

Article

Simulations of Damage Scenarios in Urban Areas: The Case of the Seismic Sequence of L'Aquila 2009

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Abstract

Simulation of damage scenarios is an important tool for seismic risk mitigation. While a detailed analysis of each building would be preferable to assess their vulnerability to seismic hazard, simplified yet robust methodologies are necessary at a large urban scale to overcome computational costs or data unavailability. Moreover, most damage assessments simulate single seismic shocks, though in many real sequences, with a series of aftershocks following the mainshocks, it is observed that buildings endure damage accumulation, which increases their vulnerability over time. The present study builds on a recently developed methodology for simulating urban-scale damage scenarios across seismic sequences, explicitly accounting for damage accumulation and the evolution of vulnerability. In particular, the availability of a dataset reporting the damage observed in the L'Aquila area (Italy) during the severe earthquake sequence of 2009, in combination with the georeferenced maps representing the spatial distribution of the ground motion, allows for the calibration of the methodology through the comparison between the simulations' results and the sequence's real data. Although calibrated on the L'Aquila dataset, the proposed procedure could also be applied to different urban areas, with both real and synthetic seismic sequences, enabling the forecasting of damage scenarios to support the development of effective strategies for seismic risk mitigation.

Keywords: damage forecast; seismic vulnerability; urban areas



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1. Introduction

As urban areas become increasingly vulnerable to seismic hazards with ageing infrastructure on one hand and rapid urbanization on the other, forecasting earthquake-induced damage is essential for risk mitigation and emergency planning. Detailed modelling of individual buildings is often computationally challenging; for this reason, simplified yet robust methodologies have been developed to capture key aspects of structural vulnerability [1–3]. At a large urban scale, evaluating a significant number of buildings is impractical and requires efficient methods that balance accuracy and speed. Furthermore, reliable data on the construction materials, structural design, and condition of each building is often lacking or difficult to obtain, especially in older cities.

Among the most widely used approaches is Rapid Visual Screening (RVS) [4], which relies on visual inspections to estimate vulnerability based on external characteristics. More advanced methodologies, which also have been applied to seven European cities in the context of the RISK-EU project [5], include Vulnerability Index Methods (VIMs), which assign numerical vulnerability scores based on structural features and historical damage data, and the macroseismic approach [6], which relates vulnerability indices to expected damage at given intensities using analytical functions (vulnerability curves) derived from the European Macroseismic Scale EMS-98 [7]. Damage Probability Matrices (DPMs) and fragility functions are two commonly used tools for assessing the likelihood of structural damage under seismic action. DPMs provide the probability of a structure being in each predefined damage state at specific intensity levels, typically in a discrete, tabular format [8–10]. Fragility functions express the probability of exceeding a given damage state as a continuous function of seismic intensity, capturing uncertainty in structural response. While DPMs are often derived from empirical observations or expert judgement, fragility functions are usually developed through analytical modelling or statistical analysis of observed damage data [11,12]. In recent years, Machine Learning Algorithms (MLAs) have also been introduced as they process large datasets and identify patterns across building typologies, helping to automate the vulnerability estimation process, particularly when detailed structural information is unavailable [13].

Seismic damage scenario simulation can be performed using a variety of tools and methodologies that combine hazard information, building vulnerability models, and exposure data. Among these tools, one widely used is OpenQuake [14], developed by the Global Earthquake Model Foundation (GEM), that offers a global, open-source computational engine, which has been employed, for example, in the Italian Risk Maps platform (IRMA) [15]. While these methods provide standardized and computationally efficient frameworks, they typically focus on a single event scenario or on Probabilistic Seismic Hazard Assessment (PSHA), overlooking the cumulative effects of earthquake sequences, where foreshocks and aftershocks can progressively weaken structures over time, increasing their vulnerability. Recent advances in Performance-Based Earthquake Engineering (PBEE) have highlighted the importance of accounting for sequential seismic loading, for example, by incorporating state-dependent fragility functions in a Markovian framework to capture damage cumulation over multiple mainshock–aftershock events, addressing limitations of traditional single-event probabilistic seismic risk models [16]. Moreover, advanced MLAs have also been applied to predict structural damage under successive earthquakes, demonstrating promising results in terms of accuracy and computational efficiency [17,18]. In this context, the 2009 earthquake sequence in the L’Aquila region of central Italy presents a valuable opportunity for methodological development and empirical validation. The sequence, which included a destructive mainshock and several significant aftershocks, caused widespread damage across the urban area, which has been documented and collected in the Database of the Observed Damage Da.D.O. (“Database del Danno Osservato” in Italian) developed by the Eucentre Foundation [19,20].

In this paper, we follow an innovative approach for simulating seismic damage accumulation at the urban scale proposed in recent studies by some of the present authors and focused on the numerical simulation of earthquake sequences [21,22]. The insights and innovations compared to the previous models are multiple and mainly include the adoption of a real seismic sequence (instead of an artificial one) and of a real damage dataset (not available in preceding studies). In particular, we consider as a case study the area affected by the 2009 L’Aquila sequence, and our main goal is to simulate, by reproducing the sequence of earthquakes that occurred during the period of most intense seismic activity, the damage caused to the buildings in the considered area. This sequence is reconstructed

using the ShakeMaps, georeferenced maps representing the spatial distribution of the ground motion, generated by the Italian National Institute of Geophysics and Volcanology (INGV) for the corresponding seismic events [23–25].

The simulated damage is then compared with the actual damage data reported in the Da.D.O., which includes a comprehensive record of 74,049 buildings in proximity to L'Aquila. The comparison with the observed data will allow us to calibrate the simulation methodology in order to provide more accurate and reliable results. Once successfully calibrated on the L'Aquila data, this method could be extended and applied to other seismically active areas for both real and artificial seismic sequences. It can significantly aid in developing effective risk management strategies, particularly when supplemented with additional data on road infrastructure, if available [26].

This paper is structured as follows: in Section 2 we introduce the L'Aquila case study and the datasets used for calibration; Section 3 details the methodological framework for modelling damage accumulation and vulnerability update; in Section 4 we present and discuss the results of the simulations and their implications for urban seismic risk mitigation; and finally, Section 5 summarizes the main findings of this study and outlines possible directions for future research.

2. The Case Study of L'Aquila

In 2009, the Abruzzo region in central Italy experienced a prolonged sequence of seismic events. The sequence began in December 2008 and culminated on 6 April 2009, with a major earthquake of moment magnitude M_w 6.1, occurring at 3:32 AM local time. The mainshock, followed by numerous aftershocks, had its epicentre near the city of L'Aquila, the capital of the Abruzzo region. The earthquake's shallow depth of approximately 8.8 km significantly contributed to the extensive damage observed in the area.

The Quick Earthquake Survey Team (QUEST) was mobilized immediately after the mainshock to conduct the macroseismic survey on the affected localities [27]. According to the authors of the report, the assessment was challenging due to the high variability of the construction typology and state of maintenance, especially between historical centres and suburban areas. The observed damage spatial distribution reflected the location and orientation of the seismogenetic source (a 40 km long NW-SE trending normal fault system) [28,29], although intensity anomalies were observed due to local site effects and topography influence. The resulting report in Mercalli–Cancani–Sieberg scale (MCS) [30] is said to reflect mainly the mainshock and its effect on the historical centres of the localities. However, the survey was conducted between 6 April and 1 July, involving 316 localities, with several requiring a re-evaluation, and some being revised according to the EMS-98.

The L'Aquila 2009 sequence provided an ideal case study for the application and validation of the U.S. Geological Society (USGS) software ShakeMap [23], which had recently been adapted for Italy by the INGV [24]. In the INGV ShakeMap application to L'Aquila, the resulting instrumental MCS intensity ShakeMap was compared with the MCS intensity values reported by the QUEST, showing qualitative similarity and highlighting the accuracy of the instrumental intensity estimates [31].

Moreover, the Italian Department of Civil Protection (DPC) led an extensive post-earthquake damage survey campaign to gather data on the buildings affected by the event. The collected information was later conveyed in the Da.D.O. [19,20], together with other relevant Italian post-earthquake campaigns, providing an invaluable resource for studies on seismic damage and building vulnerability.

In this study, we exploit the instrumentally derived intensity maps provided by the INGV and the L'Aquila 2009 dataset from Da.D.O. to test, through extensive numerical

simulations, some hypotheses of damage accumulation and to compare the simulation results with the observed damage scenario.

2.1. The Seismic Input: INGV Instrumental Intensity ShakeMaps

In Italy, the INGV ShakeMap implementation rapidly generates the spatial distribution of ground motion parameters after each seismic event of moment magnitude (Mw) greater than 3.0. The software interpolates ground shaking measurements recorded at seismic stations with seismological data on the event (epicentral coordinates, moment magnitude, and depth) and on the seismic source (style of faulting) through models that predict ground motion (Ground Motion Prediction Equation, GMPE) based on seismic wave propagation, and also accounting for geological site effects. The resulting maps are available in terms of Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Spectral Acceleration (SA) at three periods, and macroseismic intensity. The latter is derived instrumentally by applying Ground Motion to Intensity Conversion Equations (GMICEs), or IPEs (Intensity Prediction Equations) when data is limited. The INGV ShakeMap initial implementation employed regional GMPEs derived for the Italian territory earthquakes of magnitude < Mw 5.5, while equations developed more broadly for the European context were used for events of greater magnitudes ([24] and reference therein). A following update of the software introduced a new GMICE [32], hereinafter “FM10”. The current INGV ShakeMap implementation [25] selects the best performing ground motion model based on seismotectonic zonation (e.g., Bindi et al. [33], hereinafter “ITA10”, for areas such as the L’Aquila 2009 territory). Most recently, since March 2023, the GMICE by Oliveti et al. [34] has replaced the previous GMICE. The new model, regressed on a more comprehensive dataset [35], demonstrated greater accuracy and improved predictive performance, addressing the limitations of the FM10 GMICE, which slightly overestimate the intensity for earthquakes of magnitude greater than Mw 5.0.

The seismic sequence selected as a case study in this paper occurred prior to the most recent update of the GMICE. Consequently, the associated ShakeMaps in the INGV ShakeMap Archive (<https://shakemap.ingv.it/archive.html>, last accessed on 16 January 2025) were generated using the ITA10 GMPE and the FM10 GMICE, according to the metadata of the downloadable products available on the cited website. In Figure 1, we show the ShakeMap generated for the mainshock over the affected area of the Abruzzo region.

The data, provided in vector format, delineate irregular polygons, each characterized by a unique value of macroseismic intensity in MCS scale, expressed in roman numerals from I (not felt) to XII (extreme). The irregularities of the polygon shapes reflect local site effects, as geological conditions influence ground motion. These aspects are taken into account in the ShakeMap generation process, as previously mentioned.

