Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2023) 5229-5241

ECCOMAS Proceedia

COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-14 June 2023

SEISMIC FRAGILITY AND EXPECTED DAMAGE OF MASONRY SCHOOL BUILDINGS IN ITALY

Elisa Saler[1] **and Francesca da Porto**[1]

[1] Department of Geosciences, University of Padova
Via Gradenigo 6, 35131 Padova, Italy
e-mail: {elisa.saler, francesca.daporto}@unipd.it

Abstract

The relevance of school buildings in the response of a community to a seismic event is well-known, and it was observed in the aftermath of recent seismic events. The consequences of school collapses are huge, and their unusability after an earthquake may impact on community disaggregation due to the lack of an essential service for children and youth. In addition, school buildings may be crucial elements in the post-event planning, offering shelters for dislocated people in the first emergency phases. Therefore, seismic risk and scenario estimates for school buildings are fundamental to plan realistic post-event operations, as well as to devise mitigation strategies.

With this purpose, in this contribution, mechanics-based fragility sets were derived for 265 macro-classes of masonry school buildings, representative of the taxonomy of Italian school building, based on the national school building registry. This fragility sets were then used to derive maps of expected damage through the web-tool IRMA schools, developed by Eucentre. Damage estimates were computed for a specific return period (conditional damage) and for a time window (unconditional damage). In addition, damage scenarios were calculated by implementing shake maps of recent earthquake occurred in Central Italy.

Keywords: masonry buildings; school buildings; seismic maps; seismic scenario; seismic vulnerability; mechanical method.

ISSN:2623-3347
Peer-review under responsibility of the organizing committee of COMPDYN 2023.
doi: 10.7712/120123.10796.20967

1 INTRODUCTION

School buildings represents a fundamental asset to be evaluated towards natural disasters, for civil protection purposes, emergency preparedness and mitigation planning. Not only are school relevant due to the consequences associated to their collapse [1,2], they also represent one of the largest stock of public buildings, and they can provide shelter to displaced people during a post-event emergency.

Within the Italian framework, the seismic vulnerability of school buildings was largely investigated, often in the aftermath of a seismic event [3–7].

However, risk analyses require the seismic vulnerability to be expressed in probabilistic terms. Fr this purpose, fragility curves were generally used. Despite the importance of school buildings, there remains a paucity of studies on this specific asset, and much of these were derived with reference to national context other than Italy [8–11].

Vulnerability of specific assets, such as schools, has yet to be included in the Global Earthquake Model (GEM) [12].

In the Italian framework, a cooperative national project has been funded by the Department of Civil Protection (DPC), involving two Centres of Competence of the DPC: EUCENTRE (*European Centre for Training and Research in Earthquake engineering*) and ReLUIS (*Network of university laboratories for seismic engineering*). Seismic risk was primarily investigated for ordinary buildings [13,14], providing novel fragility models for masonry [15–18] and r.c. [19,20] structures. Then, vulnerability assessment was extended to specific assets [21], such as schools and churches [22].

In this framework, a web platform (named IRMA) [23] was developed by EUCENTRE to compute seismic damage and risk of the investigated assets.

In this work, maps of expected damage for unreinforced masonry (URM) school buildings in Italy were derived thanks to the IRMA platform. Damage maps depends on all risk components: *i*) the hazard model, directly implemented in the platform [24]; *ii*) the exposure model, referring to the national registry of the Italian Ministry of Education [25], presented in the next section; and *iii*) on the vulnerability model which was derived by the authors through a mechanics-based fragility assessment procedure [26], briefly presented in section 3.

In addition, simulated scenarios were developed based on the shake maps of two recent seismic events which hit Italy (the 2009 L'Aquila earthquake and the 2016 Norcia earthquake).

2 EXPOSURE: ITALIAN SCHOOL BUILDING REGISTRY

Risk assessment at a large scale for a specific asset requires a dataset of exposure to be collected and georeffered, throughout the investigated area. Collected typological data (and structural information when available) contribute to defining the building taxonomy which should be consistent with building types adopted in the vulnerability model.

In this contribution, the reference dataset for exposure model was adopted according to the Italian school building registry (ISBR) [25], by the Ministry of Education, of 2005.

Data from the registry were processed and made available within the IRMA platform by *Eucentre* [27,28]. By querying the IRMA platform, data distributions presented in this section were obtained.

The registry counts 49351 school buildings, for which a limited number of parameters was collected:

- Structural type and construction material; masonry, r.c. precast, steel, and mixed structures are the proposed types.
- Construction ages (Before XIX century, XIX century, 1900-1920, 1921-1945, 1946-1960, 1961-1976, and after 1976).

- Number of storeys, grouping together buildings with four or more storeys.
- Covered plan area (less than 500 m2, 500-1000 m2, 1000-2000 m2, 2000-5000 m2, and more than 5000 m2).
- Type of floors; r.c. with clay elements, steel beams with clay elements, timber, vaults, and mixed are the proposed types, with also "other" as possible choice.

The three most ancient construction ages (i.e., "Before XIX century", "XIX century", and "Before 1920") were grouped together hereinafter, assuming homogeneous seismic behaviour.

This dataset was not collected homogeneously throughout the country. It was affected by lack of data, in particular concentrated in some Italian regions, as showed in Figure 1.

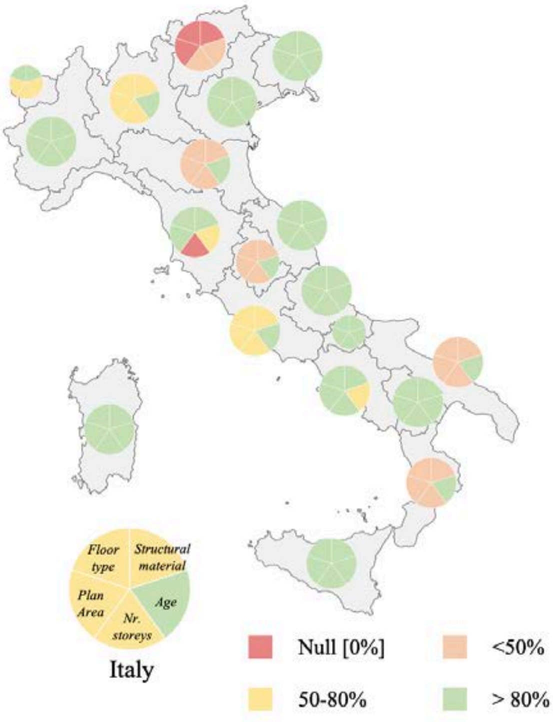


Figure 1. Completeness of data for Italian regions and overall country.

