regression is to determine the best plane or curved surface which interpolates the data, and to do this, the regression coefficients β_{i} must be estimated for each structural typology investigated. The response surfaces are derived considering both the weak direction, using parameters corresponding to the lowest PGA_c, and for the strong direction, corresponding to the highest PGA_c.

2.3.2 Extension of available data using Monte Carlo method

After obtaining the regression coefficients and the corresponding RSs, fragility curves are derived using the Monte Carlo method (Chen and Chen 2017). This computational approach is based on random sampling from probability distributions of independent variables; in particular, in this study, the sampling process involves random extractions from log-normal distributions of the independent variables x_i, distributions which can be calibrated using representative data from the analysed typological buildings.

At least 100’000 random extractions of $ln\left(x_i\right)$ values are performed to compute the corresponding values of $\ln\left(PGA_c\right)$ for the LS limit state, obtained using the polynomial function of the RS model, combined with the regression parameters. The resulting large dataset of PGA_c values is then compared with a set of PGA_d values, in correspondence of which the failure probability is calculated for the LS limit state. The derived data are interpolated using a cumulative log-normal distribution to generate the fragility curves, defined by its mean value μ_{ln} and standard deviation σ_{ln}.

For each masonry typology, the outlined procedure is applied to both weakest and strongest direction. This approach provides a reliable range of fragility curves for the LS limit state, capturing the variability in seismic vulnerability for buildings of a given typology.

2.4 Derivation of fragility curves for various sectors of the municipality

Starting from the fragility curves of the prevailing types of masonry in the municipality, the fragility curves of the various Sectors can be evaluated, based on the initial CARTIS survey and considering the percentages of the prevailing typologies in each Sector, keeping the distinction between directions. The approach proposed by Shinozuka et al. (2000) is adopted in order to combine the typological fragility curves for each Sector, using percentage data. Being M the total number of data groups (i.e., masonry typologies in one sector), the combined fragility curve may be assumed to be lognormal with respect to the mean μ and the variance σ^2, which can be estimated on the basis of the variances of the single fragility curves, see Eq. (2).

$$
\begin{aligned}
&\mu = \sum_{k=1}^{M} p_k \cdot \mu_k \\
&\sigma^2 = P^T \cdot \boldsymbol{\Sigma} + A^T \cdot Q \cdot A \\
&P^T = \left[p_1, \ldots, p_M\right] \\
&\boldsymbol{\Sigma}^T = \left[{\sigma_1}^2, \ldots, {\sigma_M}^2\right] \\
&A^T = \left[\mu_1, \ldots, \mu_M\right] \\
&Q = \begin{bmatrix} p_1 \cdot (1 - p_1) & \cdots & -p_1 \cdot p_M \\ \vdots & \ddots & \vdots \\ -p_M \cdot p_1 & \cdots & p_M\left(1 - p_M\right) \end{bmatrix}
\end{aligned}
\tag{2}
$$

where:

- $\boldsymbol{P}$ is the vector of the percentage data for the typologies present in the Sector;
- $\boldsymbol{\Sigma}$ is the vector of the variances of the fragility curves for the typologies;
- $\boldsymbol{A}$ is the vector of the means of the fragility curves for the typologies;
- $\boldsymbol{Q}$ is the matrix, which combines the percentages values p_i.

3 Validation of the simplified methodology for vulnerability assessment of single buildings

Before applying the proposed approach to a case study, it is essential to first evaluate the reliability of the simplified methodology for vulnerability assessment, presented in Sect. 2.2, that underpins the approach. This step is pivotal to demonstrate that the methodology is robust and suitable for extension to large-scale applications. For this purpose, real data on existing buildings were collected: through a collaboration between the University of Bologna and the municipality of Maranello, located in the province of Modena within the Emilia-Romagna region, access was granted to the archives of the municipal technical department, including detailed documentation about some specific representative buildings. Thanks to the availability of the data, this municipality was also selected as the case study for the application of the proposed procedure for large-scale vulnerability assessment, as will be described in Sect. 4.

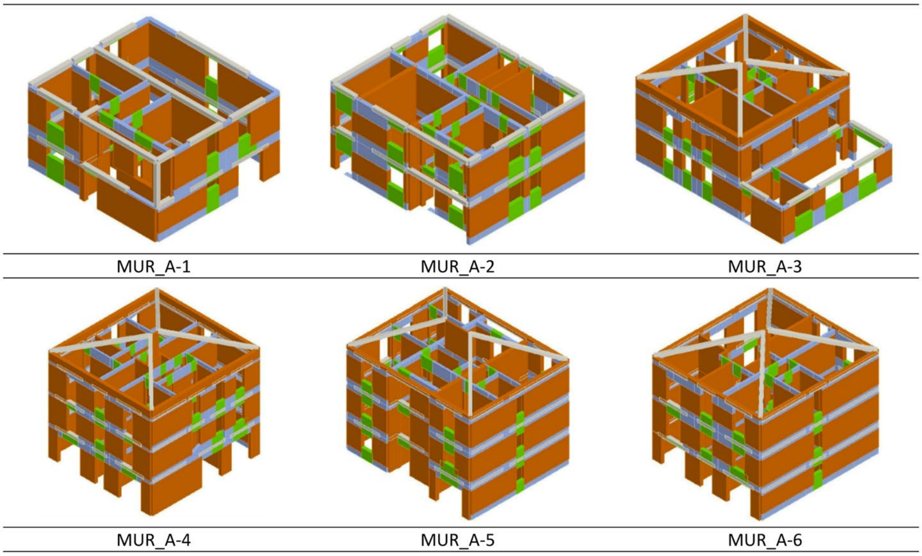
To validate the methodology, six masonry buildings were chosen. These structures consisted of 2 to 4 stories above ground and they were constituted predominantly by clay brick masonry with hollow-core slabs. Built during the second half of the 20th century, they exhibited floor areas ranging from 70 to 170 m^2.

