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Vulnerability and casualty of an existing urban compound in Lisbon

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The proposed research examines seismic vulnerability and consequent losses in Baixa Pombalina, a suburban compound of Lisbon's historic center (Portugal), using an index-based approach specific for unreinforced masonry structures (URM) placed in aggregate conditions. A comprehensive exposure model was developed by combining satellite remote sensing, GIS software, census statistics, historical data, and an external field survey to determine the key features of the identified structural units (S.U.). The vulnerability analysis is conducted using a multi-criteria decision-making technique, MCDM. Specifically, the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) have been used. The primary outcomes are provided in terms of damage scenarios, damage probability matrices, fragility curves, and mean damage ratio curves for the examined vulnerability classes. Next, economic losses are calculated in terms of direct economic losses. Finally, the loss estimate is completed by calculating the number of collapsed and unusable structures as well as fatalities and homelessness.

Keywords: Seismic vulnerability, index-based methods, damage estimation, loss estimation; collapsed and unusable buildings, casualties.

1. Introduction

The protection of cities against seismic events is still an ongoing topic, as strong events, including recent ones, have resulted in significant human and economic repercussions underscoring the importance of making communities more robust to disasters (Oliveira et al. 2024). Improving earthquake resistance is especially important in historic city centers, which have great economic and cultural value. The topic is complex because they are characterized by old masonry buildings vulnerable to earthquakes and difficult to analyze given their articulated configuration, frequently placed in aggregate condition, for which it is difficult to know the geometric and material properties (Mascheri et al. 2024; Chieffo et al. 2022). Large-scale seismic vulnerability assessment is difficult, and empirical methods are most useful to provide simple tools for decision makers, such as municipalities, to reduce and manage disaster risks, since they can rapidly yet properly evaluate vulnerability across a larger sample (Chieffo et al. 2021). The vulnerability index method (VIM) proposes a continuous approach for evaluating vulnerability based on building structural attributes, which are then weighted and summed up to produce an overall vulnerability index that is then linked to a damage grade calculated using vulnerability functions calibrated with statistical data from observed damage (Vicente et al. 2011; Chieffo et al. 2022). In this context, this study intends to assess the seismic risk of ordinary unreinforced masonry (URM) structures in Lisbon's historic center using an index-based methodology that applies a rigorous and repeatable multi-criteria-decision-making (MCDM) approach.

2. Baixa Pombalina area

The study area (Baixa Pombalina) is in the heart of Lisbon and has considerable economic and cultural importance (see Fig. 1). Indeed, in addition to being a popular tourist destination, it is also known for being completely destroyed by the 1755 earthquake, which was followed by a tsunami and fires, and then rebuilt with the introduction of the "Pombalino" structural typology, which was distinguished by several features related to improving seismic performance, the most notable of which was the introduction of the Gaiola Pombalina (pombalino cage), (Mascheri et al. 2024; Lopes et al. 2014). Indeed, these structures consist of a series of internal walls formed of triangular timber frames filled with low-quality masonry known as "frontal walls," which are connected at the corners by vertical wood bars from the orthogonal frontal walls. The façades and walls between adjacent buildings are normally made with regular rubble stone masonry, while the floors are created with a system of wood joists and perpendicular wood boards, which are usually supported by the façade and frontal walls (Lopes et al. 2014; Mascheri et al. 2024).

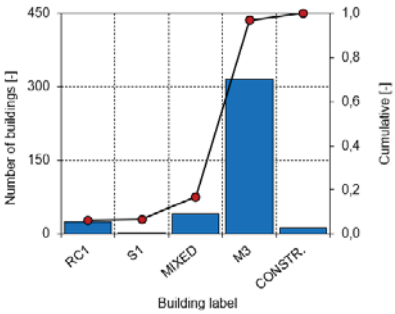
Fig. 1. The case study area in Lisbon city center.