We selected two possible configurations of seismic input for damage assessment: either considering only the Mw 6.1 mainshock or including all the earthquakes of magnitude greater than Mw 4.0, from the mainshock of 6 April 2009 to the last Mw 5.0 event on 9 April 2009. Notice that this is an arbitrary choice, since our model allows us to choose any desired number of events. The eighteen earthquakes of the considered sequence are characterized by the following parameters in Table 1: date, UTC time, epicentral coordinates, depth, and moment magnitude, all included in the array $Q_i = \{E_i, D_i, T_i, Lat_i, Lon_i, De_i, Mw_i\}$, $i = 1, \dots, 18$.

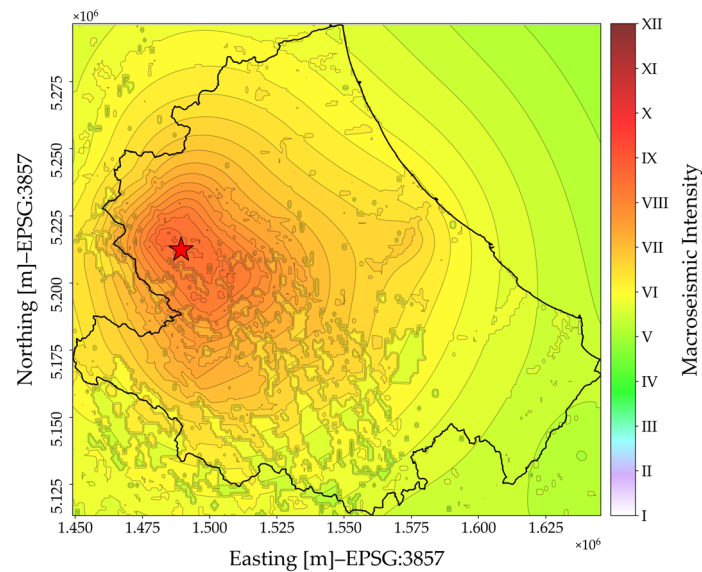


Figure 1. Macro seismic intensity ShakeMap generated by the INGV for the L'Aquila 2009 mainshock (available on the INGV ShakeMap Archive, <https://shakemap.ingv.it>). The colours represent the macro seismic intensity expressed in MCS scale, from I (not felt) to XII (extreme). The grey polygons outline areas of equal intensity, taking into account local site conditions. The administrative boundaries of the Abruzzo region are outlined in black. The red star marks the epicentre of the mainshock.

Table 1. The eighteen earthquakes of magnitude greater than Mw 4.0 selected from the L'Aquila 2009 sequence. The events of magnitude greater than Mw 5.0 ¹ are highlighted in grey.

	Event Id	Date [yyyy-mm-dd]	Time UTC [hh:mm:ss]	Latitude [°]	Longitude [°]	Depth [km]	Mw
1	1895389	2009-04-06	01:32:00	42.342	13.380	8.3	6.1
2	1895409	2009-04-06	01:36:39	42.352	13.346	9.7	4.7
3	1895419	2009-04-06	01:40:50	42.417	13.402	11	4.1
4	1895429	2009-04-06	01:41:32	42.377	13.319	8.5	4.0
5	1895439	2009-04-06	01:41:37	42.364	13.456	8.7	4.3
6	1895449	2009-04-06	01:42:49	42.300	13.429	10.5	4.2
7	1895879	2009-04-06	02:37:04	42.360	13.328	8.7	4.8
8	1896349	2009-04-06	03:56:45	42.335	13.386	9.3	4.3
9	1897629	2009-04-06	07:17:10	42.356	13.383	9	4.1
10	1901099	2009-04-06	16:38:09	42.363	13.339	10	4.3
11	1903809	2009-04-06	23:15:00	42.463	13.385	9.7	5.0
12	1906339	2009-04-07	09:26:28	42.336	13.387	9.6	4.9
13	1908319	2009-04-07	17:47:00	42.303	13.486	17.1	5.4
14	1909629	2009-04-07	21:34:29	42.364	13.365	9.6	4.3
15	1916789	2009-04-09	00:52:00	42.489	13.351	11	5.2
16	1917479	2009-04-09	03:14:52	42.335	13.444	17.1	4.2
17	1917839	2009-04-09	04:32:45	42.445	13.434	9.8	4.1
18	1921649	2009-04-09	19:38:00	42.504	13.35	9.3	5.0

¹ Data from the INGV ShakeMap Archive.

2.2. The Da.D.O. Buildings Dataset

In this paper, we utilize the extensive Da.D.O. dataset [19,20], which includes detailed records of 74,049 buildings located near L'Aquila. It provides pre-event characteristics such as the buildings' age, construction materials, and geometry, along with post-event

damage evaluations conducted after the five most significant earthquakes, each exceeding a magnitude of Mw 5.0, which occurred between 6 April and 9 April 2009. The data are accessible to authorized researchers through a WebGIS platform developed by the Eucentre Foundation. In Figure 2, panel (b), the epicentres of these earthquakes are indicated by red star symbols, with the main event of magnitude Mw 6.1 additionally marked by a yellow circle. The spatial distribution of the buildings in the dataset is illustrated in panel (c) of the same figure, showing their geographical locations within the impacted area.

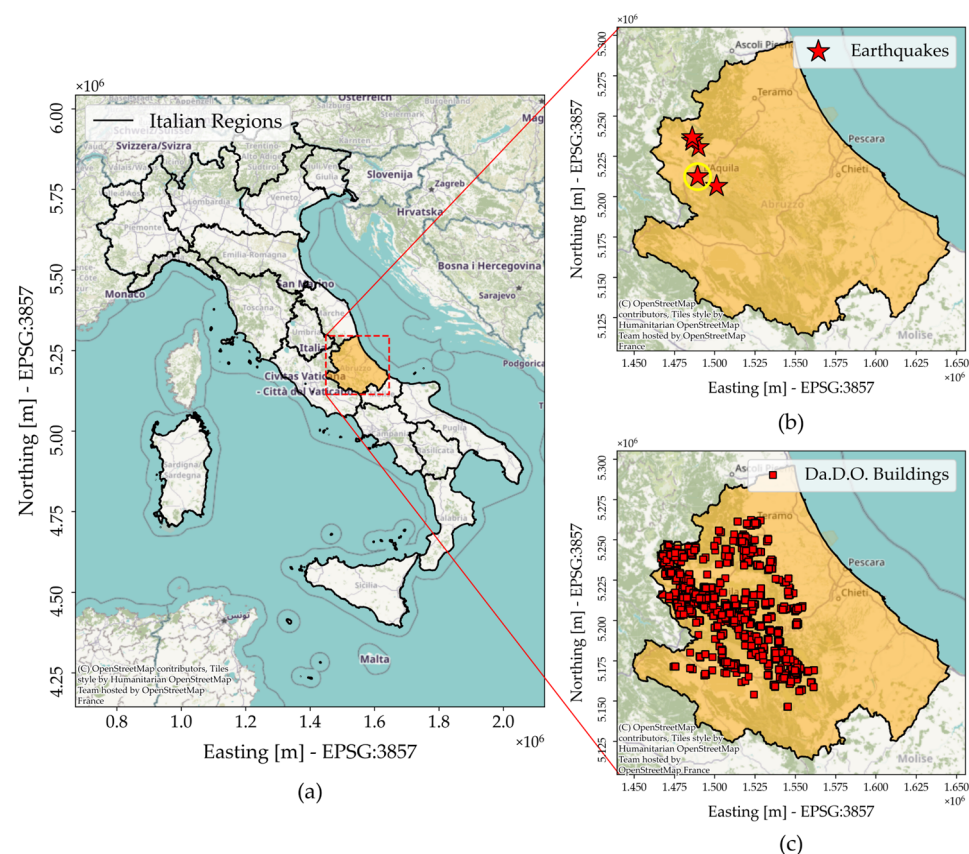


Figure 2. (a) Map of Italy; (b) an enlargement of the Abruzzo region reporting the epicentres of the 2009 five main shocks, represented as star symbols (the main event is also marked with a circle); and (c) geographical position of masonry buildings in the Da.D.O. L'Aquila 2009 dataset [19,20].

The 74,049 buildings of the original Da.D.O. dataset can be classified according to their construction types, which include masonry, reinforced concrete (RC), mixed, and steel. Figure 3 illustrates the composition of the dataset, reporting the corresponding percentages of each class.

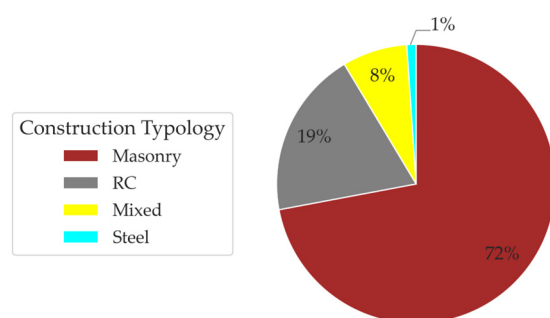


Figure 3. Percentages of construction types of buildings in the Da.D.O. L'Aquila 2009 dataset [19,20].

As further specified in Figure 4, more than half of the masonry buildings considered were constructed before 1919. This distribution reflects historical construction trends in Italy, where unreinforced masonry was the predominant structural system until the early 20th century. Starting from the 1970s, a significant shift occurred, following the progressive development of seismic design codes and the growing adoption of reinforced concrete systems [36]. This led to a steady decline in the use of masonry for new constructions.