The technical documentation provided by the municipality, including architectural and structural drawings, allowed for the precise digitization of the masonry layouts, ensuring accurate definition of the dimensions of the building and the identification of the structural elements. Furthermore, it facilitated the acquisition of detailed information on the mechanical and construction properties of the buildings, including the composition of slabs, roof systems, and masonry walls. The seismic vulnerability assessment of these buildings was performed using the simplified methodology. In order to validate the reliability of the simplified method, non-linear static analyses were also carried out and results were compared.

3.1 Numerical modelling and non-linear static analyses

For the seismic vulnerability assessment of the six selected masonry buildings, non-linear static analyses were carried out using the 3Muri software (Lagomarsino et al. 2013; Penna et al. 2014), which adopts an equivalent frame modelling approach. These analyses focused exclusively on the global behaviour of the structures, under the assumption that orthogonal masonry walls and horizontal diaphragms are adequately connected, aligning with the assumptions of the simplified methodology, which does not explicitly address local failure mechanisms.

After the accurate geometric modelling of the structures (see Fig. 2), based on the available technical documents, the mechanical properties of masonry were assigned considering the values recommended by the Italian Building Code (MIT 2019) for the specific masonry typologies investigated. Mean values within the suggested ranges were selected, informed by an extensive experimental campaign conducted by the University of Bologna (Ferretti et al. 2019) on similar masonry types: the study revealed that the average shear strength and compressive strength of the examined masonries were consistent with the mid-range values specified in the Code. For the shear resistance, the Turnsek-Cacovic criterion (Turnsek and Cacovic 1971) was selected for consistency with the simplified methodology, which adopts the same failure criterion to describe the diagonal cracking mechanism. Confidence factors,



MUR_A-1 MUR_A-2 MUR_A-3

MUR_A-4 MUR_A-5 MUR_A-6

Fig. 2 Equivalent frame model of the selected buildings: piers are indicated in brown, spandrels in green, rigid links in blue and reinforced concrete elements in grey

Table 1 Average mechanical parameters adopted for the different masonry typologies

Parameter	Solid bricks with lime-based mortar	Hollow bricks with cement-based mortar
Density (kN/m^3)	18	15
Elastic modulus (MPa)	1500	4550
Shear modulus (MPa)	500	1138
Compressive strength (MPa)	3.45	6.50
Shear strength – TC criterion (MPa)	0.09	0.13

to be used when dealing with existing buildings to reduce the mean mechanical properties according to the knowledge level, and partial safety factors are both considered equal to 1. Indeed, the primary aim of these analyses was to evaluate the actual seismic response of the buildings under expected seismic actions. The adopted mechanical parameters are reported in Table 1 for the two masonry typologies characterising the analysed buildings, i.e., solid bricks with lime-based mortar and hollow bricks with cement-based mortar. The buildings feature rigid hollow core slabs and, for each structure, a detailed assessment of the stratigraphy was conducted to ensure precise load estimation and to accurately model the behaviour of the slabs. While a detailed description of the geometry and material properties of each slab is not provided for the sake of brevity, these aspects were thoroughly considered in the development of the numerical models Non-bearing elements, acting as partition walls, were not modelled but considered as dead loads.

For the execution of the pushover analyses, the software enables the application of 24 loading conditions to the structural model, considering two lateral force distributions in both ±x and ±y directions, as well as the accidental eccentricities required by the Italian

Table 2 Software 3Muri results: values obtained for the six buildings in the strong direction

Building code	T $[s]$	V_r $[kN]$	PGA_c $[g]$	PGA_d $[g]$	PGA_c/PGA_d [-]
MUR_A-1	0.202	977	0.440	0.239	1.841
MUR_A-2	0.162	1041	0.488		2.043
MUR_A-3	0.211	1515	0.335		1.403
MUR_A-4	0.267	1642	0.342		1.430
MUR_A-5	0.323	2424	0.288		1.204
MUR_A-6	0.290	1794	0.331		1.385

Table 3 Software 3Muri results: average values obtained for the six buildings in the weak direction

Building code	T $[s]$	V_r $[kN]$	PGA_c $[g]$	PGA_d $[g]$	PGA_c/PGA_d [-]
MUR_A-1	0.227	669	0.288	0.239	1.205
MUR_A-2	0.155	1276	0.443		1.852
MUR_A-3	0.308	787	0.230		0.960
MUR_A-4	0.363	1198	0.270		1.129
MUR_A-5	0.379	1192	0.201		0.843
MUR_A-6	0.380	988	0.201		0.841

Building Code (MIT, 2018, 2019). In general, since a non-uniform mass distribution may cause torsional effects, an accidental mass eccentricity, equal to ± 5% of the floor dimension perpendicular to the direction of the earthquake action, can be then applied to the centre of mass of each storey. The load pattern applied is intended to reflect the distribution of horizontal forces induced by the seismic event: the Standards propose a lateral force distribution proportional to the first mode shape (modal), as well as a load distribution proportional to the masses (uniform).