Figure 2 shows the frequencies of structural types (i.e., material of vertical structures). Reinforced concrete (r.c.) and masonry were the most frequent types. However, structural type data was not available for more than 30% of registered buildings.

Masonry schools represented almost a fifth (21%) of the ISBR of 2005, corresponding to 10352 buildings. Figure 3 shows the frequency distribution of typological (a, b, c, d) and structural (e, f) parameters of URM school buildings in the reference inventory. Masonry schools were built with similar frequencies in ages up to 1975, while the rate of new URM schools after 1976 almost halved. They are mainly low-rise buildings, with a significant peak (48%) of two-storey structures. According to plan area, small to medium schools prevail, while the frequency of very large URM structures is rather low. As illustrated in Figure 3d, most schools built before 1960 had two storeys, while the frequency of single-storey buildings has grown over time, becoming prevalent in the most recent period. This fact could be due to increasing request of pre-school facilities which led to enhancing of early childhood services, typically located in single-storey buildings. Furthermore, in 1975 technical provisions for school buildings were issued [29], setting a maximum number of storeys on which didactic activities can take place, depending on the level of education. One storey was set as maximum for pre-school, two storeys for primary and lower secondary schools, and three storeys for higher secondary schools. The ISBR also collected data on types of floors. Most schools (64%) have rigid r.c. floors, while the frequencies of other types are significantly lower. Lastly, Figure 3f shows frequencies of types of masonry in the national registry. For most schools (81.5%) the pattern of masonry (either regular or irregular) was unspecified; thus, this data was insufficient to define percentage of masonry quality throughout the country.

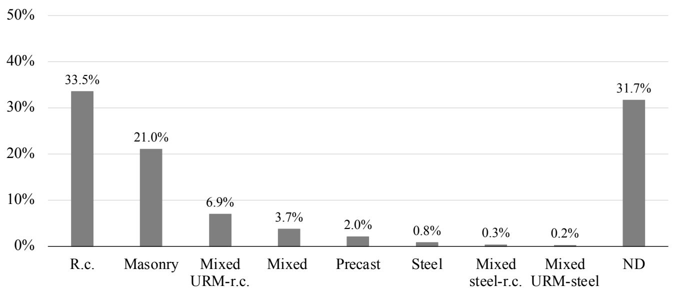


Figure 2. Frequency distribution of structural types in ISBR.

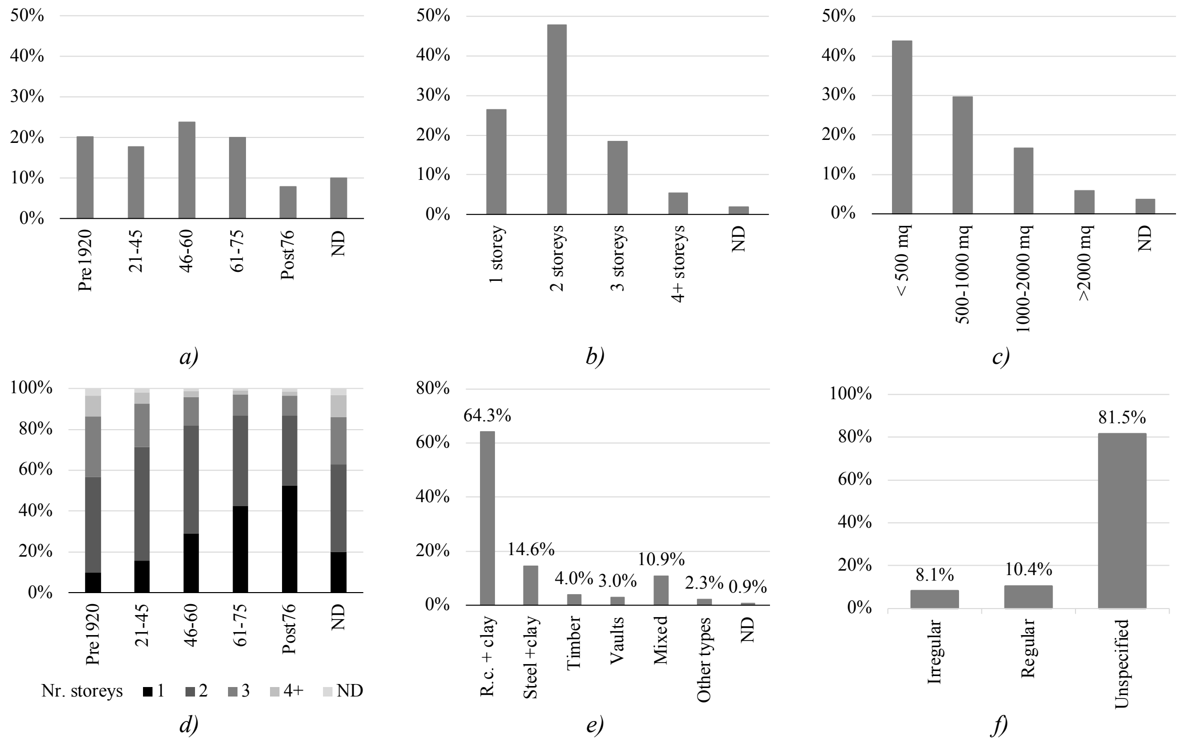


Figure 3. Frequency distribution of typological and structural parameters in ISBR.