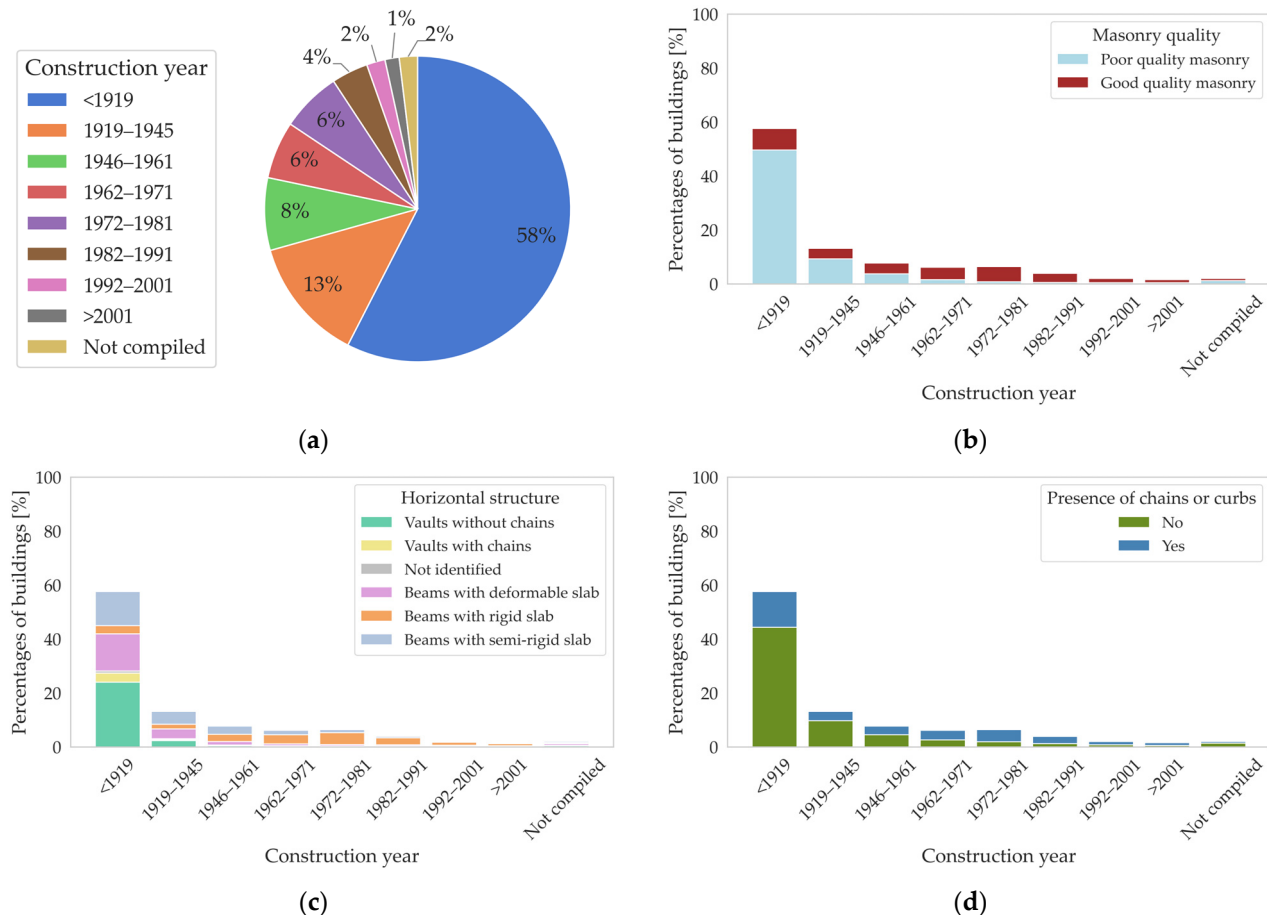


Figure 4. Overview of key building characteristics across construction years. (a) Distribution of buildings by construction year ranges; (b) percentage distribution of the masonry quality of the vertical structure across construction periods; (c) percentage distribution of horizontal structure systems across construction years; and (d) percentage distribution of the presence of chains across construction years. Data are from the Da.D.O. L'Aquila 2009 dataset [19,20].

The Abruzzo region had already been severely affected by a major seismic event in 1915, known as the Marsica earthquake, which caused widespread destruction and over 30,000 casualties. In response, the Royal Decree n. 573 of 29 April 1915 was issued, marking one of the first attempts to introduce seismic zoning in Italy, with the classification of several municipalities, including those in Abruzzo, as seismic zones.

From the 1970s onwards, increased attention was paid to the quality of masonry construction, as shown in Figure 4b. This was partly due to the introduction of the Italian Law n. 64 of 2 February 1974 and subsequent technical standards, which provided measures for structures, with particular emphasis on those in seismic areas. These regulations significantly contributed to the modernization of construction practices, including stricter requirements for materials, detailing, and structural analysis. They led to improvements not only in vertical load-bearing walls, but also in the design of horizontal diaphragms and in the presence of chains or curbs, as shown in Figure 4. Beginning from that period,

traditional vaulted systems and flexible timber slabs (see Figure 5a,b), which exhibit poor in-plane stiffness, began to be progressively replaced by reinforced concrete beams and semi-rigid or rigid slabs (see Figure 5c). This shift resulted in improved in-plane stiffness and a more effective transfer of seismic forces between structural elements.

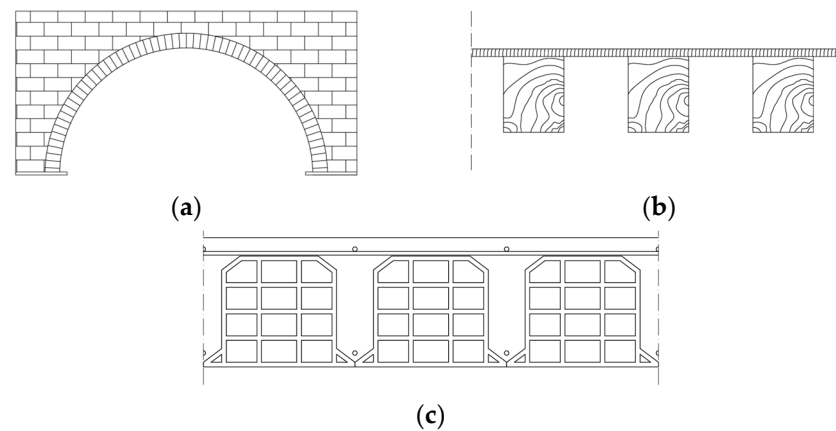


Figure 5. Different types of horizontal structures: (a) vaulted system, (b) flexible timber slab, and (c) rigid slabs with hollow clay blocks and concrete.

A preliminary statistical overview of the dataset under analysis reveals that it is composed of masonry buildings with a low to medium height profile, typically ranging from 1 to 4 storeys. The interstorey height is concentrated in the 2.50–3.50 m interval, and the floor area is mostly under 100 m². These distributions, shown in Figure 6, are representative of the predominant typologies of buildings in the studied region, characterized by compact footprints and modest vertical development.

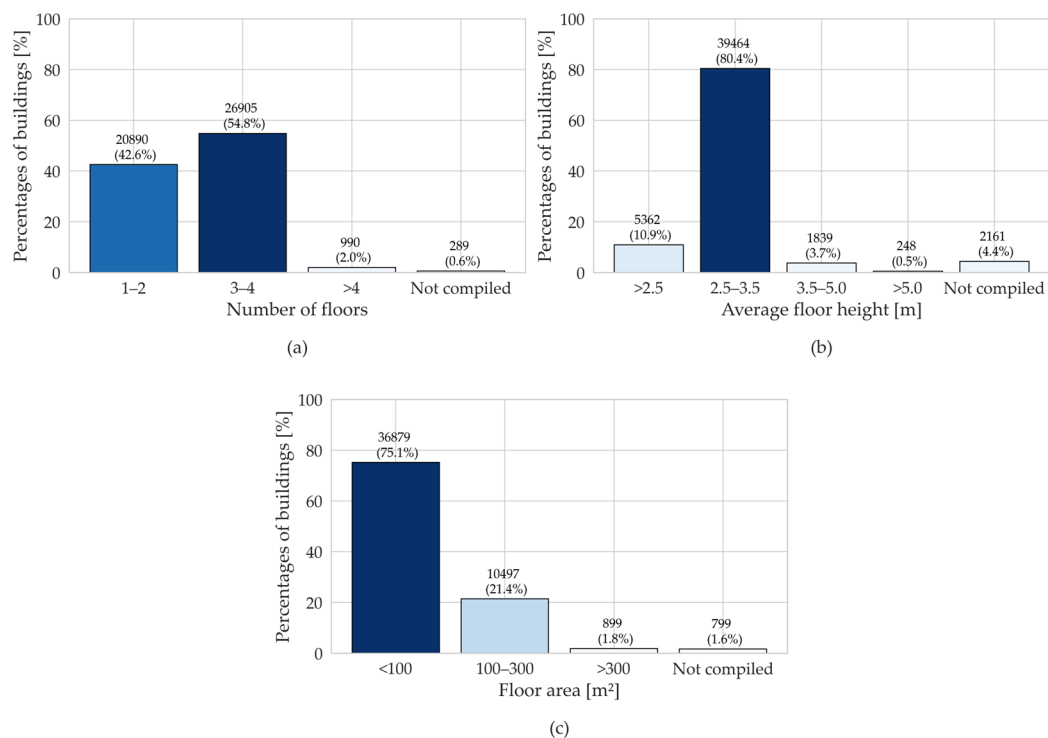


Figure 6. Distribution of number of floors (a), average floor height (b), and floor area (c). Data are from the Da.D.O. L'Aquila 2009 dataset [19,20].

In this paper, we focus exclusively on masonry buildings for the following reasons: (1) they constitute the highest percentage of the dataset, (2) they experienced the most

severe levels of damage but, at the same time, (3) a significant percentage of them remained lightly damaged or undamaged, (4) the macroseismic survey is mostly representative of the historic city centres, where the masonry buildings are predominant, and, finally, (5) the fragility model utilized in this analysis has been developed specifically for masonry structures (see Section 3). We applied standard preprocessing to the initial dataset to exclude entries with missing information on location, observed damage, and vulnerability classification. The final operative dataset used in the simulations consists, therefore, of 47,049 masonry buildings.

2.3. Initial Vulnerability Class and Observed Damage in the Da.D.O. Dataset

The information contained in the Da.D.O. dataset includes building identification, building description (number of floors, age, purpose of use, etc.), types of vertical and horizontal structures, damage to structural and non-structural elements, external danger induced by other constructions, and morphology of the site.

Using this information, an initial vulnerability score can be determined for each building. This score is categorical, ranging from level A (indicating the highest vulnerability) to level D2 (indicating the lowest vulnerability). The EMS-98 defines six vulnerability classes from A to F. The distinction between classes C1 and C2 and D1 and D2 has been introduced to adapt the scale to the Italian context ([20] and references therein). For masonry buildings, the vulnerability class based on the quality of the vertical structure, the horizontal structure, and the presence of chains (see Table 2) is assigned. Therefore, the resulting vulnerability classification for masonry buildings ranges from A to C1. The buildings constructed after the seismic Italian Law should be associated with D1 class, but there are very few of them and they are therefore classified as C1 class. For other typologies of construction, not considered here, a different method is adopted: reinforced concrete structures are assigned either in class C2 or D2 based on the year of construction with respect to the year of seismic classification of the municipality; steel and mixed buildings are assigned to D2 and C2, respectively.

Table 2. Vulnerability classes of masonry buildings, evaluated on the basis of some of their structural features, following the indications present on the Da.D.O. web platform [19,20]. Adapted from Table 10 in [20].