The first step in the evaluation was to define the exposure model by creating a strong and reliable database of buildings characteristics using various resources, including literature review, Google Maps, external building inspections using the QField app (QField, n.d.), municipality data, historical documentation, and census data, which, thanks to the versatile use of QGIS (QGIS, n.d.), allowed for efficient data management.

In the area of interest, 420 structural units (S.U.) have been identified, with 6% (25 buildings) identified as non-ordinary buildings (such as churches, museums, shopping malls, etc.) and thus omitted from analysis. The remaining 395 ordinary buildings show that 80% (315 buildings) are masonry type (M3), with the remaining 20% (80 buildings) being non-masonry buildings such as RC1, S1, MIXED, and under construction (CONSTR.), see Fig. 2a. The definition of the aforementioned building typologies was necessary given the introduction of many interventions to buildings throughout history (Mascheri et al. 2024; Lopes et al. 2014). In this context, recent studies have further investigated the seismic performance of masonry aggregates, analyzing the effects of localized retrofitting on individual structural units (Vaiano 2025), comparing equivalent frame and block-based modeling approaches for historic masonry (Fabbrocino et al. 2024), and assessing the response of typological residential buildings under ground settlements (Vaiano et al. 2024).

With the exception of MIXED structures, which the authors had to include because of the existence of buildings that have an internal vertical structure made of steel or reinforced concrete that works with the external masonry load-bearing walls, these categories resemble those specified in the Risk-UE methodology (Milutinovic and Trendafiloski 2003).

Many attributes of the 315 ordinary URM buildings have been collected and analyzed, as shown in Fig. 2b, where the majority of ordinary URM buildings, 96%, have between 5 and 7 floors, 2% have less than 5 floors, and 2% have more than 7 floors.



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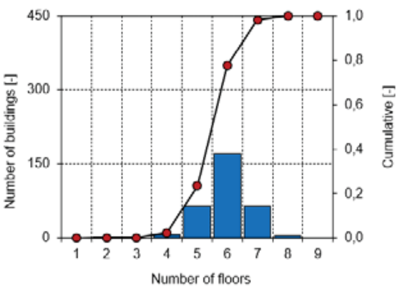


(b)

Fig. 2. Example of evaluation of building's attributes: a) Building typology; b) Number of floors.

Lastly, the buildings' monetary exposure is evaluated considering all levels above ground and multiplying the market value per unit area [€/m^2] by the building footprint area [m^2]. The market value has been set at 6400 €/m^2 for commercial areas and 3950 €/m^2 for residential areas according to census data in (INE 2023a, 2023b).

3. Vulnerability

3.1. *Parameters selection and MCDM analysis*

The Analytic Hierarchy Process (AHP) was used to determine classes scores and parameters weights, since it calculates the relative relevance of each criterion via a series of pairwise comparisons, allowing subjective judgements on a range of 1 (equal preference) to 9 (extreme preference) to be transformed into quantitative values, please refer to (Pathan et al. 2022; Mascheri et al. 2024) for more information on AHP. The results have been found, and the consistency of judgements has been checked using the consistency ratio (CR). Table 1 displays the weights of the 14 indicators selected through a thorough review of the literature.

Table 1. AHP results for parameters weights.

Nr.	Parameter	Weight
1.	Nature of vertical structures	0.080
2.	Conventional strength	0.099
3.	Topographic condition	0.034
4.	Number of floors	0.045
5.	Horizontal diaphragms	0.083
6.	In-plane regularity	0.062
7.	Vertical regularity	0.055
8.	Wall façade openings and alignments	0.082
9.	Presence of adjacent buildings with different height	0.055
10.	Position of the building in the aggregate	0.077
11.	Structural or typological heterogeneity among adjacent structural units	0.052
12.	Percentage difference of opening areas among adjacent façades	0.049
13.	Conservation status	0.178
14.	Aggregate distance	0.049

3.2. *Seismic vulnerability assessment*

Then, based on the assumption that the optimum solution has the smallest distance from the positive ideal solution, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was used to calculate the vulnerability index (I_V) of each building and rank them from most to least vulnerable (Mascheri et al. 2024). Moreover, the European macroseismic approach (Milutinovic and Trendafiloski 2003; Lagomarsino and Giovinazzi 2006) was used to calculate the mean damage grade (μ_D) for a certain intensity measure based on the vulnerability index (V).