3 VULNERABILITY: MECHANICS-BASED FRAGILITY MODEL

The vulnerability of unreinforced masonry (URM) was quantified through a fragility model derived through a mechanics-heuristic method [17,26]. Fragility curves were derived for analyses at national scale, by defining a taxonomy of buildings consistent with ISBR [25], thus defined by a limited number of parameters (i.e., construction age, number of storeys, plan area).

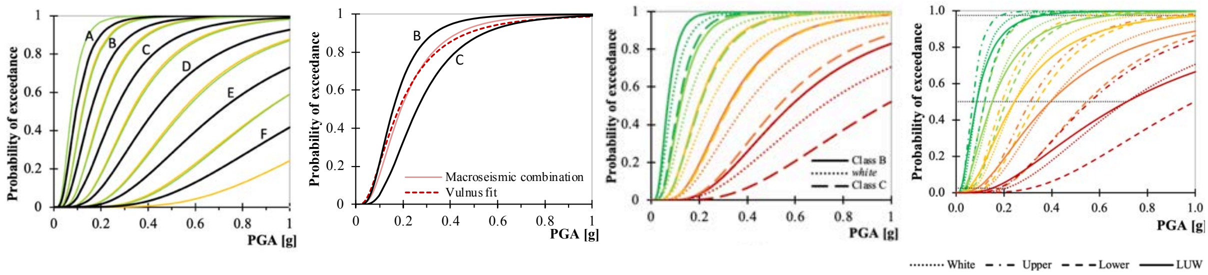
The procedure for fragility assessment combined a mechanics-based approach (*Vulnus*) [30–32], developed at the University of Padova, and a macroseismic heuristic model from the literature [33]. The following steps were performed to estimate fragility of URM schools in Italy:

1. Definition of a dataset of more than 7500 prototype school buildings, based on the architectural configuration of 14 existing buildings [34–36].
2. Analysis of each prototype with Vulnus to derive fragility curves for a damage state intermediate between DS2 and DS3 (thus, DS2.5 hereinafter), according to the definition by EMS98 [37].
3. Linear combination of prototype fragilities according to exposure matrix, to obtain fragility model of the considered taxonomy (for DS2.5).
4. Calibration of the reference macroseismic-heuristic model [33] to derive fragility sets from DS1 to DS5 (i.e., from slight damage to collapse). Optimal coefficient of combination were calculated through NSGA-II algorithm (i.e., nondominated sorting genetic algorithm) [38].
5. Combination (named LUW) of fragility sets (average, lower- and upper-bounds) to include uncertainties and increase dispersion.

The steps of the procedure are showed in Figure 4. For further details on the fragility assessment, please refer to Saler et al. [26]. Log-normal fragility curves were thereby derived for 265 macro-classes of URM school buildings in Italy. Peak ground acceleration (PGA) was adopted as intensity measure. The parameters – median value (μ) and logarithmic standard deviation (β) – of more generalised macro-classes (based on construction age and number of storeys only) are summarised in Table 1.

Figure 5 summarises the main findings, in terms of trends of median values, of the proposed fragility model. Figure 5a and b refers to the representative macro-class of schools with two-storey, and they show median values as the ages and plan areas vary, respectively. The school vulnerability tends to decrease during ages, and small buildings appeared less vulnerable than medium to large schools. This latter result can be linked to a common greater complexity of larger buildings.

Figure 5c and d show trends of median values as number of storeys changes. The former refers to the period 1921-1945, and it is representative also of other epochs, excluding the most recent (Post 1976), thus displayed in the latter figure. For most macro-classes, the seismic vulnerability tended to increase with the number of storeys. A modest inversion was instead observed for schools built after 1976, for which two-storey schools appeared less vulnerable than single-storey buildings. This result may be explained by the decreased susceptibility of modern buildings to local mechanisms, and thereby a prevalence of in-plane shear failures. The resistance towards these latter mechanisms can be increased by vertical loads due to the second storey, compared to single-storey buildings.



Curves DS2.5 of reference macroseismic model | *Calculation of optimal coefficient to calibrate macroseismic model* | *Combination of macroseismic curves* | *LUW geometric combination*

DS1 DS2 DS3 DS4 DS5

Figure 4. Steps of mechanics-based fragility assessment.

		DS1		DS2		DS3		DS4		DS5	
Age	*Storeys*	*μ (g)*	*β (-)*	*μ (g)*	*β (-)*	*μ (g)*	*β (-)*	*μ (g)*	*β (-)*	*μ (g)*	*β (-)*
Pre 1920	1	0.105	0.790	0.187	0.798	0.302	0.797	0.488	0.811	0.894	0.825
Pre 1920	2	0.085	0.740	0.151	0.753	0.244	0.747	0.394	0.762	0.713	0.795
Pre 1920	3	0.073	0.772	0.130	0.802	0.209	0.804	0.338	0.825	0.613	0.860
Pre 1920	4	0.064	0.767	0.114	0.794	0.184	0.787	0.297	0.805	0.535	0.834
1921-1945	1	0.118	0.738	0.209	0.757	0.337	0.761	0.546	0.768	0.997	0.780
1921-1945	2	0.105	0.761	0.186	0.779	0.300	0.777	0.485	0.786	0.888	0.791
1921-1945	3	0.092	0.745	0.163	0.763	0.263	0.759	0.426	0.778	0.774	0.811
1921-1945	4	0.084	0.704	0.148	0.729	0.239	0.725	0.387	0.740	0.701	0.781
1946-1960	1	0.142	0.668	0.253	0.688	0.408	0.690	0.659	0.703	1.197	0.745
1946-1960	2	0.114	0.656	0.203	0.677	0.328	0.677	0.530	0.683	0.970	0.737
1946-1960	3	0.102	0.649	0.181	0.674	0.292	0.670	0.473	0.682	0.864	0.740
1946-1960	4	0.088	0.682	0.157	0.700	0.253	0.693	0.409	0.711	0.743	0.763
1960-1975	1	0.172	0.792	0.305	0.818	0.493	0.814	0.800	0.802	1.463	0.859
1960-1975	2	0.143	0.771	0.254	0.789	0.410	0.792	0.662	0.795	1.202	0.838
1960-1975	3	0.129	0.761	0.229	0.783	0.370	0.791	0.597	0.813	1.086	0.870
1960-1975	4	0.107	0.806	0.190	0.815	0.306	0.821	0.496	0.838	0.909	0.846
Post 1976	1	0.200	0.832	0.356	0.870	0.574	0.884	0.923	0.858	1.650	0.867
Post 1976	2	0.211	0.835	0.375	0.872	0.605	0.880	0.970	0.873	1.727	0.872
Post 1976	3	0.182	0.854	0.322	0.890	0.521	0.904	0.844	0.864	1.538	0.890
Post 1976	4	0.160	0.864	0.284	0.890	0.458	0.906	0.742	0.874	1.352	0.901

Table 1. Fragility curves for generalised macro-classes of URM schools in Italy.