Vulnerability Class	Vertical Structure	Horizontal Structure	Chains
A	Bad quality	Vaults without chains, vaults with chains, deformable slab, semi-rigid slab, unidentified	No
	Bad quality	Vaults without chains, unidentified	Yes
	Good quality	Vaults without chains, vaults with chains, deformable slab, unidentified	No
B	Bad quality	Rigid slab	No
	Bad quality	Vaults with chains, deformable slab, semi-rigid slab, rigid slab	Yes
	Good quality	Semi-rigid slab	No
	Good quality	Vaults without chains, vaults with chains, deformable slab, unidentified	Yes
C1	Good quality	Rigid slab	No
	Good quality	Semi-rigid slab, rigid slab	Yes

In the numerical simulations, the vulnerability class of each building was iteratively updated based on the damage caused by the seismic ground motion intensity. The observed damage data served as the target reference for evaluating the simulation results. The four

potential issues described in the following should be addressed when working with the Da.D.O. dataset for the L'Aquila 2009 buildings.

First, while the buildings are categorized into vulnerability classes based on a limited number of structural features, alternative methods consider additional factors such as maintenance level, position, resonance effects, and topography. This raises the concern that the assigned vulnerability classes may not fully represent the true vulnerability of the building and, consequently, the observed damage.

Second, as already analyzed in [11], the L'Aquila 2009 dataset together with the Irpinia 1980 dataset are the only dataset in Da.D.O. that have the highest completeness ratio of 90%, which is the fraction of buildings surveyed during damage assessment campaigns compared to the total number of buildings reported by national census (for L'Aquila 2009, the reference census is the ISTAT 2001). However, some buildings in the dataset were completely surveyed, while others were assessed only partially or externally. This discrepancy is accounted for in [37], where different weights are applied to the damage on structural elements based on the level of assessment.

Third, according to the authors of the Da.D.O., the buildings were semi-automatically georeferenced by means of a tool developed by the Eucentre, with a reported error of 5–10% of buildings located at the barycentre of the municipality. However, we noted that some buildings are also located at the centroid of the locality, a smaller administrative boundary in Italy. These georeferencing errors could represent an issue when associating to the building the intensity value from the ShakeMap.

Finally, the source of the observed damage data in Da.D.O. is the AeDES ("Agibilità e Danno nell'Emergenza Sismica" in Italian) form [38,39], which has been used as the operational inspection tool for surveys after seismic emergencies since 1997, as defined by the DPC. For events prior to the introduction of the AeDES, different inspection tools and forms were used. This tool assesses the damage by evaluating the structural elements, assigning them one of four damage levels: D0 ("no damage"), D1 ("light damage"), D2/D3 ("moderate/severe damage"), and D4/D5 ("extremely severe damage"). Additionally, to quantify the extension of the damage, a value is assigned ranging from less than 1/3 to between 1/3 and 2/3 or greater than 2/3. In Da.D.O., an observed damage grade (D_{DaDO}) associated only with the vertical structure of the building is assigned. This damage grade is derived by employing a conversion table (Table 14 in [20]) that translates the damage levels and extensions from the AeDES form into the six levels of the EMS-98 from D0 to D5.

A global damage level is evaluated here by means of the expression provided in [37], which weighs the damage at the different structural elements based on the extension and damage level:

$$D_{Global} = \sum_{i=1}^5 w_i \sum_{j=1}^3 (2j-1)v_{i,j} \quad (1)$$

where the weights w_i for a given structural element, as anticipated, differ whether the survey was complete or partial; $v_{i,j}$ are the percentages of the structural element i (where $i = 1, \dots, 5$ corresponds to vertical structures, horizontal structures, stairs, roof, and infills) in which the damage j was observed (where $j = 1, \dots, 3$ correspond to the AeDES damage levels D1, D2/D3, and D4/D5). For detailed information regarding the formula and the values of the weights, please refer to the original article [37].

In Figure 7, for each vulnerability class, we compare the difference between the damage levels observed according to Da.D.O. method (D_{DaDO}) and to Equation (1) (D_{Global}).

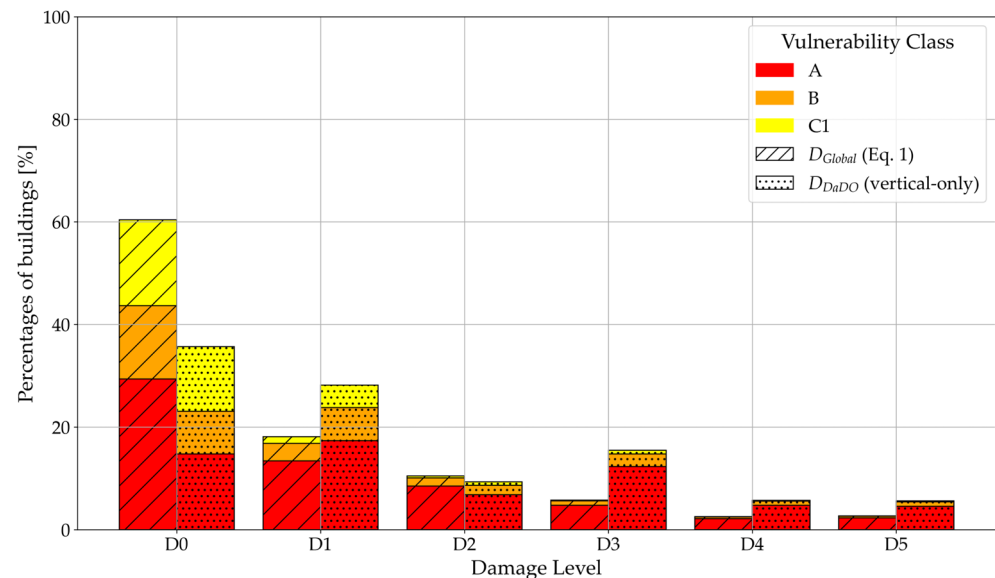


Figure 7. Distribution of the observed damage levels (D0–D5). For each damage level, stacked bars also illustrate the distribution of the initial vulnerability classes of the buildings: A (red), B (orange), and C1 (yellow). Diagonally hatched bars refer to the distribution of the global damage grade assigned using Equation (1), while dotted hatched bars represent the distribution of the damage grades estimated according to the method employed in Da.D.O. (representative of the vertical structural components only).

The D_{Global} damage distribution, representing a comprehensive elaboration of the observed damage, was used as a benchmark to assess the consistency of the simulated damage results.

3. Simulation of Damage Evolution

As anticipated in the Introduction, in this paper, we followed an approach proposed in recent studies [21,22], focused on the simulation of earthquake sequences in large urban areas and on the evaluation of the consequent seismic damage accumulation on buildings. The original approach was based on an agent-based model, which allows for the simulation of an artificial seismic sequence using an opportune version of the Olami–Feder–Christensen (OFC) model [40,41], to assess the resulting damage on an urban setting through a given fragility model, updating the vulnerability of the buildings and accumulating the damage after each event of the synthetic sequence. Differently, in this study, we incorporated data from real recorded seismic sequences and from observed damage datasets in order to evaluate the effects of different seismic inputs (either a single event or a sequence), in terms of fragility models, damage accumulation, and vulnerability evolution functions on damage scenarios simulations.

One of the main reasons for further developing the previous approach was the possibility of using the data from the Da.D.O. dataset, which allowed a more accurate calibration. To this aim, the OFC-based synthetic sequence was replaced with data from actual registered seismic sequences.

Given a list of georeferenced earthquakes as detailed in Paragraph 2.1, each building was assigned an intensity value I from the corresponding available macroseismic intensity ShakeMap generated by the INGV.

After the first shock, the most probable value of expected damage was assigned to each building based on a fragility model. In this study, we adopted the model developed by Lagomarsino, Cattari, and Ottonelli (2021) [37], hereinafter “L21”, which derived its methodology from the macroseismic model by Lagomarsino and Giovinazzi (2006) [6]

("L06") but was recalibrated on the Da.D.O. datasets. This calibration aimed at improving the regression of the vulnerability curves, which express the mean expected damage μ_D on each building as a function of the intensity I of the earthquake and of the building's vulnerability V :

$$\mu_D = \begin{cases} 2.5 \left[1 + \tanh\left(\frac{I+3.45V-11.7}{0.9+2.8V}\right) \right] & \text{for } V \geq 0.32 \\ 2.5 \left[1 + \tanh\left(\frac{I+6.25V-12.6}{1.8}\right) \right] & \text{for } V < 0.32 \end{cases} \quad (2)$$

In this paper, I is the instrumental intensity from the ShakeMap, which, as already detailed, was derived from recorded PGM and from ground motion models that take into account the amplification value of the soil below the building.

Each building was initially assumed to be in an undamaged state, namely D0, and it was assigned a starting vulnerability value V_0 , randomly selected within the plausible range corresponding to its vulnerability class, as defined by the fragility model (Table 3). It must be noted that the L21 model considers the standard EMS-98 classification of vulnerability from A to F. Since this study focuses on masonry buildings, only classes A, B and C1 were considered; with class C1 values adapted as the upper interval of class C.

Table 3. Vulnerability indices. Adapted from Table 10 in [37] and modified for vulnerability class C1.

Vulnerability Class	Plausible Range
A	0.95–1.05
B	0.75–0.85
C1	0.60–0.65

In order to consider the cumulative damage process related to repetitive events, a possible choice was the simple original strategy proposed by Greco et al. [21] for evaluating the reduction in structural performance associated with a sequence of earthquakes.

After each earthquake i , the mean damage level $\mu_{D,i}$ was computed according to the vulnerability model (Equation (2)), as a function of the seismic intensity I_i , felt at the building's site, and of the vulnerability V_{i-1} of the building, that is the updated vulnerability after the previous event. The building's damage level DL_i was then evaluated as the most probable mean damage level $\mu_{D,i}$. Then, the total damage level TDL_i for each building is defined as the sum of the damage levels DL_i for each previous seismic event. After being damaged, the building increases its vulnerability to V_i which is assumed to follow an update rule. Starting from the linear formulation proposed in [21], we tested several alternative functional forms: quadratic, sigmoidal, and exponential.

In this paper, we propose a new vulnerability update rule, Equation (3), based on the following constraints: (a) the initial vulnerability is assumed to vary from 0 to 1 or slightly exceeds this range, as it shown in the plausible ranges in Table 3; (b) to employ the fragility models, the vulnerability index is required to vary in those ranges; (c) the EMS-98 states that during a sequence, the vulnerability of an already damaged building might differ from its initial vulnerability; (d) however there is no data on how far could those intervals be extended or shifted for the vulnerability of a damaged building; and (e) Grimaz and Molisan's (2017) [42] proposition regarding the definition of a higher vulnerability class, A-, that would characterize buildings that have experienced a damage grade $\geq D3$ prior to the new shock. We have therefore tried to develop a vulnerability update rule that would increase more rapidly if a building has suffered a damage level equal to or greater than D3 after the previous event, and so that the updated vulnerability reaches its maximum as

the upper bound of the plausible range for a new class of vulnerability A-, as defined in Table 4.