With the objective of comparing the results of the pushover analyses with the outcomes of the simplified methodology, a limited number of loading conditions was selected for consistency, i.e., a modal load distribution without the accidental mass eccentricity.

Tables 2 and 3 present, for the 6 masonry buildings analysed, the results in terms of fundamental vibration period T, Peak Ground Acceleration capacity PGA_c, demand PGA_d, (PGA_c/PGA_d) ratio and value of resistant shear V_r, evaluated from the capacity curves in correspondence with the displacement associated to the attainment of the Life Safety Limit state. This value is calculated as average from different 4 pushover analyses. With regard to PGA_d, following the indications of the National and International Standard (CEN 1998; MIT, 2018, 2019), the software automatically calculates the design response spectrum as a function of the geographic position of the building and the morphological and stratigraphic characteristics of the soil. For each building, the average values of these parameters are considered. Furthermore, for each building, the difference between strong and weak direction was made based on the value of the resisting shear obtained from the pushover analyses performed in the two directions.

The fundamental vibration periods of the investigated masonry buildings are also reported in Tables 2 and 3, considering the first modes of vibration in strong and weak directions. In view of the application of the simplified methodology (Sect. 3.2), it is worth mentioning that, considering the design response spectrum for the city of Maranello, these period values fall within the region corresponding to constant spectral accelerations.

3.2 Seismic vulnerability using the simplified methodology

For the application of the simplified methodology on the six selected buildings, according to the procedure proposed in Ferretti et al. (2024), the same geometrical and mechanical properties employed in the numerical modelling were considered. To ensure comparability with results from the 3Muri software, the following considerations were made:

- The calculation was kept distinct along the x- and y-directions, i.e., there will be two distinct values for the shear resistance V_r, for the ratio between the resisting and reference acting shear V_r/V_s, spectral acceleration $S_{a,c}$, Peak Ground Acceleration capacity PGA_c and the ratio between capacity and demand PGA_c/PGA_d.
- In the case of coexistence of different masonry typologies in the same building, the shear strength for the evaluation of the resisting shear V_r, according to TC criterion, is calculated as the weighted average of the shear strength of the different masonry typologies, according to the amount of the resistant areas.

The reduction coefficient C_{rid}, used to adjust the conventional capacity to account for the real structural complexity, is derived from GNDT II Level form (Regione Toscana 2003), through the technical documentation provided by the Maranello municipality. Among the parameters to be assessed for the evaluation of the coefficient C_{rid} (see Sect. 2.2), the ones which more significantly affected the structural capacity of the investigated buildings were: (i) the connections between orthogonal walls, (ii) the horizontal structural elements (not always rigid and well connected to the masonry), (iii) the roof typology.

In Tables 4 and 5, the results for strong and weak directions are presented, respectively, in terms of reduction coefficient C_{rid}, Peak Ground Acceleration capacity PGA_c and demand PGA_d, PGA_c/PGA_d ratio and resistant shear V_r. It should be specified that, for the purposes of comparison, the reported value of V_r is that obtained by multiplying it by C_{rid}, while, in the methodology presented, the reduction coefficient is applied only in final step for the calculation of PGA_c.

3.3 Comparative analysis of the results

In this Section, a comparison is presented between the results of the seismic vulnerability analyses for the six selected buildings, obtained with the simplified methodology and with

Table 4 Simplified methodology results: values obtained for the six buildings in the strong direction

Building code	C_{rid} $[-]$	V_r $[kN]$	PGA_c $[g]$	PGA_d $[g]$	PGA_c/PGA_d [-]
MUR_A-1	0.90	1229	0.501	0.239	2.097
MUR_A-2	0.94	1300	0.539		2.257
MUR_A-3	0.90	1198	0.434		1.816
MUR_A-4	0.94	1711	0.331		1.386
MUR_A-5	0.92	1936	0.365		1.527
MUR_A-6	0.93	1747	0.418		1.749

Table 5 Simplified methodology results: values obtained for the six buildings in the weak direction

Building code	C_{rid} $[-]$	V_r $[kN]$	PGA_c $[g]$	PGA_d $[g]$	PGA_c/PGA_d [-]
MUR_A-1	0.90	665	0.338	0.239	1.413
MUR_A-2	0.94	1189	0.494		2.065
MUR_A-3	0.90	890	0.323		1.350
MUR_A-4	0.94	1149	0.270		1.129
MUR_A-5	0.92	1296	0.261		1.093
MUR_A-6	0.93	858	0.205		0.858