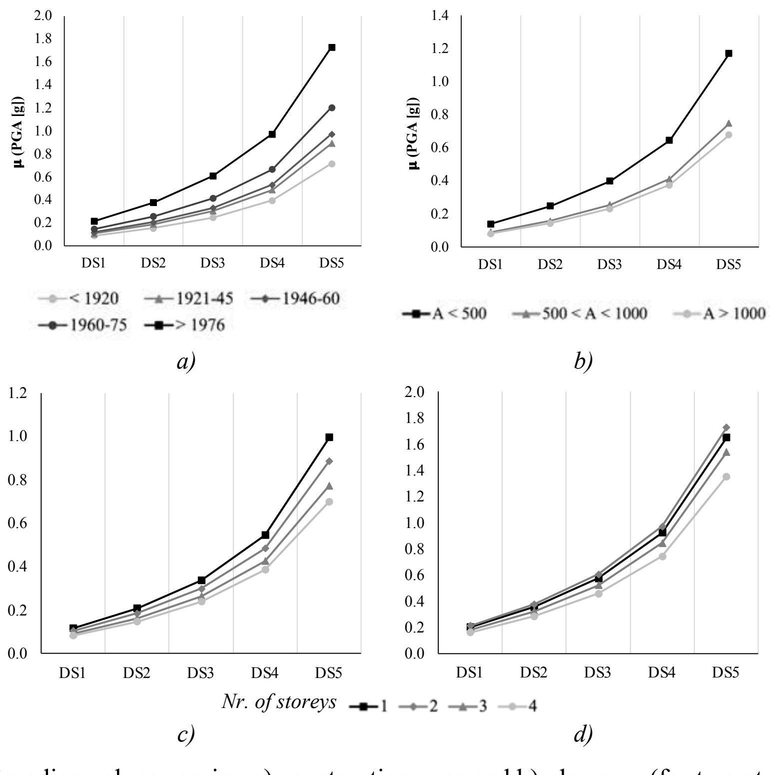


Figure 5. Trend of median values varying a) construction ages and b) plan area (for two-storeys schools); and number of storeys for construction periods c) 1921-1945 and d) post 1976.

4 SEISMIC MAPS OF THE ITALIAN URM SCHOOL ASSET

Maps of expected damage at national scale were derived for URM schools in Italy, based on the proposed mechanics-based fragility model.