Table 4. Proposal of a plausible range of initial vulnerability V_0 for the L21 fragility model.

Vulnerability Class	V_0 Plausible Range
A-	1.15–1.25

$$V_i^{EXP} = V_0 + (\max(A^-) - V_0) \frac{e^{k(TDL_i-3)} - e^{-3k}}{e^{2k} - e^{-3k}}, \quad k = 1/V_0 \quad (3)$$

In this case, the vulnerability increases with the damage following an exponential curve, as shown in Figure 8. Again, subsequent earthquakes can progressively injure both already damaged and undamaged buildings, increasing their Total Damage Level TDL_i . After the last event of the sequence, the final total damage level assigned to each building is converted into a categorical value, from D0 to D5.

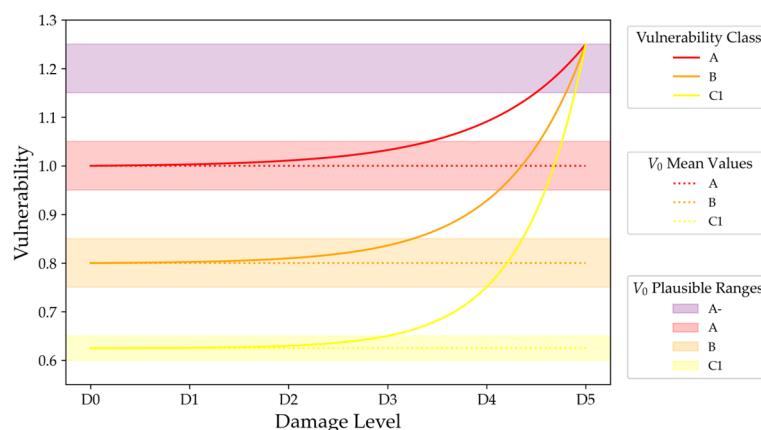


Figure 8. The vulnerability update rule proposed in this paper. The initial values (dotted lines) and the plausible ranges (shaded horizontal bars) are those estimated for the fragility model L21 (Table 3).

4. Results and Discussion

In this section, we apply the model to the data to address two main seismic scenarios: a mainshock-only scenario and a whole-sequence scenario.

To compare the simulation results with the observed data, the percentage distribution of buildings per vulnerability class across damage levels was computed and, both qualitatively and quantitatively, compared to the observed one by calculating the Root Mean Squared Error (RMSE) as follows:

$$RMSE = \sqrt{\frac{1}{6} \sum_{i=0}^5 (F_i^{obs} - F_i^{sim})^2} \quad (4)$$

where F_i^{obs} and F_i^{sim} are, respectively, the observed and simulated frequencies for each final damage level, from D0 to D5.

For a given model configuration, multiple simulation runs were performed, and the final damage distributions were averaged in order to obtain more reliable statistics. To assess how many runs are needed to stabilize the averaged quantities, we decided to produce $N = 100$ different realizations. To evaluate the stability of the simulation results, the mean damage level calculated over all the buildings at the end of each realization was computed by translating its D0–D5 categorical value into an integer value included in the range $[0, 5]$. This value has been further averaged over the previous realizations and plotted

as a function of the number of runs, together with its corresponding standard deviation. The stability results will be shown for each seismic scenario.

4.1. Mainshock-Only Scenario

In the mainshock-only scenario, the damage tends to be overestimated, likely as a result of the overprediction of the intensity values. Figure 9 shows the results of the damage distribution after the main event of Mw 6.1, considering all the masonry buildings present in the L'Aquila 2009 Da.D.O. dataset. Looking at the percentages of buildings presenting a given final simulated damage for each initial vulnerability class, it clearly appears that these percentages are significantly overestimated (in particular for intermediate levels of damage) when compared to the observed distribution.

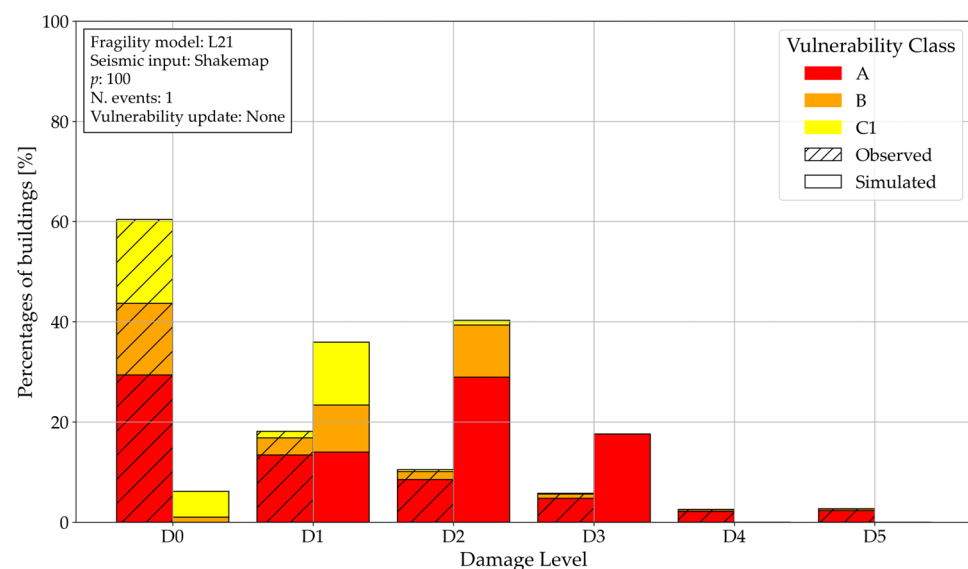


Figure 9. Distribution of final total damage levels simulated for the mainshock-only scenario, for $p = 100\%$ and using the L21 model (solid bars). For each damage level, stacked bars also illustrate the distribution of the initial vulnerability classes of the buildings: A (red), B (orange), and C1 (yellow). For comparison, the diagonally hatched bars refer to the distribution of the global damage grade D_{Global} shown in Figure 7. See text for further details.

To address this issue and account for the potential influence of additional factors not explicitly included in the model, a certain amount of randomness was incorporated into the analysis. This was achieved by assigning to each building an initial random vulnerability value within the range specified by its vulnerability class. Furthermore, for each seismic event, the number of buildings subjected to damage accumulation was randomly sampled using a control parameter p , which corresponds to the percentage of buildings located within each ShakeMap polygon (see Figure 1). We stress that each polygon is characterized by a unique value of the intensity.

Varying the p parameter and calculating for each value of p the Root Mean Squared Error RMSE between the simulated and observed damage distributions, we found that the minimum RMSE is observed at $p = 40\%$ (Figure 10).

The distribution associated with $p = 40\%$ is shown in Figure 11. The fragility model appears to fail to populate the highest damage grades, leaving room for testing the hypothesis of damage accumulation when applying it to the whole sequence.

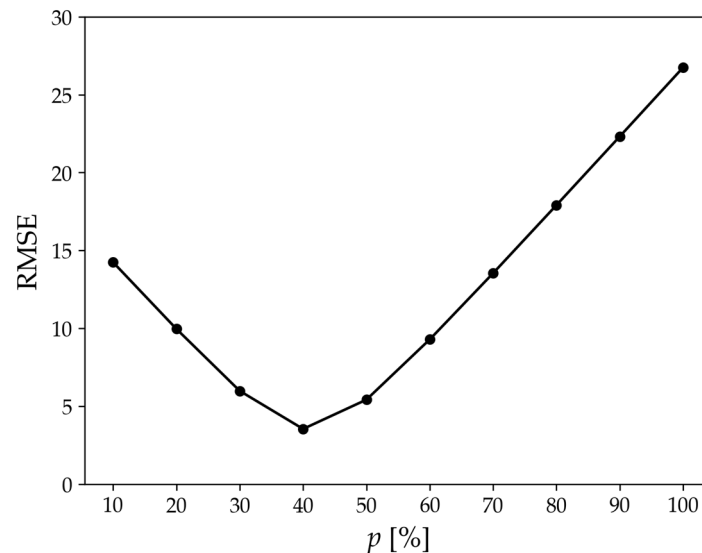


Figure 10. RMSE values, calculated between the observed and simulated damage distributions for the mainshock scenario, against parameter p from 10% to 100%. The minimum RMSE (3.53) is reached at $p = 40\%$.

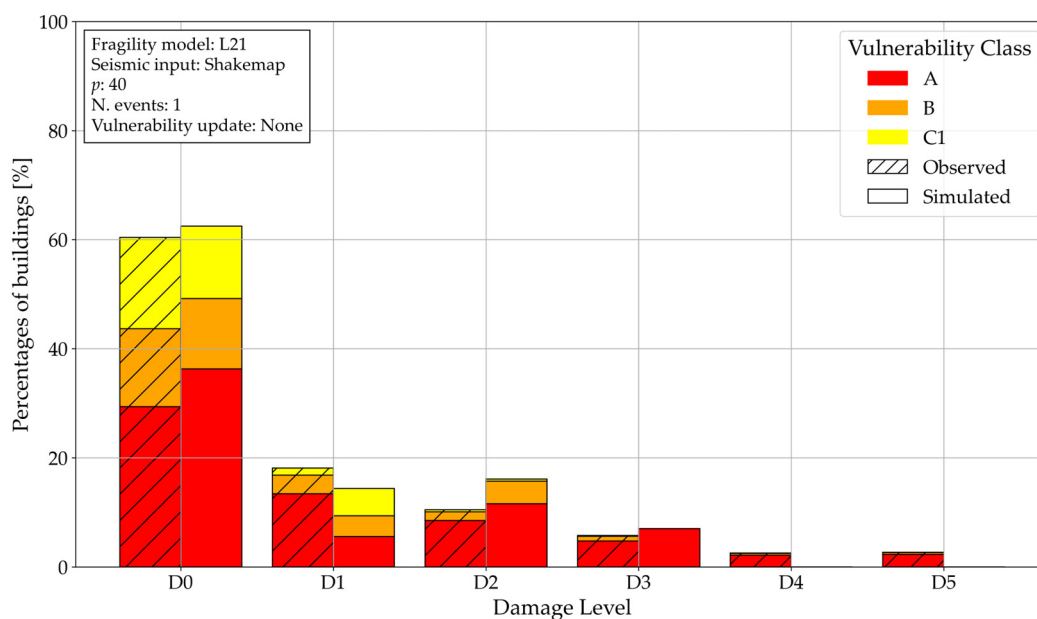


Figure 11. Distribution of final total damage levels simulated for the mainshock-only scenario, for $p = 40\%$ and using the L21 model (solid bars). For each damage level, stacked bars also illustrate the distribution of the initial vulnerability classes of the buildings: A (red), B (orange), and C1 (yellow). For comparison, the diagonally hatched bars refer to the distribution of the global damage grade D_{Global} shown in Figure 7. See text for further details.