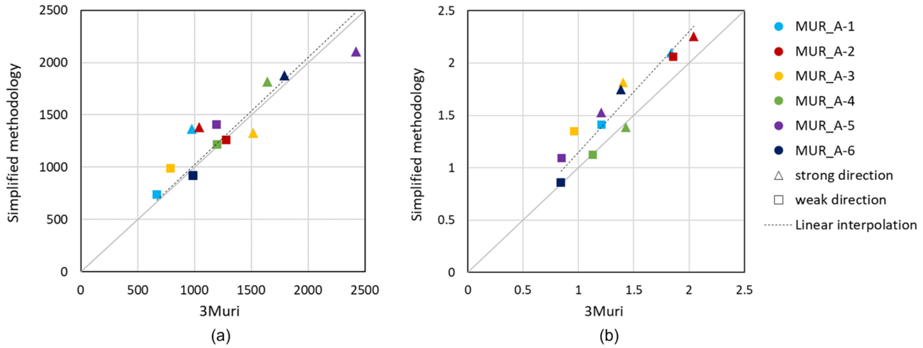


Fig. 3 Comparison between the results obtained through the simplified methodology and 3Muri software in terms of (**a**) V_r and (**b**) PGA_c/PGA_d along the strong and weak direction

the pushover analyses. The comparison confirms the accuracy and reliability of the simplified methodology in predicting the seismic behaviour, focusing on the resistant shear V_r multiplied by C_{rid} and on the ratio between capacity and demand, PGA_c/PGA_d.

Figure 3 shows the comparison of the results obtained for the six buildings along the two directions, highlighting a very good correlation between the two methods. Especially in terms of resisting shear (Fig. 3a), the good estimation, provided by the simplified methodology, is confirmed: it makes use of simple mechanical considerations about the seismic behaviour of the buildings combined with an expert judgement for the evaluation of the reduction coefficient C_{rid}. Looking at the single building results, the slight differences in terms of shear resistance between the simplified methodology and the pushover analysis can be explained considering several factors. First of all, different failure criteria are considered for the resistant elements, since the simplified methodology exclusively evaluates the diagonal cracking failure mode, while the 3Muri software takes also into account the flexural behaviour of the wall. Moreover, in the numerical analyses the actual state of stress on the walls is evaluated, considering the layout of the slab and the variation of axial stress during the seismic analysis. It should also be mentioned that, in the pushover analyses, not all the elements reached their ultimate capacity at the Life Safety limit state. In addition, thanks to the box-like behaviour assumption in the numerical models, wall elements in the direction orthogonal to the seismic action collaborate to the system response, whereas they are disregarded in the simplified approach.

The simplified methodology tends to yield slightly less conservative estimates than those obtained through pushover analyses in terms of ratio between capacity and demand PGA_c/PGA_d (Fig. 3b), consistently with findings from prior studies on masonry buildings (Ferretti et al. 2024). It should be noted that the evaluation of PGA_c is carried out, in the pushover analyses, by considering a displacement-assessment method, while, in the simplified methodology, it is determined from the spectral acceleration, assuming to fall within the constant acceleration part of the response spectrum.

This preliminary validation provided a good foundation for extending the methodology to the entire building stock in Maranello. It is in fact worth remembering that the simplified approach requires a much lower effort and few data to be gathered from the on-site inspections, so confirming its potential for large-scale seismic risk assessment.

4 Application to a case study: Maranello municipality

The municipality considered as the case study for conducting the seismic vulnerability assessment of residential buildings, starting from CARTIS survey, and estimating fragility curves, is the municipality of Maranello. The analysis will cover the entire municipal territory, discussing the predominant residential construction typologies, with a specific focus on masonry buildings to derive fragility curves.

4.1 Territorial analysis and typological identification

Maranello is a small Italian city in the administrative district of Modena (Emilia-Romagna, Italy) counting 17,309 inhabitants (from ISTAT 2022). It is $137\ m$ above sea level with an extension of about $33\ km^2$. The municipality is basically composed by the older city centre, with the most ancient buildings located around the castle, and by the newer part of the city, surrounding the centre. Thanks to an accurate analysis of the territory from a historical point of view, the evolution of the built environment was identified in order to perform the CARTIS surveys, and it was possible to subdivide the municipal area of Maranello into ten homogeneous Sectors, i.e., homogenous area characterized by the presence of similar buildings in terms of typological/construction characteristics and construction age (Fig. 4).

For each Sector, the prevailing masonry building types (MUR) and/or reinforced concrete building types (CAR) were identified. They were populated as shown in Table 6.

From the study and comparison of the structural typologies identified in the municipality, it is evident that some of them, belonging to different Sectors, share the same structural characteristics. For this reason, a further classification is proposed, starting to the identification of prevailing structural typologies over the entire municipality. The present study focused on ordinary masonry buildings and, therefore, the reinforced concrete types are not considered in the following. The four identified masonry typologies, examples of which are given in Fig. 5, are listed below:

- MUR_A0: early 20th century buildings, made of clay brick masonry and hollow-block concrete slabs, having 3 stories above ground and an average floor area in the range of 70 to 130 m^2. This typology was identified by the common characteristics found between MUR 1 of C001 and MUR 1 of C008.