However, in order to calculate V, the MCDM vulnerability index (I_V), which is based on the core parameters of the GNDT methodology (GNDT 1993), should be translated into the macroseismic vulnerability index (V) (Vicente et al. 2011). Therefore, the authors, based on methodology explained in (Vicente et al. 2011), derived a GNDT-Macroseismic correlation by comparing vulnerability curves for the mean of each damage grade (μ_{D1}=0.5, μ_{D2}=1.5, μ_{D3}=2.5, μ_{D4}=3.5, μ_{D5}=4.5), in the following equation (Mascheri et al. 2024):

$$V=0.6125+0.008\ I_V \tag{1}$$

The I_V calculated for all 315 URM buildings was reported on a scale of 0-100 to maintain consistency with the GNDT scale, and the conversion into vulnerability index (V) was conducted using Eq. (1). Results show that 3 buildings have V between 0.6-0.7, 260 buildings between 0.7-0.8, 19 buildings between 0.8-0.9, and 33 buildings more than 0.9. Finally, the vulnerability index (V) may be assigned a macroseismic vulnerability class according to the EMS-98 scale (Grünthal 1998), which for masonry structures typically can be classified as: A (V≥ 0.88), B (0.72 ≤ V < 0.88), or C (0.56 ≤ V < 0.72), based on (Bernardini et al. 2007; Kassem et al. 2020). This, allowed to classify the building sample as follows: 33 buildings belong to vulnerability class A ($V_{mean,A}$=0.99), 252 buildings to class B ($V_{mean,B}$=0.76), and 30 buildings to class C ($V_{mean,C}$=0.71).

3.3. *Damage and fragility assessment*

DPMs and fragility curves were evaluated by calculating the predicted damage of each building using μ_D, as follows (Lagomarsino and Giovinazzi 2006):

$$\mu_D = 2.5 \times \left[1 + \tanh\left(\frac{I + 6.25\,V - 13.1}{Q}\right)\right] \tag{2}$$

where V is the vulnerability index, and Q is a ductility factor assumed equal to 2.3 (Lagomarsino and Giovinazzi 2006). The macroseismic intensity (I) has been defined for different return periods through the empirical formulae reported in (Lantada et al. 2018), considering as input value the expected PGA of 0.17g (in rock) for Lisbon Metropolitan Area, which is associated with a return period, T_r, of 475 years (IPQ 2010), and allow to establish PGAs for other return periods, later transformed into macroseismic intensity.

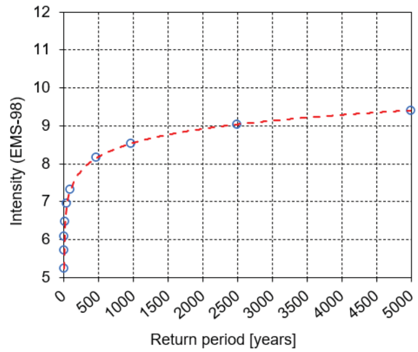
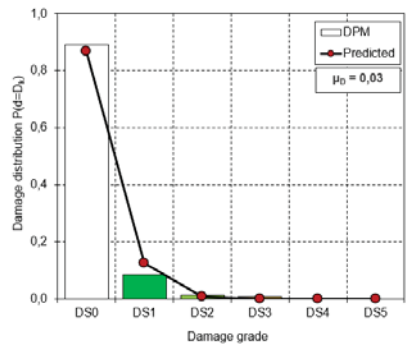


Fig. 3. EMS-98 intensity values for return periods.