As anticipated, a stability analysis was performed on the simulations. The results in Figure 12 show the stability plot for the mainshock-only scenario simulated for $p = 40\%$ and using L21 as the fragility model. The average value quickly converges to around 1.693 (red dashed line in Figure 12) and remains constant, with its standard deviation, after approximately 30 simulation runs. This indicates that the simulation produces consistent and reliable results already beyond this threshold. However, as expected, the mean simulated value overestimates the observed mean final damage (0.799), indicating potential systematic bias in the simulation or the need for further refinement of the model parameters.

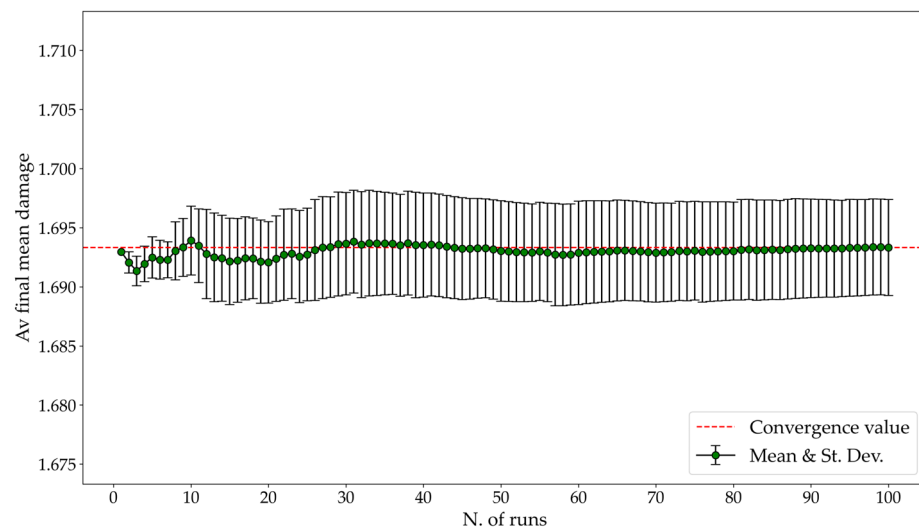


Figure 12. Stability plot over 100 runs for the mainshock-only scenario using L21 and for $p = 40\%$: the mean final damage level (converted from the categorical values D0–D5 to a numerical continuous value in the range 0–5) at the end of each run is averaged with the values of the previous runs. This quantity, as shown in the plot in green dots, converges after 30 simulation runs to around 1.693 (red dashed line), which represents the mean of the final mean damage values obtained in the 100 runs. The standard deviation (black error bar) also stabilizes at around 0.004.

4.2. 18-Event Scenario

We selected, from the L'Aquila 2009 sequence, the events of moment magnitude greater than Mw 4.0 only, hereinafter referred to as the “18-event scenario”. To assess which value of p would mitigate the effect of the overestimated intensity and simulate a distribution that best represents the observed data, the Root Mean Squared Error (RMSE) was calculated for different values of p (Figure 13).

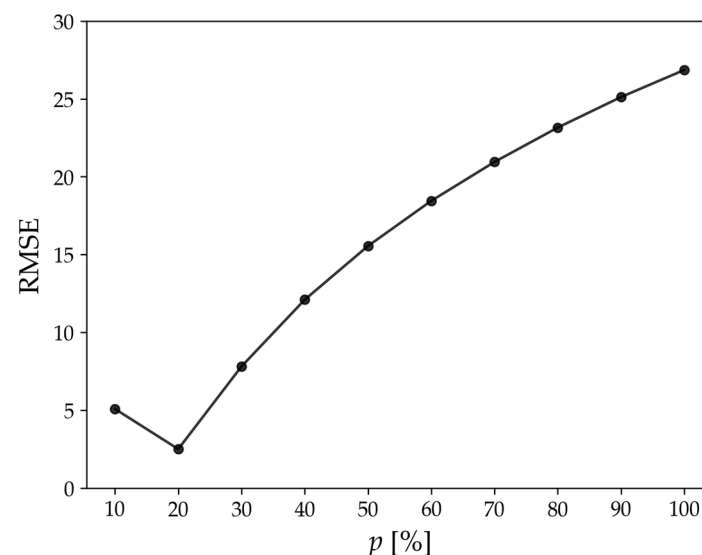


Figure 13. RMSE values against parameter p from 10% to 100% for fragility model L21 using the vulnerability update rule proposed in this study. The minimum RMSE (2.50) is reached at $p = 20\%$. See text for details.

Based on the results, the simulated distribution at $p = 20\%$ was identified as the most representative of the observed data.

To be noted, the value $p = 20\%$ means that for each intensity value of a ShakeMap, 20% of the buildings associated with that intensity (i.e., included within the corresponding

polygon) are randomly selected to be damaged. The selection of buildings within this 20% varies for each seismic event of the sequence. As a result, at the end of the sequence, the total number of buildings that have experienced damage at least once is approximately 98.2% of the overall building stock. By reflecting the proportion of buildings sampled in relation to their corresponding intensity values, this approach introduces randomness while ensuring a meaningful representation of the observed data.

The final damage distribution, shown in Figure 14, indicates that the simulation obtained by combining the L21 fragility model with the proposed update rule shows a better qualitative agreement with the observed damage data.

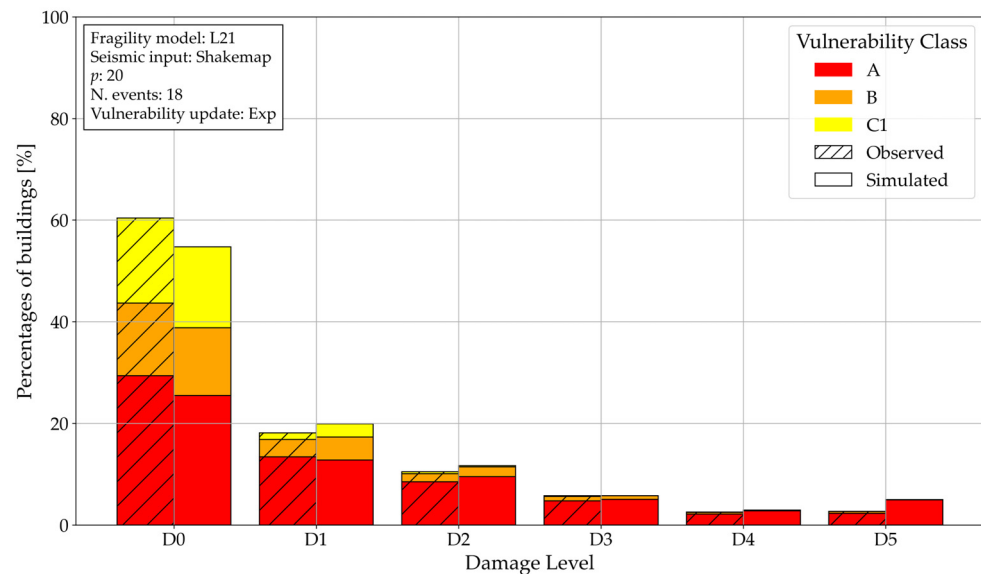


Figure 14. Distribution of final total damage levels simulated for the 18-event scenario for $p = 20\%$ and using the L21 model as well as the proposed vulnerability update rule (solid bars). For each damage level, stacked bars also illustrate the distribution of the initial vulnerability classes of the buildings: A (red), B (orange), and C1 (yellow). For comparison, the diagonally hatched bars refer to the distribution of the global damage grade D_{Global} shown in Figure 7. See text for further details.

A stability analysis was also performed on this case scenario. The results in Figure 15 show the stability plot for the 18-event scenario simulated for $p = 20\%$ and using L21 as the fragility model, with the proposed exponential vulnerability update rule. The average value quickly converges to around 0.990 and remains constant, with its standard deviation, after approximately 15 simulation runs. In this final case, the mean simulated value slightly overestimates the observed mean final damage (0.799), indicating an improved agreement with the observed data.

Finally, to assess the reliability of the control parameter p , we conducted a series of simulations in which each earthquake of the sequence was removed in turn, and the RMSE between the new final damage simulated and the observed data was calculated. Results in Figure 16 show that the RMSE remains stable across the different sequences, indicating that the calibration of p is robust with respect to variations in the seismic input, although we noted slight oscillations in correspondence with the sequence simulated by removing an earthquake of magnitude greater than Mw 5.0.

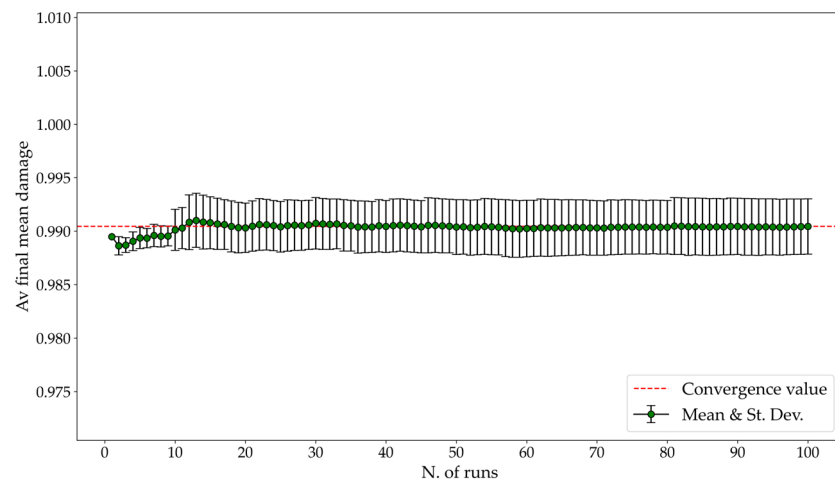


Figure 15. Stability plot over 100 runs for the 18-event scenario using L21 and for $p = 20\%$ and exponential vulnerability update rule. The averaged value (green dots) converges after 15 simulation runs to around 0.990 (red dashed line). The standard deviation (black error bars) also stabilizes at around 0.002. See text for further details on the plotted quantities and for the comparison with Figure 12.