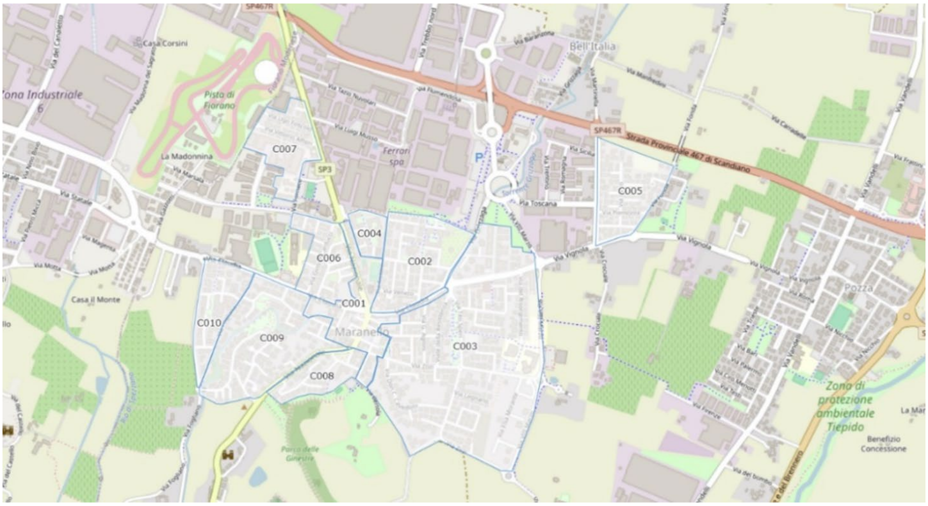


Fig. 4 The ten urban Sectors identified in the municipality of Maranello

Table 6 Distribution of MUR and CAR in the identified sectors

Sector code	Sector name	Building type	Building type code with percentage
C001	Historical centre	MUR	MUR1 (100%)
C002	First expansion	MUR	MUR1 (40%)
		CAR	CAR1 (30%)
			CAR2 (30%)
C003	Second expansion	MUR	MUR1 (35%)
		CAR	CAR1 (60%)
			CAR2 (5%)
C004	Last expansion	CAR	CAR1 (100%)
C005	Crociale district	MUR	MUR1 (50%)
		CAR	CAR1 (20%)
			CAR2 (30%)
C006	City capital	MUR	MUR1 (250%)
		CAR	CAR1 (25%)
			CAR2 (50%)
C007	Ferrari expansion	MUR	MUR1 (60%)
		CAR	CAR1 (40%)
C008	Residential Ferrari Park	MUR	MUR1 (30%)
			MUR2 (70%)
C009	Graziosi district	MUR	MUR1 (25%)
			MUR2 (25%)
		CAR	CAR1 (50%)
C010	La Punta expansion	CAR	CAR1 (100%)

MUR_A0 MUR_A

MUR_B MUR_C

Fig. 5 Buildings examples of the masonry typologies identified in the CARTIS Sectors of Maranello

- MUR_A: buildings of the second half of the 20th century, made of clay brick masonry and hollow-block concrete slabs, having 2 to 4 stories above ground and an average floor area in the range of 70 to 170 m^2. This typology was identified by the common characteristics found between MUR 1 of C002, MUR 1 of C003, MUR 1 of C005, MUR 1 of C006, MUR 1 of C007 and MUR 1 of C009.
- MUR_B: buildings from the second half of the 20th century, made of clay brick masonry and hollow-block concrete slabs, having 3 to 5 stories above ground and an average floor area in the range of 170 to 300 m^2. This typology was identified by the common characteristics found between MUR 2 of C002, MUR 2 of C003 and MUR 2 of C008.
- MUR_C: late 19th – early 20th century buildings, made by stone or brick masonry and wooden floors, having up to 3 stories above ground and an average floor area in the range of 70 to 170 m^2. This typology was identified by the common characteristics found between the MUR 2 of C001 and the MUR 2 of C009.

The percentages of typologies over the number of ordinary masonry buildings are calculated using the CARTIS data: the prevailing typology in Maranello results to be MUR_A (54.90%), followed by MUR_B (24.53%), MUR_A0 (18.13%) and finally MUR_C (3.15%). buildings.

4.2 Application of the simplified methodology on typological buildings

In order to apply the simplified vulnerability assessment methodology, information on a number of selected buildings, representative of the masonry typologies, i.e., MUR_A0, MUR_A, MUR_B, MUR_C, were provided by the Maranello municipality for this study, since more detailed information – with respect to the CARTIS form – were required. In fact, as already mentioned, it was possible to gain access to the archives of the technical department and related documentation. In particular, 40 buildings were examined, belonging to the four types identified: 2 for MUR_A0, 20 for MUR_A, 15 for MUR_B and 3 for MUR_C.

The simplified methodology was applied to all the typologies: the geometrical survey was conducted from the collected technical documents and the mechanical properties were chosen as the mean values of the ranges suggested by the Italian Building Code for the corresponding typologies (see Table 1) (CEN 1998; MIT, 2018, 2019).