Fig. 3 shows the evaluation for 2-5-10-20-50-100-475-975-2500 and 5000-year return periods. Then, μ_D results have been divided into six damage grades (Grünthal 1998): DS0 ($\mu_D \leq$ 0.5); DS1 (0.5 < $\mu_D \leq$ 1.0); DS2 (1.0 < $\mu_D \leq$ 2.0); DS3 (2.0 < $\mu_D \leq$ 3.0); DS4 (3.0 < $\mu_D \leq$ 4.0) and DS5 (4.0 < $\mu_D \leq$ 5.0). Thus, the damage distribution has been defined using the Damage Probability Matrices (DPMs), as indicated in (Chieffo et al. 2022).



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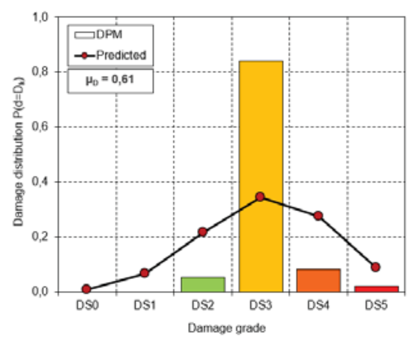

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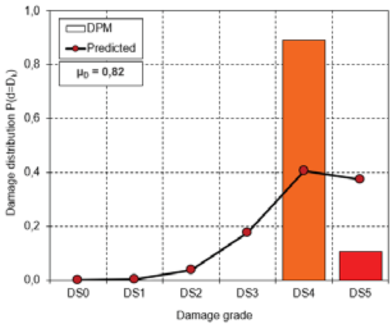


(c)

Fig. 4. DPMs: a) 2-year; b) 475-year; c) 5000-year.

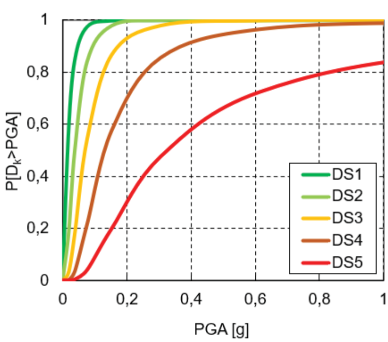
DPMs were evaluated for each scenario under consideration, however, only the 2-475-5000-year DPMs have been reported in Fig. 4.

The vulnerability of the analyzed area was also evaluated using fragility curves, which relate the probability of exceeding a certain damage level to the ground motion measure. These curves were created by combining the binomial distribution (p_k) with the cumulative probability mass function, as described in (Chieffo et al. 2022):

$$P(D_i \geq D_k|I) = \sum_{k=1}^{5} p_k \qquad (3)$$

The ground motion measure has been expressed in terms of PGA by considering the correlation between macroseismic intensity and PGA in (Lantada et al. 2018) previously introduced.

Fig. 5 shows the evaluated fragility curves for the defined vulnerability classes.



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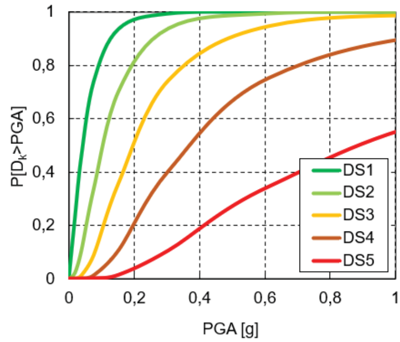

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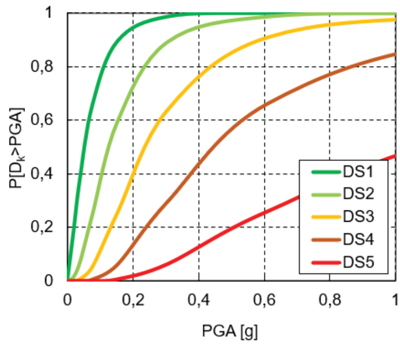


(c)

Fig. 5. Fragility curves for the identified vulnerability classes: a) Class A; b) Class B; c) Class C.