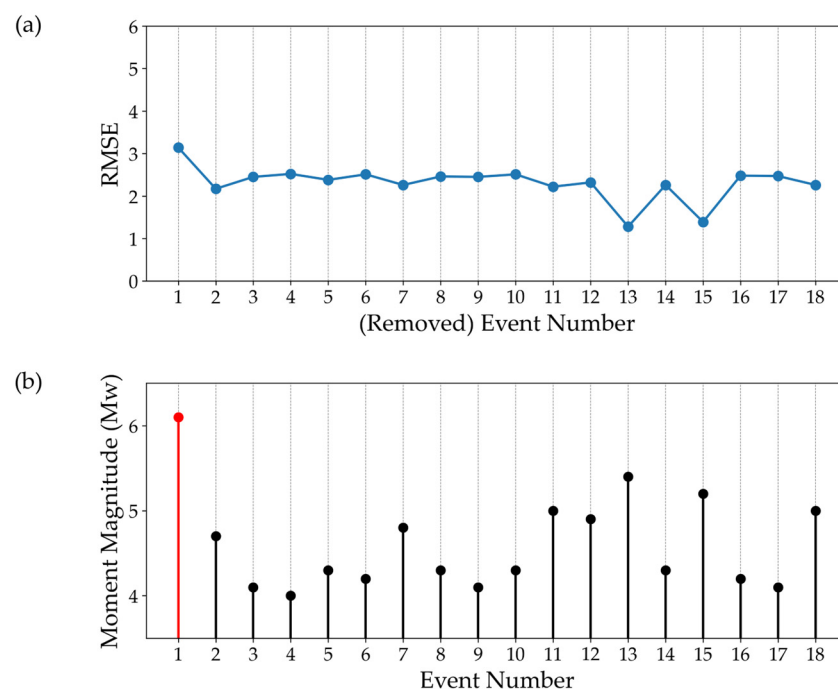


Figure 16. (a) RMSE values obtained by removing a single event from the seismic sequence of eighteen earthquakes. The event index on the x-axis indicates which earthquake was excluded (e.g., the first RMSE value corresponds to removing only the mainshock; the second to removing only the second event, and so on); (b) chronological sequence of the 18 earthquakes, with their corresponding moment magnitudes. The red marker indicates the mainshock.

4.3. Discussion

It is interesting to point out that, although model L21 has been calibrated assuming that the observed Da.D.O. damage scenario was caused only by the mainshock (first event of the sequence), the damage distribution resulting from our simulation of the mainshock-only scenario (see Figure 11) already shows quite a good agreement with real data. On the other hand, taking into account the 18-event sequence, the correspondence between simulated and real damage distribution improves significantly (see Figure 14),

thus confirming the importance of considering the cumulative effects due to the entire available seismic sequence.

Some challenges and limitations of this study can also be identified as follows. The available ShakeMaps produced by the INGV for the L'Aquila 2009 sequence were generated using a previous configuration of the ShakeMap software, which relied on a GMICE known to overestimate the intensity. To mitigate the effect of this overprediction, we introduced the control parameter p to reduce the percentage of buildings affected by damage. A better solution could involve recalculating the ShakeMaps for each event employing the most recent ground motion models, such as the GMICE by Oliveti et al. [34], which is already implemented in the current version of the INGV software adaptation, or the Lanzano et al. GMPE [43], which offers an improvement over the ITA10 model.

On the other hand, we acknowledge that a fixed value of p might not capture possible dependencies on seismic intensity or on the spatial distribution of the buildings' vulnerability. Therefore, future model developments could integrate a more dynamic formulation of p .

Additionally, the initial vulnerability classification in the Da.D.O. dataset was based on a few structural features, potentially overlooking factors like maintenance, topography, and resonance effects. This may have led to the underrepresentation of the actual building vulnerability.

Another limitation lies in the assumption that all buildings were undamaged prior to the earthquake, whereas the QUEST report highlighted the presence of buildings in a state of deterioration and pre-existing damage. Such factors could significantly influence the observed damage patterns and should be taken into account in future analysis for a more accurate assessment. Furthermore, the study relied on damage data supposedly representative of the scenario observed at the end of the seismic sequence. Integrating information on damage progression would provide valuable insights for future simulations to ensure an optimal implementation. Finally, while our analysis focuses on masonry structures and applies a fragility model as a function of macroseismic intensity, recent studies highlight that alternative or more complex intensity measures (IMs) can improve fragility predictions, not only for masonry buildings [44,45] but also for other structural materials [46–48]. Therefore, while our methodology provides consistent insights for masonry, extending the approach to also buildings of different construction types and employing alternative IMs represents a direction for future research.

5. Conclusions

This study focused on understanding and modelling the damage scenario caused by the L'Aquila 2009 sequence in the Abruzzo area, testing the potential effect of damage accumulation and investigating several aspects that might have contributed to the observed final damage distribution. Aiming at reproducing accurately the seismic input responsible for the observed scenario, we employed the instrumentally derived value from the ShakeMaps produced by the INGV as the intensity input for the fragility model. From the extensive dataset of buildings available by Da.D.O., we used the information on the initial vulnerability classes and on the damage levels observed at the end of the sequence. We focused on masonry buildings, which are the most vulnerable and representative building types in historic city centres. In this study, we explored the hypothesis that, during a sequence, the buildings exposed to several seismic actions increase their vulnerability and therefore might be affected by greater overall damage due to the accumulation of damage coming from shocks of smaller intensity. Preliminary simulations, employing the fragility model L21 and updating the vulnerability through a new rule proposed in this study, have shown a noticeable agreement with the observed damage distribution when

considering the entire 18-event sequence of earthquakes with magnitudes greater than Mw 4.0. Nevertheless, limitations remain related to the overestimation of the seismic input in the ShakeMaps, the simplified vulnerability classification, and the fixed formulation of the control parameter.

Future research will address the identified criticalities in order to further enhance the robustness and applicability of this methodology in simulating various seismic damage scenarios.

In conclusion, the present study demonstrates promising results, and the proposed upgraded model could be applied, in future research, to other building datasets in different seismically active areas, subject to either real or artificial seismic sequences.

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Abbreviations

The following abbreviations are used in this manuscript:

AeDES	Agibilità e Danno nell’Emergenza Sismica
Da.D.O.	Database del Danno Osservato
DPM	Damage Probability Matrix
DPC	Department of Civil Protection
EMS-98	European Macroseismic Scale
GEM	Global Earthquake Model Foundation
GMPE	Ground Motion Prediction Equation
GMICE	Ground Motion to Intensity Conversion Equation
INGV	National Institute of Geophysics and Volcanology
IRMA	Italian Risk Maps
MCS	Mercalli–Cancani–Sieberg
MLA	Machine Learning Algorithm
PBEE	Physics-Based Performance Engineering
PGA	Peak Ground Acceleration
PGM	Peak Ground Motion
PGV	Peak Ground Velocity
PSHA	Probabilistic Seismic Hazard Assessment
QUEST	Quick Earthquake Survey Team
RC	Reinforced Concrete
RMSE	Root Mean Squared Error
RVS	Rapid Visual Screening
SA	Spectral Acceleration
USGS	United States Geological Society
UTC	Coordinated Universal Time
VIM	Vulnerability Index Method

References

- Greco, A.; Caddemi, S.; Calì, I.; Fiore, I. A Review of Simplified Numerical Beam-like Models of Multi-Storey Framed Buildings. *Buildings* **2022**, *12*, 1397. [\[CrossRef\]](#)
- Greco, A.; Fiore, I.; Occhipinti, G.; Caddemi, S.; Spina, D.; Calì, I. An Equivalent Non-Uniform Beam-Like Model for Dynamic Analysis of Multi-Storey Irregular Buildings. *Appl. Sci.* **2020**, *10*, 3212. [\[CrossRef\]](#)
- Fiore, I.; Caddemi, S.; Calì, I.; Greco, A. An Inelastic Beam-Like Model for Nonlinear Dynamic Analyses of Multi-Storey Buildings. *Eng. Struct.* **2024**, *308*, 117852. [\[CrossRef\]](#)
- Perrone, D.; Aiello, M.A.; Pecce, M.; Rossi, F. Rapid Visual Screening for Seismic Evaluation of RC Hospital Buildings. *Structures* **2015**, *3*, 57–70. [\[CrossRef\]](#)
- Mouroux, P.; Le Brun, B. Risk-UE Project: An Advanced Approach to Earthquake Risk Scenarios with Application to Different European Towns. In *Assessing and Managing Earthquake Risk*; Oliveira, C.S., Roca, A., Goula, X., Eds.; Geotechnical, Geological and Earthquake Engineering; Springer: Dordrecht, The Netherlands, 2008; Volume 2, pp. 479–508. [\[CrossRef\]](#)
- Lagomarsino, S.; Giovinazzi, S. Macroseismic and Mechanical Models for the Vulnerability and Damage Assessment of Current Buildings. *Bull. Earthq. Eng.* **2006**, *4*, 415–443. [\[CrossRef\]](#)
- Grünthal, G. (Ed.) *European Macroseismic Scale 1998*; Cahiers du Centre Européen de Géodynamique et de Séismologie; Conseil de l'Europe: Luxembourg, 1998.
- Eleftheriadou, A.K.; Karabinis, A.I. Evaluation of damage probability matrices from observational seismic damage data. *Earthq. Struct.* **2013**, *4*, 299–324. [\[CrossRef\]](#)
- Li, S.Q.; Chen, Y.S. Analysis of the Probability Matrix Model for the Seismic Damage Vulnerability of Empirical Structures. *Nat. Hazards* **2020**, *104*, 705–730. [\[CrossRef\]](#)
- Surana, M.; Meslem, A.; Singh, Y.; Lang, D.H. Analytical Evaluation of Damage Probability Matrices for Hill-Side RC Buildings Using Different Seismic Intensity Measures. *Eng. Struct.* **2020**, *207*, 110254. [\[CrossRef\]](#)
- Rosti, A.; Rota, M.; Penna, A. Empirical fragility curves for Italian URM buildings. *Bull. Earthq. Eng.* **2021**, *19*, 3057–3076. [\[CrossRef\]](#)
- Da Porto, F.; Donà, M.; Rosti, A.; Rota, M.; Lagomarsino, S.; Cattari, S.; Borzi, B.; Onida, M.; De Gregorio, D.; Perelli, F.L.; et al. Comparative Analysis of the Fragility Curves for Italian Residential Masonry and RC Buildings. *Bull. Earthq. Eng.* **2021**, *19*, 3209–3252. [\[CrossRef\]](#)
- Ferranti, G.; Greco, A.; Pluchino, A.; Rapisarda, A.; Scibilia, A. Seismic Vulnerability Assessment at Urban Scale by Means of Machine Learning Techniques. *Buildings* **2024**, *14*, 309. [\[CrossRef\]](#)
- Pagani, M.; Monelli, D.; Weatherill, G.; Danciu, L.; Crowley, H.; Silva, V.; Henshaw, P.; Butler, L.; Nastasi, M.; Panzeri, L.; et al. OpenQuake Engine: An Open Hazard (and Risk) Software for the Global Earthquake Model. *Seismol. Res. Lett.* **2014**, *85*, 692–702. [\[CrossRef\]](#)
- Borzi, B.; Onida, M.; Faravelli, M.; Polli, D.; Pagano, M.; Quaroni, D.; Cantoni, A.; Speranza, E.; Moroni, C. IRMA Platform for the Calculation of Damages and Risks of Italian Residential Buildings. *Bull. Earthq. Eng.* **2021**, *19*, 3033–3055. [\[CrossRef\]](#)
- Iervolino, I.; Chioccarelli, E.; Suzuki, A. Seismic Damage Accumulation in Multiple Mainshock–Aftershock Sequences. *Earthq. Eng. Struct. Dyn.* **2020**, *49*, 1007–1027. [\[CrossRef\]](#)
- Lazaridis, P.C.; Kavvadias, I.E.; Demertzis, K.; Iliadis, L.; Papaleonidas, A.; Vasiliadis, L.K.; Elenas, A. Structural Damage Prediction Under Seismic Sequence Using Neural Networks. In Proceedings of the 8th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPdyn 2021), Athens, Greece, 28–30 June 2021; ECCOMAS Proceedia: Athens, Greece, 2021; pp. 3820–3836. [\[CrossRef\]](#)
- Yuan, X.; Li, L.; Zhang, H.; Zhu, Y.; Chen, G.; Dagli, C. Machine Learning-Based Seismic Damage Assessment of Residential Buildings Considering Multiple Earthquake and Structure Uncertainties. *Nat. Hazards Rev.* **2023**, *24*, 04023024. [\[CrossRef\]](#)
- Dataset Developed by Eucentre (European Center for Training and Research in Seismic Engineering); Dolce, M.; Speranza, E.; Giordano, F.; Borzi, B.; Bocchi, F.; Conte, C.; Di Meo, A.; Faravelli, M.; Pascale, V. Da.D.O.—Uno Strumento per la Consultazione e la Comparazione del Danno Osservato Relativo ai Più Significativi Eventi Sismici in Italia dal 1976. In *Atti del XVII Convegno ANIDIS “L’ingegneria Sismica in Italia”*; Pisa University Press: Pisa, Italy; pp. 347–357, ISBN 978-886741-854-1. Available online: http://egeos.eucentre.it/danno_osservato/web/danno_osservato (accessed on 29 June 2024).
- Dolce, M.; Speranza, E.; Giordano, F.; Borzi, B.; Bocchi, F.; Conte, C.; Di Meo, A.; Faravelli, M.; Pascale, V. Observed Damage Database of Past Italian Earthquakes: The Da.D.O. WebGIS. *Boll. Geofis. Teor. Appl.* **2019**, *60*, 141–164. [\[CrossRef\]](#)
- Greco, A.; Pluchino, A.; Barbarossa, L.; Barreca, G.; Calì, I.; Martinico, F.; Rapisarda, A. A New Agent-Based Methodology for the Seismic Vulnerability Assessment of Urban Areas. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 274. [\[CrossRef\]](#)
- Fischer, E.; Barreca, G.; Greco, A.; Martinico, F.; Pluchino, A.; Rapisarda, A. Seismic risk assessment of a large metropolitan area by means of simulated earthquakes. *Nat. Hazards* **2023**, *118*, 117–153. [\[CrossRef\]](#)
- Wald, D.J.; Quitoriano, V.; Heaton, T.H.; Kanamori, H.; Scrivner, C.W.; Worden, C.B. TriNet “ShakeMaps”: Rapid generation of peak ground motion and intensity maps for earthquakes in Southern California. *Earthq. Spectra* **1999**, *15*, 537–555. [\[CrossRef\]](#)