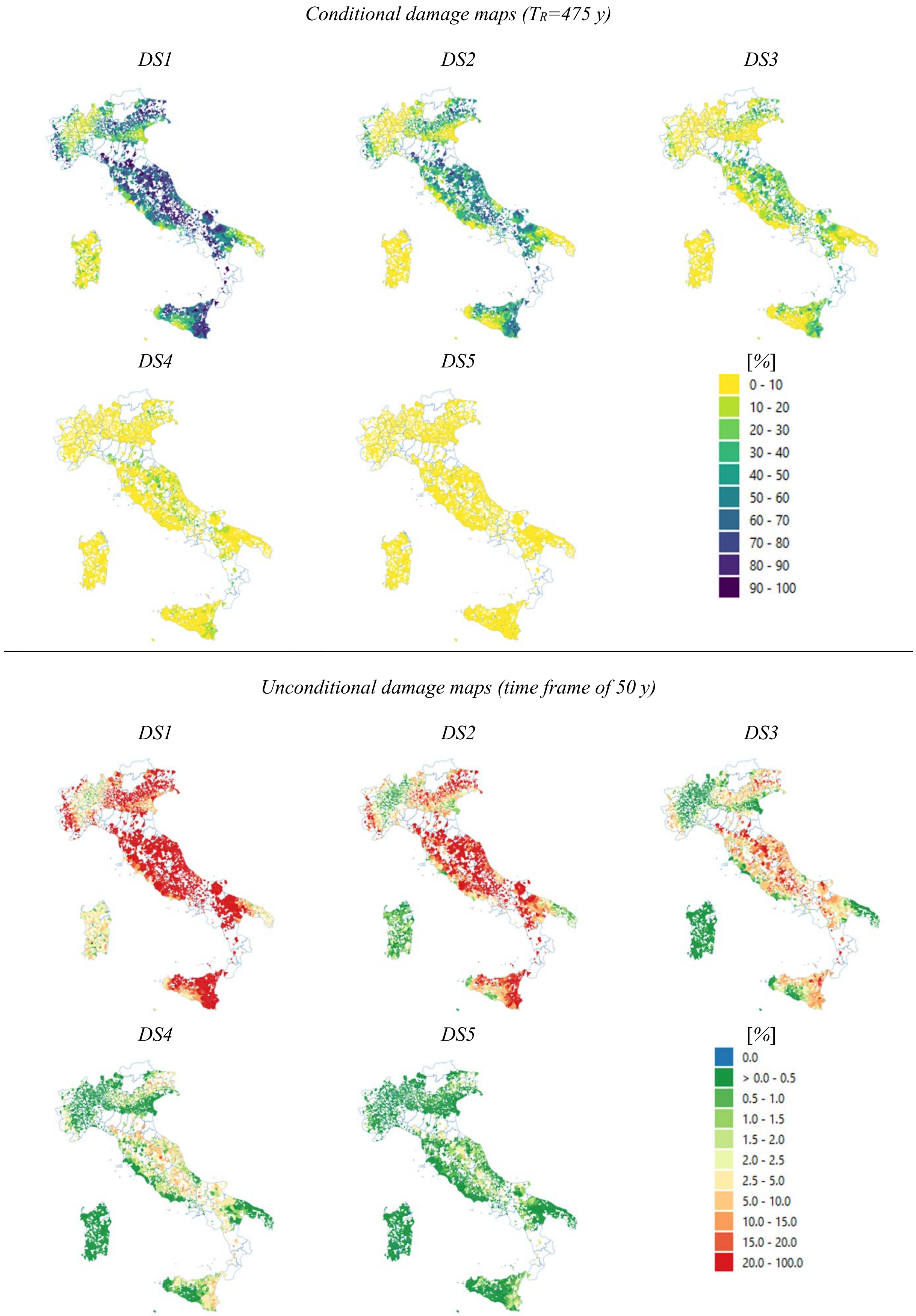


Figure 6. Conditional and unconditional damage maps: rate of URM schools for each DS.

These maps were developed within the IRMA (i.e., Italian Risk Maps) web platform, developed by EUCENTRE (*European Centre for Training and Research in Earthquake engineering*) [27,28]. The web platform was developed in the framework of the cooperative national project *ReLUIS-DPC 2019-2021* [21] for residential buildings and for specific assets (e.g., schools, churches).

IRMA implemented OpenQuake engine [39] to compute seismic risk. Hazard was based on national maps by Stucchi et al. (namely, MPS04) [24], while exposure referred to the above-mentioned Italian School building Registry of 2005 [25]. Vulnerability models should be uploaded by researchers taking parts in the national project. In this work, the proposed fragility model presented in the previous section was implemented.

Conditional and unconditional damage/risk computation were included in the web platform, which respectively refers to a specific return period and to an observation time frame. Note that the design return period (Life Safety limit state) for relevant structures with design working life of 50 years (712 years), such as schools [40], was not included. Unconditional damage/risk can be computed for the following time frames: 1, 10, and 50 years.

Maps for both conditional and unconditional damage were derived for the five damage states (DS) of the European Macroseismic Scale [37] described in the vulnerability model. In this case, maps represented the expected frequencies of each DS (Figure 6). Another possible representation of both conditional and unconditional damage is the expected mean damage, ranging from 0 to 5 (Figure 7).

In the derived maps, presented as follows, some regions (such as Emilia-Romagna and Calabria) resulted mainly blank, despite being characterised by moderate or high seismic risk. This stems from the lack of data in these regions (Figure 1). Indeed, structural type was available for none of schools in the Trentino-Alto Adige region, and only for 10% of schools in the Emilia-Romagna region, and 28% in the Calabria region. Thus, a set of 9233 out of 10352 URM schools were included in the computation of risk. About 10% of the total amount of URM school buildings in the registry [25] were indeed not processed due to lack of typological data that were needed to assign them to building macro-classes, associable to fragility curves.

Maps of expected damage appeared to be primarily dependent on hazard, and then on the distribution over the country of macro-classes (and then exposure and vulnerability), which make the colouring gradient irregular between contiguous municipalities.

Maps of damage were also derived for URM school buildings for two scenarios: the mainshock of the L'Aquila earthquake (6th April 2009), in Figure 8; and the Norcia earthquake (30th October 2016), in Figure 9. The shake maps [41] of these events (in terms of peak ground acceleration) were available in the web platform.

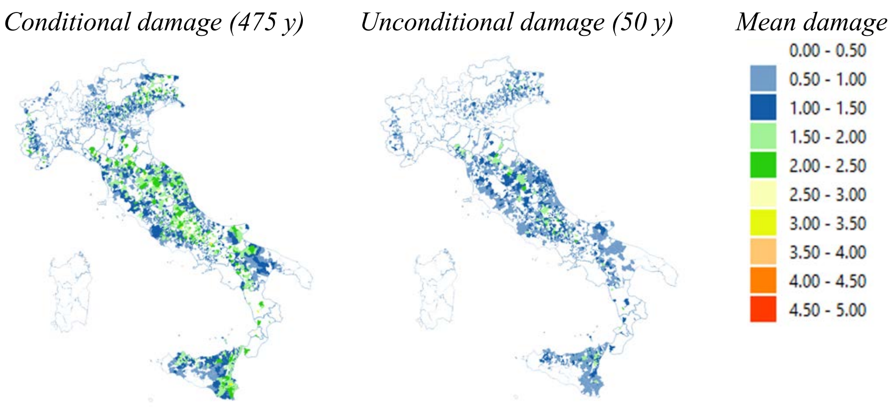


Figure 7. Conditional and unconditional damage maps: mean expected damage.