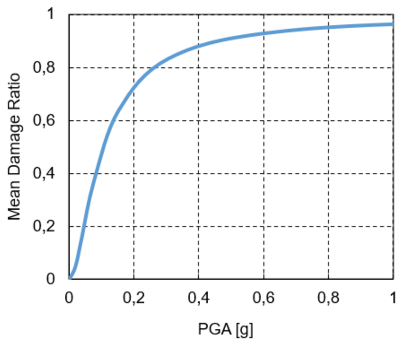
4. Risk

4.1. *Loss assessment*

The direct economic losses were quantified using the Mean Damage Ratio (MDR), which is determined by multiplying the probability of each damage state $P(DS_k|I)$ by the corresponding damage ratio DR_{DSk} (Nassirpour 2018):

$$MDR_{DS|I} = \sum_{DS=1}^{k} P(DS_k|I) \times DR_{DS_k} \qquad (4)$$

The damage ratio is the ratio of a building's repair cost to its replacement value determined for each damage state, also known as Damage-to-Loss model (Nassirpour 2018). Many models are available in literature based on expert opinion or empirical post-earthquake data, however the model used in this study is (Roca et al. 2006): DS1=0.01; DS2=0.2; DS3=0.4; DS4=0.8; DS5=1. With this approach, the MDR curves for each class (A, B, and C) may be generated, as illustrated in Fig. 6.



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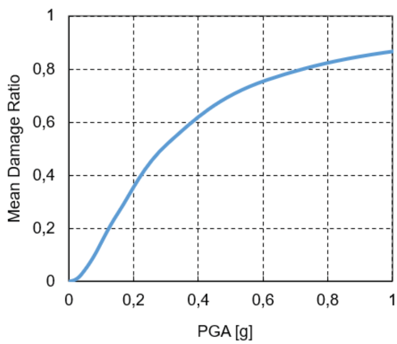

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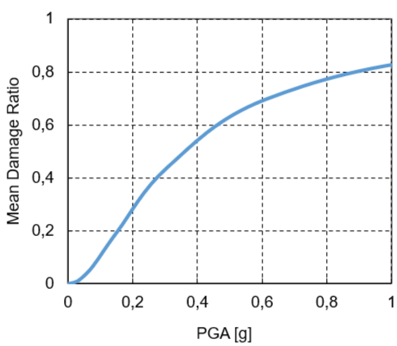


(c)

Fig. 6. MDR curves for the identified vulnerability classes: a) Class A; b) Class B; c) Class C.

Lastly, according to (Nassirpour 2018), the expected consequences can be calculated in terms of monetary losses by multiplying the MDR by the replacement value of the buildings. However, the market value was utilized instead to assess the exposure, as defined in Section 2, because of a lack of data.

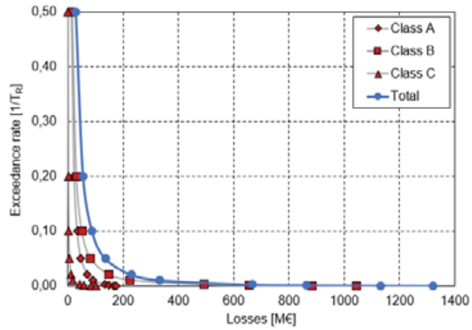


Fig. 7. LEC curve.

Fig. 7 shows the risk LEC curve, that relates the losses, in millions of euros, to the exceedance rate ($1/T_R$). It is possible to see that for longer return periods building losses are higher: 30 M€ for 2-year, 669M€ for 475-year, 1321M€ for 5000-year.

4.2. *Collapsed and unusable buildings*

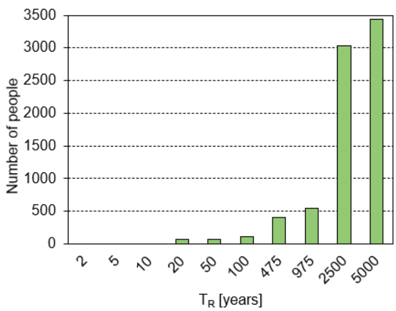
There are various empirical formulas in the literature for calculating the number of collapsed and unusable buildings; however, the ones presented in (Chieffo et al. 2021) have been used in the current paper. Results are displayed in Table 2.