24. Michelini, A.; Faenza, L.; Lauciani, V.; Malagnini, L. Shakemap implementation in Italy. *Seismol. Res. Lett.* **2008**, *79*, 688–697. [[CrossRef](#)]
25. Michelini, A.; Faenza, L.; Lanzano, G.; Lauciani, V.; Jozinović, D.; Puglia, R.; Luzi, L. The new ShakeMap in Italy: Progress and advances in the last 10 years. *Seismol. Res. Lett.* **2020**, *91*, 317–333. [[CrossRef](#)]
26. Sorrentino, L.; Giresini, L. Risk Assessment of Road Blockage after Earthquakes. *Buildings* **2024**, *14*, 984. [[CrossRef](#)]
27. Galli, P.; Camassi, R. (Eds.) *Rapporto Sugli Effetti del Terremoto Aquilano del 6 Aprile 2009*; Rapporto Tecnico QUEST; DPC-INGV: Roma, Italy, 2009; 12p. (In Italian) [[CrossRef](#)]
28. Chiarabba, C.; Amato, A.; Anselmi, M.; Baccheschi, P.; Bianchi, I.; Cattaneo, M.; Cecere, G.; Chiaraluce, L.; Ciaccio, M.G.; De Gori, P.; et al. The 2009 L'Aquila (Central Italy) M_W 6.3 Earthquake: Main Shock and Aftershocks. *Geophys. Res. Lett.* **2009**, *36*, 2009GL039627. [[CrossRef](#)]
29. Chiaraluce, L.; Valoroso, L.; Piccinini, D.; Di Stefano, R.; De Gori, P. The Anatomy of the 2009 L'Aquila Normal Fault System (Central Italy) Imaged by High Resolution Foreshock and Aftershock Locations. *J. Geophys. Res.* **2011**, *116*, B12311. [[CrossRef](#)]
30. Sieberg, A. Scala MCS (Mercalli-Cancani-Sieberg). *Geol. Der Erdbeben Handb. Der Geophys.* **1930**, *2*, 552–555.
31. Faenza, L. Rapid Determination of the Shakemaps for the L'Aquila Main Shock: A Critical Analysis. *BGTA* **2011**, *52*, 407–425. [[CrossRef](#)]
32. Faenza, L.; Michelini, A. Regression Analysis of MCS Intensity and Ground Motion Parameters in Italy and Its Application in ShakeMap. *Geophys. J. Int.* **2010**, *180*, 1138–1152. [[CrossRef](#)]
33. Bindi, D.; Pacor, F.; Luzi, L.; Puglia, R.; Massa, M.; Ameri, G.; Paolucci, R. Ground motion prediction equations derived from the Italian strong motion database. *Bull. Earthq. Eng.* **2011**, *9*, 1899–1920. [[CrossRef](#)]
34. Oliveti, I.; Faenza, L.; Michelini, A. New reversible relationships between ground motion parameters and macroseismic intensity for Italy and their application in ShakeMap. *Geophys. J. Int.* **2022**, *231*, 1117–1137. [[CrossRef](#)]
35. Oliveti, I.; Faenza, L.; Michelini, A. INGe: Intensity-ground motion data set for Italy. *Ann. Geophys.* **2022**, *65*, DM102. [[CrossRef](#)]
36. Rossetto, T.; Peiris, N.; Alarcon, J.E.; So, E.; Sargeant, S.; Free, M.; Sword-Daniels, V.; Del Re, D.; Libberton, C.; Verrucci, E.; et al. Field observations from the Aquila, Italy earthquake of April 6, 2009. *Bull. Earthq. Eng.* **2009**, *9*, 11–37. [[CrossRef](#)]
37. Lagomarsino, S.; Cattari, S.; Ottonelli, D. The heuristic vulnerability model: Fragility curves for masonry buildings. *Bull. Earthq. Eng.* **2021**, *19*, 3129–3163. [[CrossRef](#)]
38. Baggio, C.; Bernardini, A.; Colozza, R.; Corazza, L.; Della Bella, M.; Di Pasquale, G.; Dolce, M.; Goretti, A.; Martinelli, A.; Orsini, G.; et al. *Manuale per la Compilazione Della Scheda di 1° Livello di Rilevamento del Danno, Pronto Intervento e Agibilità per Edifici Ordinari Nell'Emergenza Post-Sismica (AeDES)*, 1st ed.; Dipartimento della Protezione Civile: Roma, Italy, 2002.
39. Dolce, M.; Papa, F.; Pazza, A. *Manuale per la Compilazione Della Scheda di 1° Livello di Rilevamento del Danno, Pronto Intervento e Agibilità per Edifici Ordinari Nell'Emergenza Post-Sismica (AeDES)*, 2nd ed.; Dipartimento della Protezione Civile: Roma, Italy, 2014.
40. Caruso, F.; Pluchino, A.; Latora, V.; Vinciguerra, S.; Rapisarda, A. A new analysis of Self-Organized Criticality in the OFC model and in real earthquakes. *Phys. Rev. E* **2007**, *75*, 055101(R). [[CrossRef](#)]
41. Caruso, F.; Latora, V.; Pluchino, A.; Rapisarda, A.; Tadić, B. Olami-Feder-Christensen Model on Different Networks. *Eur. Phys. J. B* **2006**, *50*, 243–247. [[CrossRef](#)]
42. Grimaz, S.; Malisan, P. How could cumulative damage affect the macroseismic assessment? *Bull. Earthq. Eng.* **2017**, *15*, 2465–2481. [[CrossRef](#)]
43. Lanzano, G.; Luzi, L.; Pacor, F.; Felicetta, C.; Puglia, R.; Sgobba, S.; D'Amico, M. A revised ground-motion prediction model for shallow crustal earthquakes in Italy. *Bull. Seismol. Soc. Am.* **2019**, *109*, 525–540. [[CrossRef](#)]
44. Caicedo, D.; Tomić, I.; Karimzadeh, S.; Bernardo, V.; Beyer, K.; Lourenço, P.B. Optimal Intensity Measure and Probabilistic Seismic Demand Model for the Assessment of Historical Masonry Buildings: Application to Two Case Studies. *Reliab. Eng. Syst. Saf.* **2025**, *261*, 111149. [[CrossRef](#)]
45. Gehl, P.; Seyedi, D.M.; Douglas, J. Vector-Valued Fragility Functions for Seismic Risk Evaluation. *Bull. Earthq. Eng.* **2013**, *11*, 365–384. [[CrossRef](#)]
46. Muho, E.V.; Kalapodis, N.A.; Beskos, D.E. Multi-Modal and Multi-Level Structure-Specific Spectral Intensity Measures for Seismic Evaluation of Reinforced Concrete Frames. *Bull. Earthq. Eng.* **2024**, *22*, 6955–6989. [[CrossRef](#)]
47. Monsalvo Franco, I.E.; Smerzini, C.; Rosti, A.; Rota, M.; Paolucci, R.; Penna, A. Seismic Fragility Curves with Unconventional Ground Motion Intensity Measures from Physics-Based Simulations. *Bull. Earthq. Eng.* **2025**, *23*, 1885–1915. [[CrossRef](#)]
48. Kalapodis, N.A.; Muho, E.V.; Beskos, D.E. Structure-Specific, Multi-Modal and Multi-Level Scalar Intensity Measures for Steel Plane Frames. *Soil Dyn. Earthq. Eng.* **2025**, *190*, 109185. [[CrossRef](#)]

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