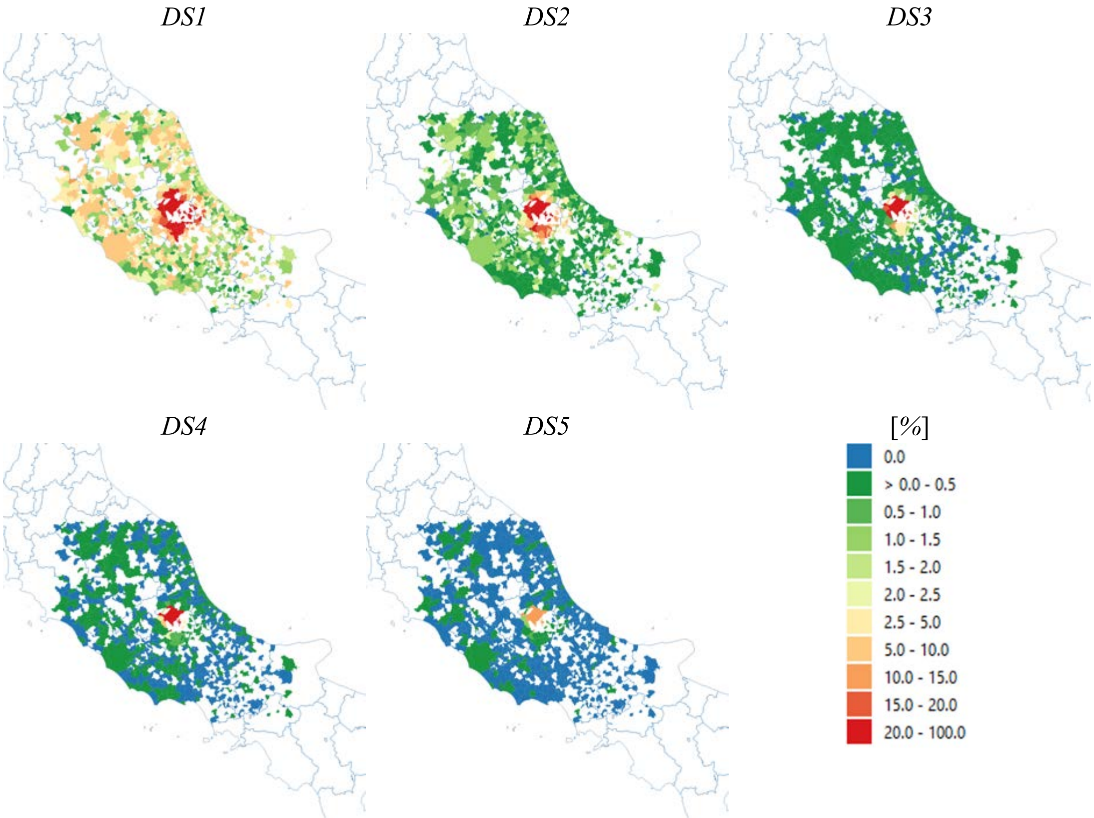


Figure 8. Damage scenario for the L'Aquila mainshock (6th April 2009).

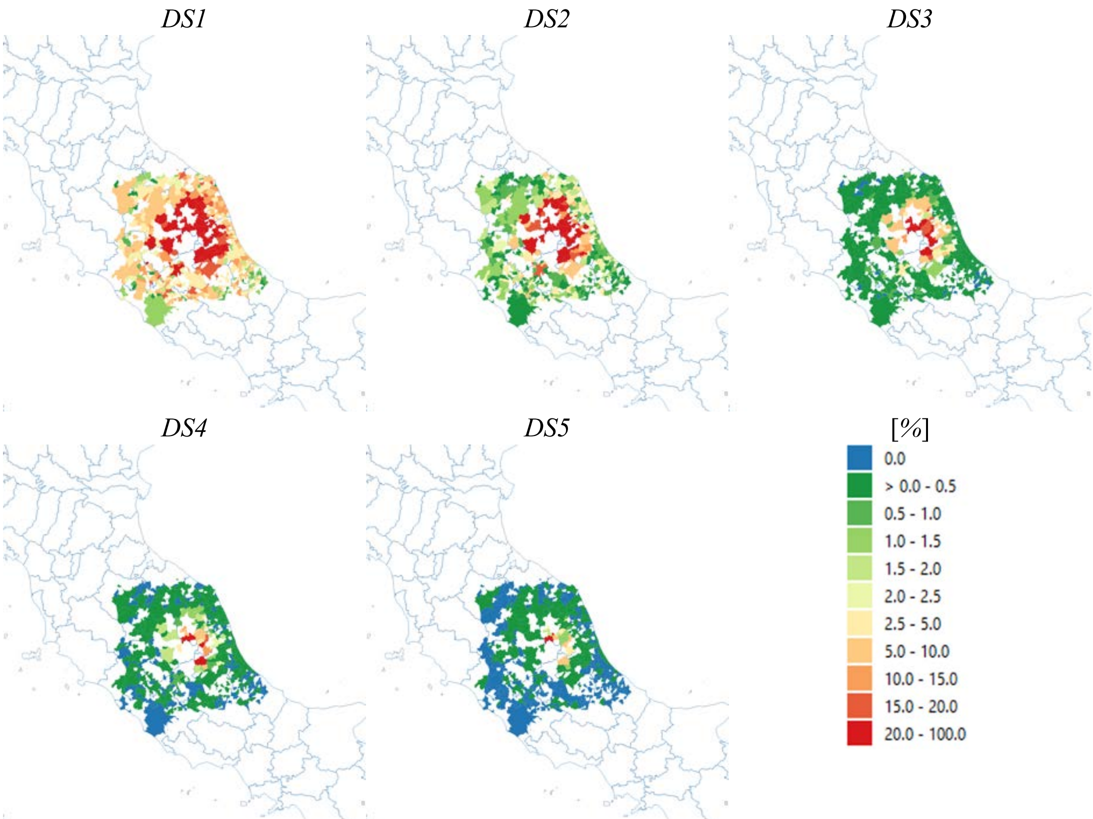


Figure 9. Damage scenario for the Norcia earthquake (30th October 2016).

5 CONCLUSIONS

- In this paper, a novel proposed fragility model for masonry school buildings was applied to develop maps of expected damage at national scale. The proposed fragility model was derived through a mechanical-heuristic approach, and it described the probability of exceeding five damage states (EMS98 [37]) conditional to peak ground acceleration, as intensity measure.
- The adopted macro-typology was based on a limited number of parameters available in the Italian school building registry, collected at national scale. These parameters were construction ages, number of storeys, and plan area. Typological parameters, such as number of storeys, construction ages and plan area appeared to consistently influence the seismic response of the investigated asset.
- Maps of expected damage were derived for Italy, for a time frame (i.e., unconditional damage) and for a return period (i.e., conditional damage). These maps appeared primarily influenced by the local seismicity, but also by the distribution of macro-classes.
- Further research should focus on determining consequence functions specific for school buildings, required to properly evaluating seismic risk associated to this relevant asset.

ACKNOWLEDGEMENTS

Special thanks are due to ReLUIS and the Italian Department of Civil Protection, as the research was carried out in the framework of the *ReLUIS-DPC Project 2022-2024 – Work Package 4 – Task 4: Schools and hospitals*.