Table 2. Collapsed and unusable buildings.

T_R [years]	Collapsed buildings [nr.]	Unusable buildings [nr.]
2	0 (0%)	4 (1%)
5	0 (0%)	19 (6%)
10	0 (0%)	20 (6%)
20	3 (1%)	26 (8%)
50	3 (1%)	155 (49%)
100	5 (2%)	187 (59%)
475	17 (5%)	185 (59%)
975	23 (7%)	184 (58%)
2500	129 (41%)	169 (54%)
5000	146 (46%)	169 (54%)

4.3. *Deaths and homelessness*

The analysis of collapsed and unusable buildings allows for a simplified estimation of fatality rates (the number of deaths and severely injured) as well as homelessness. Formulations from (Chieffo et al. 2021) have been used. However, unlike Chieffo's proposal, which uses the total number of residents, given the type of data available and the more touristy nature of the area, the number of residents, of beds in hotels and of users of touristic apartments was used, for a total number of people involved equal to 9304. Given the typology of data available regarding the people staying in the buildings, the total number of analyzed buildings are all ordinary buildings including non-masonry typologies (395).



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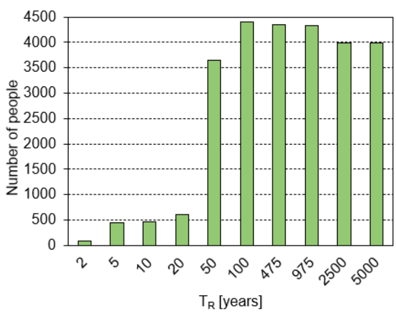

(b)

Fig. 8. Number of people involved: a) Deaths and injuries; b) Homelessness.

5. Conclusion

The proposed manuscript used an index-based approach to assess the seismic vulnerability and risk of typical unreinforced masonry (URM) structures in Lisbon's historic district Baixa Pombalina. The study enhances the methodology and allows it to be easily adapted and repeated in various contexts. Main results about vulnerability show that 3 buildings have macroseismic vulnerability index between 0.6-0.7, 260 buildings between 0.7-0.8, 19 buildings between 0.8-0.9, and 33 buildings more than 0.9. Direct economic losses result to be higher for longer return periods: 30 M€ for 2-year, 669M€ for 475-year, 1321M€ for 5000-year. In terms of collapsed and unusable buildings for 2-year return period no are buildings collapsed and 4 buildings are unusable, for 475-year 17 buildings collapsed and 185 are unusable while for 5000-year 146 are collapsed and 169 unusable.

6. Discussion

This study is the first step toward a large-scale assessment of seismic vulnerability and earthquake casualties. The suggested methodology can assist decision makers in developing risk mitigation plans, particularly when available data on earthquake damage is limited. However, some limitations emerge, particularly due to the lack of data on previous seismic events and the current reliance on remote data for building attributes, despite the improvement achieved through the involvement of the Lisbon City Council. Furthermore, the MCDM approach relies on subjective judgments, meaning the resulting "optimal" solution can reflect the preferences of the decision-makers rather than being entirely objective. Additionally, the estimation of collapsed or unusable structures, as well as casualties and homelessness, is based on simplified empirical formulations that could be enhanced with additional data. For instance, various studies adopted (Vicente et al. 2011; Manfredi et al. 2023) incorporate factors such as the percentage of occupants at the time of the earthquake, which could be integrated to further refine this method in future developments.

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References

Bernardini, A., S. Giovinazzi, S. Lagomarsino, and S. Parodi (2007). Vulnerabilità e Previsione Di Danno a Scala Territoriale Secondo Una Metodologia Macrosismica Coerente Con La Scala EMS-98. *Proceedings of the 12th Italian Conference on Earthquake Engineering-ANIDIS*, June 2007, Pisa (Italy). Available online: http://hdl.handle.net/10092/4060. Accessed May 2024.