In light of the approach outlined earlier, the independent variables to be considered for the definition of the RSs are selected. Consequently, the ratio of resistant area to total area (A_r/A_t) and the average shear strength (τ_0) are identified as the most significant parameters. With reference to the buildings of the most populated typology (MUR_A), Fig. 6 illustrates the dependence of the PGA_c on the two variables for the weak and strong directions. To better analyse the correlation between the capacity and the two independent variables, different symbols are used for low and high values of these parameters (as described in the

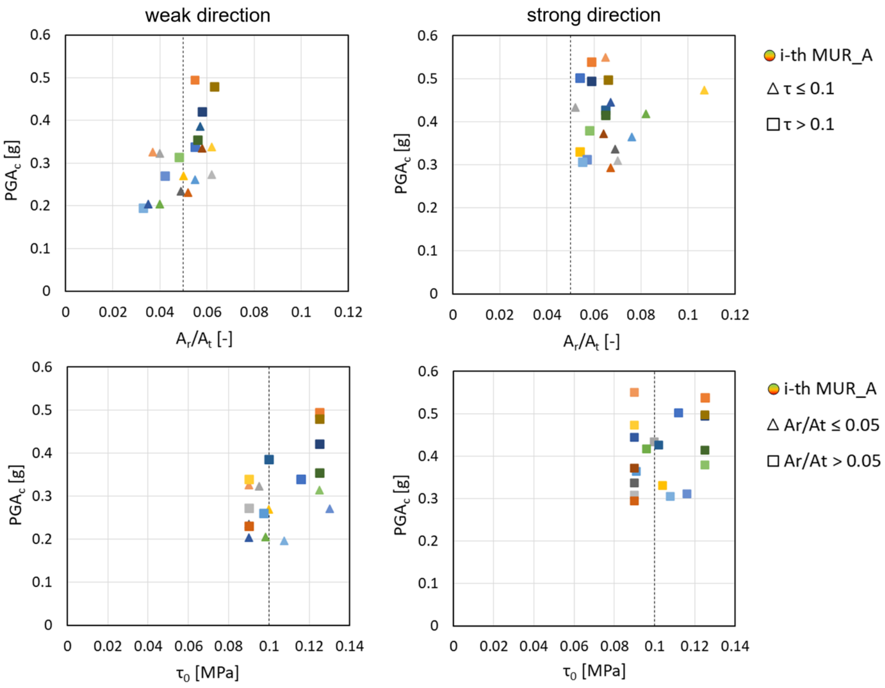


Fig. 6 Dependence of PGA_c on the selected variables for weak and strong directions. Note that buildings from MUR_A-1 to MUR_A-6 are the same as those considered in Sect. 3 for the validation of the methodology

legend of Fig. 5). In general, despite the dispersion of the results, an increasing trend can be noticed in terms of PGA_c vs. A_r/A_t and τ_0. In particular, for the weak direction, fixing a value for the independent variable (either A_r/A_t and τ_0), it can be seen that higher PGA_c values correspond to higher values of the second variable, i.e., the one not directly represented in the considered graph. These observations confirm the fact that the two selected parameters are appropriate for the definition of Response Surfaces.

4.3 Derivation of typological fragility curves

Response surface models are here employed to explore the relationships between PGA_c, derived for buildings analysed using the simplified vulnerability assessment methodology, and independent input mechanical and geometric parameters, i.e., A_r/A_t and τ_0. To establish a unified correlation function, a multiple linear regression model, presented in Sect. 2.3, is utilized. In this framework, $y = PGA_c$ serves as the dependent or response variable, while the independent or predictor variables are defined as $x_1 = \tau_0$ and $x_2 = A_r/A_t$.

Two different correlation functions of increasing complexity are adopted, depending on the number of data available for each typology. In more detail, Eq. (4) is adopted for MUR_A0 and MUR_C and Eq. (5) is used for MUR_A and MUR_B, since they provide the best fitting for the two cases.

$$ln\,(y) \;=\; \beta_1 + \beta_2 \cdot\; ln\,(x_1) + \beta_3 \cdot\; ln\,(x_2) + \epsilon \tag{4}$$

$$ln\,(y) \;=\; \beta_1 + \beta_2 \cdot\; ln\,(x_1) + \beta_3 \cdot\; ln\,(x_2) + \beta_4 \cdot\; ln\,(x_1) \cdot\; ln\,(x_2) + \epsilon \tag{5}$$

where:

- β_1 is the intercept;
- β_2 and β_3 are the coefficients of the first and second characteristics, respectively;
- β_4 is the coefficient of the interaction term;
- ϵ is the zero-mean normal error.

The purpose of multiple linear regression is to determine the best plane or curved surface which interpolates the data, and to do this, the regression coefficients β_i must be estimated for each typology adopted. The choice between the two models proposed in the paper was made considering the best values of the root mean square error (RMSE) and the coefficient of determination (R-squared), even if not for all typologies an ideal value was obtained, due to the small number of data collected in some cases. By means of a Matlab code, the functions are derived for the four prevailing typologies: for each type, the procedure described is repeated for both the weak direction, using parameters giving to the lowest PGA_c and for the strong direction, corresponding to the highest PGA_c. Table 7 provides the values of the coefficients derived for the different functions.