REFERENCES

[1] M. di Ludovico, A. Digrisolo, C. Moroni, F. Graziotti, V. Manfredi, A. Prota, M. Dolce, G. Manfredi, Remarks on damage and response of school buildings after the Central Italy earthquake sequence, Bulletin of Earthquake Engineering. 17 (2019) 5679–5700. https://doi.org/10.1007/s10518-018-0332-x.

[2] D. Alexander, S. Bhatia, D. Benouar, J. Kumar, O. Cardona, School Seismic Safety: Case Studies, Encyclopedia of Earthquake Engineering. (2015) 1–16. https://doi.org/10.1007/978-3-642-36197-5_406-1.

[3] M. Dolce, A. Masi, C. Moroni, D. Liberatore, et al. Valutazione della vulnerabilità sismica di edifici scolastici della Provincia di Potenza, L'ingegneria Sismica in Italia. 1980 (2004).

[4] S. Cattari, S. Frumento, S. Lagomarsino, S. Parodi, S. Resemini, Multi-Level Procedure for the Seismic Vulnerability Assessment of Masonry Buildings: the Case of Sanremo (North-Western Italy), (2006) 3–8.

[5] F. Clementi, E. Quagliarini, G. Maracchini, S. Lenci, Post-World War II Italian school buildings: Typical and specific seismic vulnerabilities, Journal of Building Engineering. 4 (2015) 152–166. https://doi.org/10.1016/j.jobe.2015.09.008.

[6] N. Augenti, E. Cosenza, M. Dolce, G. Manfredi, A. Masi, L. Samela, Performance of school buildings during the 2002 Molise, Italy, earthquake, Earthquake Spectra. 20 (2004). https://doi.org/10.1193/1.1769374.

[7] F. Ceroni, N. Caterino, A. Vuoto, Simplified seismic vulnerability assessment methods: A comparative analysis with reference to regional school building stock in Italy, Applied Sciences (Switzerland). 10 (2020) 1–37. https://doi.org/10.3390/app10196771.

[8] P. Hannewald, C. Michel, P. Lestuzzi, H. Crowley, J. Pinguet, D. Fäh, Development and validation of simplified mechanics-based capacity curves for scenario-based risk assessment of school buildings in Basel, Eng Struct. 209 (2020) 110290. https://doi.org/10.1016/j.engstruct.2020.110290.

[9] D. D'Ayala, C. Galasso, A. Nassirpour, R.K. Adhikari, L. Yamin, R. Fernandez, D. Lo, L. Garciano, A. Oreta, Resilient communities through safer schools, International Journal of Disaster Risk Reduction. 45 (2020) 101446. https://doi.org/10.1016/j.ijdrr.2019.101446.

[10] R. Gentile, C. Galasso, Y. Idris, I. Rusydy, E. Meilianda, From rapid visual survey to multi-hazard risk prioritisation and numerical fragility of school buildings, Natural Hazards and Earth System Sciences. 19 (2019) 1365–1386. https://doi.org/10.5194/nhess-19-1365-2019.

[11] N. Giordano, F. De Luca, A. Sextos, F. Ramirez Cortes, C. Fonseca Ferreira, J. Wu, Empirical seismic fragility models for Nepalese school buildings, Natural Hazards. (2020). https://doi.org/10.1007/s11069-020-04312-1.

[12] V. Silva, D. Amo-Oduro, A. Calderon, C. Costa, J. Dabbeek, V. Despotaki, L. Martins, M. Pagani, A. Rao, M. Simionato, D. Viganò, C. Yepes-Estrada, A. Acevedo, H. Crowley, N. Horspool, K. Jaiswal, M. Journeay, M. Pittore, Development of a global seismic risk model, Earthquake Spectra. 36 (2020) 372–394. https://doi.org/10.1177/8755293019899953.

[13] M. Dolce, A. Prota, B. Borzi, F. da Porto, S. Lagomarsino, G. Magenes, C. Moroni, A. Penna, M. Polese, E. Speranza, G.M. Verderame, G. Zuccaro, Seismic risk assessment of residential buildings in Italy, Bulletin of Earthquake Engineering. (2020). https://doi.org/10.1007/s10518-020-01009-5.

[14] F. da Porto, M. Donà, A. Rosti, M. Rota, S. Lagomarsino, S. Cattari, B. Borzi, M. Onida, D. De Gregorio, F.L. Perelli, C. Del Gaudio, P. Ricci, E. Speranza, Comparative analysis of the fragility curves for Italian residential masonry and RC buildings, Bulletin of Earthquake Engineering. 19 (2021) 3209–3252. https://doi.org/10.1007/s10518-021-01120-1.

[15] G. Zuccaro, F.L. Perelli, D. De Gregorio, F. Cacace, Empirical vulnerability curves for Italian mansory buildings: evolution of vulnerability model from the DPM to curves as a function of accelertion, Bulletin of Earthquake Engineering. (2020). https://doi.org/10.1007/s10518-020-00954-5.

[16] S. Lagomarsino, S. Cattari, D. Ottonelli, The heuristic vulnerability model: fragility curves for masonry buildings, Bulletin of Earthquake Engineering. 19 (2021) 3129–3163. https://doi.org/10.1007/s10518-021-01063-7.

[17] M. Donà, P. Carpanese, V. Follador, L. Sbrogiò, F. da Porto, Mechanics-based fragility curves for Italian residential URM buildings, Bulletin of Earthquake Engineering. (2021) 1–34. https://doi.org/10.1007/s10518-020-00928-7.

[18] A. Rosti, M. Rota, A. Penna, Empirical fragility curves for Italian URM buildings, Bulletin of Earthquake Engineering. (2020). https://doi.org/10.1007/s10518-020-00845-9.

[19] A. Rosti, C. Del Gaudio, M. Rota, P. Ricci, M. Di Ludovico, A. Penna, G.M. Verderame, Empirical fragility curves for Italian residential RC buildings, Bulletin of Earthquake Engineering. 19 (2021) 3165–3183. https://doi.org/10.1007/s10518-020-00971-4.

[20] B. Borzi, M. Faravelli, A. Di Meo, Application of the SP-BELA methodology to RC residential buildings in Italy to produce seismic risk maps for the national risk assessment, Bulletin of Earthquake Engineering. 19 (2021) 3185–3208. https://doi.org/10.1007/s10518-020-00953-6.