Chieffo, N., A. Formisano, R. Landolfo, and G. Milani (2022). A Vulnerability Index Based-Approach for the Historical Centre of the City of Latronico (Potenza, Southern Italy). *Engineering Failure Analysis* 136: 106207. https://doi.org/10.1016/j.engfailanal.2022.106207

Chieffo, N., A. Formisano, and T. M. Ferreira (2021). Damage Scenario-Based Approach and Retrofitting Strategies for Seismic Risk Mitigation: An Application to the Historical Centre of Sant'Antimo (Italy). *European Journal of Environmental and Civil Engineering* 25 (11): 1929–48. https://doi.org/10.1080/19648189.2019.1596164.

Fabbrocino, F., C. Olivieri, R. Luciano, G. Vaiano, G. Maddaloni, and A. Iannuzzo (2024). Seismic Performance of Historic Masonry Buildings: A Comparative Analysis of Equivalent Frame and Block-Based Methods. Alexandria Engineering Journal 109: 359–375.

GNDT (1993). *Rischio Sismico Di Edifici Pubblici–Parte I: Aspetti Metodologici*. Centro Servizi Quasco, Bologna (Italy).

Grünthal, G. (1998). *European Macroseismic Scale 1998*. Cahiers Du Centre Européen de Géodynamique et de Séismologie, Vol. 15. Conseil De l'Europe, Luxembourg.

INE (2023a). *Valor Mediano Das Vendas Por M2 de Alojamentos Familiares Nos Últimos 12 Meses (€) Por Localização Geográfica (NUTS - 2013) e Categoria Do Alojamento Familiar; Trimestral - INE, Estatisticas de Preços Da Habitação Ao Nível Local. Período de Referência Dos Dados 4o Trimestre de 2023. Instituto Nacional de Estatística, IP - Portugal.* https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_indicadores&indOcorrCod=0011364&contexto=bd&selTab=tab2. Accessed April 2025.

INE (2023b). *Volume de Vendas Médio Por M2 de Área de Exposição e Venda (€) Nas Unidades Comerciais de Dimensão Relevante Por Localização Geográfica (NUTS - 2013) e Setor de Atividade Económica; Anual - INE, Inquérito Aos Estabelecimentos Comerciais - Unidades Comerciais de Dimensão Relevante. Período de Referência Dos Dados 2023. Instituto Nacional de Estatística, IP - Portugal.* https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_indicadores&indOcorrCod=0006950&contexto=bd&selTab=tab2. Accessed April 2025.

IPQ (2010). Eurocódigo 8 – *Projecto de estruturas para resistência aos sismos. Parte 1: Regras gerais, acções sísmicas e regras para edifícios, NP EN 1998-1:2010.* Instituto Português Da Qualidade (IPQ), Caparica (in Portuguese).

Kassem, M. M., F. M. Nazri, and E. N. Farsangi (2020). The Seismic Vulnerability Assessment Methodologies: A State-of-the-Art Review. *Ain Shams Engineering Journal* 11 (4): 849–64. https://doi.org/10.1016/j.asej.2020.04.001.

Lagomarsino, S., and S. Giovinazzi (2006). Macroseismic and Mechanical Models for the Vulnerability and Damage Assessment of Current Buildings. *Bulletin of Earthquake Engineering* 4 (4): 415–43. https://doi.org/10.1007/s10518-006-9024-z.

Lantada, N., L.G. Pujades, and A.H. Barbat (2018). Earthquake Risk Scenarios in Urban Areas: A Review with Applications to the Ciutat Vella District in Barcelona, Spain. *International Journal of Architectural Heritage* 12 (7–8): 1112–30. https://doi.org/10.1080/15583058.2018.1503367.