For the derivation of fragility curves for the considered masonry typologies at the LS limit state, the Monte Carlo method was here adopted, as described in Sect. 2.3.2. To determine the failure probability related to specific PGA_d values, each of them was compared with a set of PGA_c, derived from the response surface model by randomly selecting 100’000 samples from log-normal distributions of A_r/A_t and τ_0 parameters. A cumula-

Table 7 Regression coefficients of the multiple linear regression models for each masonry type

Masonry type	weak direction				strong direction			
	β_1 [-]	β_2 [-]	β_3 [-]	β_4 [-]	β_1 [-]	β_2 [-]	β_3 [-]	β_4 [-]
MUR_A0	0	1.02	-0.45	-	0	0.51	-0.02	-
MUR_A	26.93	11.28	8.87	3.53	10.71	4.59	3.69	1.44
MUR_B	11.85	4.73	4.09	1.46	30.86	13.99	10.69	4.68
MUR_C	4.80	1.76	0.55	-	2.64	1.16	0.33	-

Table 8 Mean μ_{ln} and standard deviation σ_{ln} of the fragility curves for MUR_A0, MUR_A, MUR_B and MUR_C, considering both directions

Masonry type	weak direction		strong direction	
	μ_{ln}	σ_{ln}	μ_{ln}	σ_{ln}
MUR_A0	-1.231	0.167	-1.161	0.070
MUR_A	-1.202	0.232	-0.890	0.121
MUR_B	-1.259	0.166	-1.040	0.107
MUR_C	-1.472	0.231	-1.290	0.206

tive log-normal distribution function was then used to define the fragility curve, so obtaining the parameters μ_{ln} (mean) and σ_{ln} (standard deviation) for each masonry typology (Table 8). Figure 7 reports graphs, constructed by combining both fragility curves, i.e., the one obtained from the weakest and strongest results, providing a possible range of fragility curves at LS limit state.

By comparing the results obtained for the case study, it can be deduced that the most vulnerable masonry type in the municipality is the masonry identified as MUR_C, followed by MUR_A0, MUR_B and MUR_A. In fact, the MUR_C typology is characterized by older buildings with load-bearing masonry made of stones and bricks, whereas the MUR_A typology is composed by more recent buildings, with a load-bearing structure composed by solid or hollow clay bricks. Therefore, the Sectors of the municipality with the highest percentage presence of MUR_C and MUR_A0 typology will be the most vulnerable in the event of an earthquake.

Additionally, it can be noted that for MUR_A0, the available starting data are insufficient, and this have led to a result affected by high level of uncertainty, as shown, for example, by the unrealistic intersection of the two curves in Fig. 7a. The issue can be overcome by collecting data for additional case study buildings. Moreover, the importance of sample size should be emphasized. In particular, a sample comprising fewer than 15 buildings, as in the case of MUR_B, may not produce sufficiently reliable results. Increasing the number of case studies would contribute to improving the robustness and reliability of the analysis. The comparison with other fragility curves from literature is not here reported since it may not be completely coherent; indeed, the underlying methodology and assumptions considered are different respect to most of literature approaches. Moreover, the fragility curves here calibrated refer to a single damage level, which limits the extent of direct comparisons with models developed for multiple and differently defined damage states.

Starting from the fragility curves of the prevailing types of masonry in the municipality, the fragility curves of the individual Sectors were evaluated, based on the initial CARTIS survey: a matrix, indicating the correspondence between the percentage data of the CARTIS typologies in each Sector and the four identified prevailing types, was created. Then, the approach proposed by Shinozuka et al. (2000), described in Sect. 2.4, was adopted in order

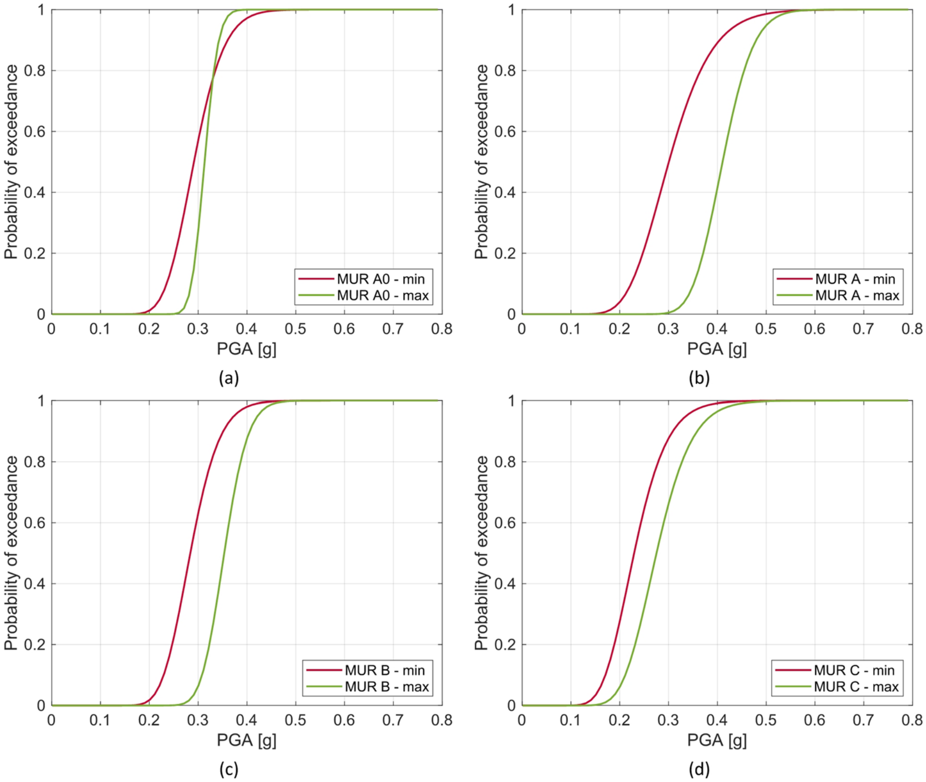


Fig. 7 Fragility curves obtained for (**a**) MUR_A0, (**b**) MUR_A, (**c**) MUR_B and (**d**) MUR_C for the weakest (min in red) and strongest (max in green) directions

to combine the typological fragility curves for each Sector, using percentage data, keeping the distinction between directions. It should be noted that Sector C004 and Sector C010 were not studied since they were only characterized by ordinary RC buildings (see Table 6). Obviously, in Sectors where there was only one masonry type, the two fragility curves concede with the ones obtained for that type, since no combination was calculated, e.g., Sector C005, C006 and C007.