[21] A. Masi, S. Lagomarsino, M. Dolce, V. Manfredi, D. Ottonelli, Towards the updated Italian seismic risk assessment: exposure and vulnerability modelling, Springer Netherlands, 2021. https://doi.org/10.1007/s10518-021-01065-5.

[22] F. Ceroni, C. Casapulla, E. Cescatti, V. Follador, A. Prota, F. da Porto, Damage assessment in single-nave churches and analysis of the most recurring mechanisms after the 2016–2017 central Italy earthquakes, Bulletin of Earthquake Engineering. 20 (2022) 8031–8059. https://doi.org/10.1007/s10518-022-01507-8.

[23] Eucentre, Italian Risk Maps (IRMA) platoform, (2018).

[24] M. Stucchi, C. Meletti, V. Montaldo, A. Akinci, E. Faccioli, P. Gasperini, L. Malagnini, G. Valensise, (2004). Pericolosità sismica di riferimento per il territorio nazionale MPS04 [Data set]. Istituto Nazionale di Geofisica e Vulcanologia (INGV)., (2004). https://doi.org/10.13127/sh/mps04/ag.

[25] L. 23/1996, Regulation for School Buildings, Official Gazzette of Italian Republic N°15 of 19th January 1996. Rome, Italy. (1996) (in Italian).

[26] E. Saler, V. Follador, P. Carpanese, M. Donà, F. da Porto, Development of mechanics-based fragility curves for the Italian masonry school asset, Submitted to the Bulletin of Earthquake Engineering. (n.d.).

[27] B. Borzi, M. Onida, M. Faravelli, D. Polli, M. Pagano, D. Quaroni, A. Cantoni, E. Speranza, C. Moroni, IRMA platform for the calculation of damages and risks of Italian residential buildings, Bulletin of Earthquake Engineering. 19 (2021) 3033–3055. https://doi.org/10.1007/s10518-020-00924-x.

[28] M. Faravelli, B. Borzi, M. Onida, S. Cattari, S. Alfano, A. Masi, V. Manfredi, S. Lagomarsino, An Italian platform for the seismic risk assessment of school buildings, Procedia Structural Integrity. 44 (2023) 107–114. https://doi.org/10.1016/j.prostr.2023.01.015.

[29] DM 18/12/1975, Norme tecniche aggiornate relative all'edilizia scolastica, ivi comprei gli indici minimi di funzionalità didattica, edilizia ed urbanistica, da osservarsi nella esecuzione di opere di edilizia scolastica (in Italian)., (n.d.).

[30] A. Bernardini, R. Gori, C. Modena, A structural model for continuous masonry building systems in historical centres, in: Structural Conservation of Stone Masonry. International Technical Conference. Athens, 31. X.-3. XI. 1989. Conservation Structurelle de La Maçonnerie En Pierre. Conférence Internationale Technique. Athènes, 31. X.-3. XI. 1989, Athens, Greece, 1989: pp. 29–36.

[31] A. Bernardini, R. Gori, C. Modena, M.R. Valluzzi, Vulnus 4.0 - Automatic procedure for the seismic vulnerability analysis of masonry buildings (in Italian), (2009).

[32] A. Bernardini, R. Gori, C. Modena, Application of Coupled Analytical Models adn Experientail Knowledge to Seismic Vulnerability Analyses of Masonry Buildings, in: A. Koridze (Ed.), Earthquake Damage Evaluation and Vulnerability Analysis of Building Structures, Omega Scientific, Wallingford, United Kingdom, 1990.

[33] S. Lagomarsino, S. Giovinazzi, Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings, Bulletin of Earthquake Engineering. 4 (2006) 415–443. https://doi.org/10.1007/s10518-006-9024-z.

[34] E. Saler, P. Carpanese, V. Pernechele, Priority-ranking procedure to assess seismic vulnerability of school buildings at territorial scale, in: XVIII CONVEGNO ANIDIS - L'ingegneria Sismica in Italia, Ascoli Piceno, Italy, 2019.

[35] N. Gattesco, I. Boem, Classification of Friuli-Venezia Giulia masonry school buildings for seismic risk models purposes, in: XVIII CONVEGNO ANIDIS - L'ingegneria Sismica in Italia, Ascoli Piceno, 15-19 September 2019, 2019: pp. 79–86.

[36] D. Ottonelli, S. Alfano, S. Cattari, M. Di Ludovico, A. Prota, Structural and damage data analysis of a stock of URM schools struck by the 2016/2017 Central Italy earthquake, in: XVIII CONVEGNO ANIDIS - L'ingegneria Sismica in Italia, Pisa University Press, Ascoli Piceno, 15-19 September 2019, 2019: pp. 43–53.

[37] G. Grünthal, EMS98 - European Macroseismic Scale 1998, Conseil de l'Europe - Cahiers du Centre Européen de Géodynamique et de Séismologie, Luxemburg, 1998.

[38] K. Deb, A. Pratap, S. Agarwal, T. Meyarivan, A fast and elitist multiobjective genetic algorithm: NSGA-II, IEEE Transactions on Evolutionary Computation. 6 (2002). https://doi.org/10.1109/4235.996017.

[39] M. Pagani, D. Monelli, G. Weatherill, L. Danciu, H. Crowley, V. Silva, P. Henshaw, L. Butler, M. Nastasi, L. Panzeri, M. Simionato, D. Vigano, Openquake engine: An open hazard (and risk) software for the global earthquake model, Seismological Research Letters. 85 (2014) 692–702. https://doi.org/10.1785/0220130087.

[40] NTC2018 - D.M. 17/01/2018, Aggiornamento delle "Norme tecniche per le costruzioni" (in Italian), Official Gazzette of Italian Republic N°42 of 20th February 2018. (2018).

[41] INGV (Istituto Nazionale di Geofisica e Vulcanologia), ShakeMap v4, (n.d.). http://shakemap.ingv.it/shake4/ (accessed February 20, 2022).