Lopes, M., H. Meireles, S. Cattari, R. Bento, and S. Lagomarsino (2014). *Pombalino Constructions: Description and Seismic Assessment*. In Costa, A., Guedes, J., Varum, H. (Eds) Structural Rehabilitation of Old Buildings. Building Pathology and Rehabilitation, edited by Aníbal Costa, João Miranda Guedes, and Humberto Varum, vol. 2. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-39686-1_7.

Manfredi, V., G. Nicodemo, and A. Masi (2023). Estimation of Human Casualties Due to Earthquakes: Overview and Application of Literature Models with Emphasis on Occupancy Rate. *Safety* 9 (4). https://doi.org/10.3390/safety9040082.

Mascheri, G., N. Chieffo, and P. B. Lourenço (2024). Multi-Attribute-Based Procedure for Seismic Loss Scenario in a Historical Area. *Bulletin of Earthquake Engineering* 22: 7323–7358, https://doi.org/10.1007/s10518-024-02029-1.

Milutinovic, Z. V., and G. S. Trendafiloski (2003). *Risk-UE An Advanced Approach to Earthquake Risk Scenarios with Applications to Different European Towns*. Contract: EVK4-CT-2000-00014, WP4: Vulnerability of Current Buildings, 110. Available online: http://www.civil.ist.utl.pt/~mlopes/conteudos/DamageStates/Risk%20UE%20WP04_Vulnerability.pdf. Accessed July 2025.

Nassirpour, A. (2018). *Performance Based Seismic Assessment of Masonry Infilled Steel Frame Structures*. Doctoral Dissertation, UCL (University College London). Available online: https://discovery.ucl.ac.uk/id/eprint/10052986. Accessed December 2025

Oliveira, C. S., M. A. Ferreira, and H. O'Neill (2024). 'The Role of Video Cameras and Emerging Technologies in Disaster Response to Increase Sustainability of Societies: Insights on the 2023 Türkiye–Syria Earthquake. *Sustainability* 16 (17). https://doi.org/10.3390/su16177618.

Pathan, A. I., P. G. Agnihotri, S. Said, and D. Patel (2022). AHP and TOPSIS Based Flood Risk Assessment- a Case Study of the Navsari City, Gujarat, India. *Environmental Monitoring and Assessment* 194 (7): 509. https://doi.org/10.1007/s10661-022-10111-x.

QField (n.d.). OPENGIS.ch. n.d. QField. V. 3.3.11 - Darién (f59b22 v3.3.11), Qt 6.6.3. https://qfield.org/.

QGIS (n.d.). QGIS.org, %%Y. QGIS Geographic Information System. QGIS Association. n.d. QGIS. V. 3.36.3-Maidenhead. http://www.qgis.org.

Roca, A., X. Goula, T. Susagna, J. Chávez, M. González, and E. Reinoso. 2006. A Simplified Method for Vulnerability Assessment of Dwelling Buildings and Estimation of Damage Scenarios in Catalonia, Spain. *Bulletin of Earthquake Engineering* 4 (2): 141–58. https://doi.org/10.1007/s10518-006-9003-4.

Vaiano, G. (2025). Seismic Performance of Irregular Masonry Aggregates: Effects of Localized Retrofitting on Individual Structural Units. International Journal of Space Structures 40 (2–3): 125–142.

Vaiano, G., S. Belliazzi, C. Olivieri, G. Ramaglia, F. Fabbrocino, and A. Miano (2024). Assessment of Typological Residential Masonry Building Under Vertical Ground Settlements. Conference presentation, GIMC SIMAI YOUNG 2024, Naples, Italy.

Vicente, R., S. Parodi, S. Lagomarsino, H. Varum, and J. A. R. Mendes Silva (2011). Seismic Vulnerability and Risk Assessment: Case Study of the Historic City Centre of Coimbra, Portugal. *Bulletin of Earthquake Engineering* 9 (4): 1067–96. https://doi.org/10.1007/s10518-010-9233-3.