The fragility curves for all Sectors are shown in Fig. 8 for strongest (a) and weakest (b) directions. From the results obtained and the comparisons made between the curves, it was evident that the most vulnerable Sector in the municipality of Maranello is Sector C001, followed by Sector C008, Sectors C002 and C003 and then Sectors C005, C006, C007 and C009. This is confirmed by the fact that Sector 1 is located in the historic city centre and it is characterized by the oldest buildings, with a mixed stone and brick load-bearing structures, and deformable wooden floors. The Sector C008 is also highly vulnerable: it is adjacent to the historic city centre and it is characterised by buildings with characteristics similar to the ones of Sector C001, but also by large villas with porticoes and loggias. Sectors C005, C006, C007 turn out to be less vulnerable: the prevailing masonry typology is MUR_A, characterised by more recent buildings with load-bearing structure in solid or hollow bricks, and cast-in-place concrete slabs. As a general remark, it can be observed that all the Sectors

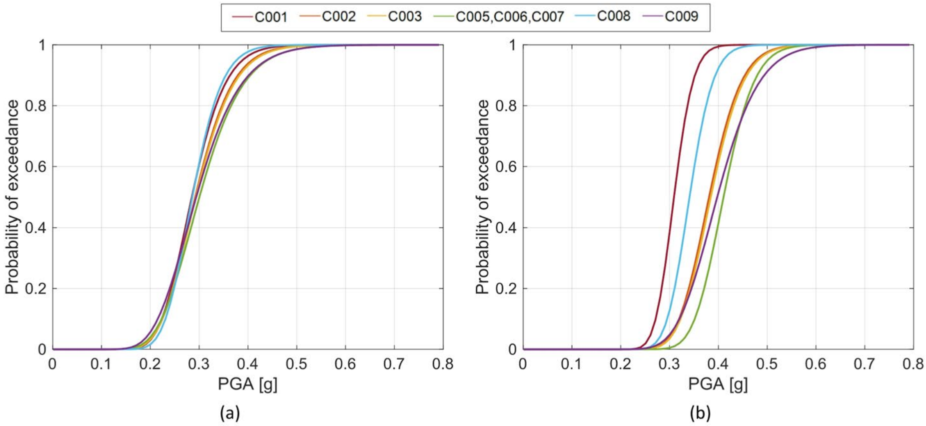


Fig. 8 Combined fragility curves for all Sectors considering (**a**) weak and (**b**) strong direction. The missing Sectors do not contain masonry typologies

characterised by a greater percentage of MUR_C and MUR_A0 types are the most vulnerable with respect to the seismic action; conversely, those with a prevalence of MUR_A and MUR_B types are less vulnerable.

5 Conclusions

In this paper, a procedure for the large-scale seismic vulnerability assessment of residential masonry buildings is proposed. With the objective of evaluating fragility curves for large building stocks, the procedure is based on the 1st level CARTIS form for the characterization of buildings belonging to a municipality, leveraging the expertise of local technicians for subdividing the studied area into homogeneous Sectors. After the identification of typological buildings, the procedure is based on the application of a simplified methodology for determining the seismic capacity of single buildings at the Life Safety limit state and, then, on the definition of response surfaces for correlating the structural capacity thus determined, expressed in terms of Peak Ground Acceleration (PGA), with relevant structural and geometrical parameters, such as the wall resisting area and shear strength. Fragility curves can then be derived through Monte Carlo simulations, and the overall fragility of the CARTIS Sectors can be evaluated by combining the fragility curves obtained for the individual typologies.

After a validation of the simplified methodology through comparison with results of pushover analyses performed on six masonry buildings, the proposed procedure was applied to the case study of the municipality of Maranello, located in the Emilia-Romagna Region, obtaining ranges of fragility curves for the building stocks of the different Sectors. The procedure represents a promising and valuable tool, applicable with a limited effort on large building stocks, for supporting stakeholders and decision-makers in defining priorities and initial actions for seismic risk mitigation on a regional scale.

The present work illustrated the application of a rapid seismic risk assessment methodology to a representative case study. Ongoing developments are directed towards enriching the building inventory with more detailed and comprehensive data, with the objective of increasing the statistical reliability and precision of the resulting fragility curves. Furthermore, the extension of the analysis to include additional structural typologies, also beyond masonry buildings, is deemed essential to capture a broader spectrum of seismic vulnerability within the investigated area. Future enhancements will also focus on integrating supplementary failure mechanisms previously neglected in the modelling framework and on the formulation of fragility functions for a wider range of damage states, thereby improving the resolution and applicability of the assessment for risk-informed decision-making and resilience planning.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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