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Preliminary analysis of the damage data collected after the 2016 Central Italy seismic sequence through AeDES forms

Gianluca Salamida^{a,*}, Nicola Buratti^b, Claudio Mazzotti^b

^aInterdepartmental Center for Industrial Research - Building and Construction, University of Bologna, Via del Lazzaretto 15/5, 40131 Bologna, Italy

^bDepartment of Civil, Chemical, Environmental, and Materials Engineering, University of Bologna, Viale del Risorgimento 2, 40136 Bologna, Italy

Abstract

Seismic risk assessment is a topic of primary importance for the Italian territory, as demonstrated by the seismic events of the last decades (2009 L'Aquila, 2012 Emilia and 2016 Central Italy). In this perspective, the seismic vulnerability of existing buildings, which can be assessed with the probability of exceeding a certain damage threshold depending on a seismic input, is still a very open topic. In the present work, a preliminary analysis was conducted on the damage observed following the 2016 Central Italy seismic sequence, collected in the AeDES forms. The observed damage was converted into five damage levels, according to the European Macroseismic Scale (EMS-98). Information on undamaged buildings was gathered from census data. Based on the sample of buildings obtained, the main taxonomies were defined. Furthermore, for the various events of the seismic sequence, the ground motion intensity at the base of each building was calculated, and Damage Probability Matrices were defined. This work represents the first step in a study aimed to develop seismic vulnerability models for existing buildings in central Italy, based on the damage observed in these areas.

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* Corresponding author. Tel.: +39-051-2093246.

E-mail address: gianluca.salamida2@unibo.it

1. Introduction

A fundamental element in reducing seismic risk is knowledge of the existing building stock characteristics and the seismic vulnerability assessment of buildings. Typically, this is based on fragility models, which estimate the probability of exceeding a certain damage in buildings, given a Ground Motion Intensity Measure (IM). Fragility can be expressed, in its most basic form, with Damage Probability Matrices (DPMs) – Eleftheriadou et al. (2013), Calvi et al. (2006). Historically, after large-scale seismic events, numerous studies have been conducted on the fragility assessment, at different territorial scales and using different approaches: Brando et al. (2021), Ferlito et al. (2013), Polese et al. (2020), Rosti et al. (2021), Zuccaro et al. (2021), Donà et al. (2021). After the 2009 L'Aquila earthquake, Del Gaudio et al. (2019) proposed empirical fragility curves based on damage to masonry buildings. Ioannou et al. (2021) developed fragility models for unreinforced masonry (URM) buildings, based on the damage observed after the 2012 Emilia earthquake. For the same seismic sequence, Monteferrante et al. (2025), developed fragility models based on observed damage from AeDES forms - Baggio et al. (2009) – and building-by-building census data, for different building classes, based on the construction age and the storey number. Based on the observed damage on a sample of 2263 buildings struck by the 2016 Central Italy earthquake, Saretta et al. (2023), proposed a set of fragility models for masonry buildings, considering four different vulnerability classes.

The present work represents a preliminary study on large scale damage data collected after the 2016-2017 Central Italy seismic sequences, through AeDES forms. In particular, following the approach adopted by Monteferrante et al. (2025), data on damaged and undamaged buildings were gathered in a dataset, by using, respectively, AeDES forms and building-by-building census data. The work focused on the analysis of the building stock features and the damage distribution. Shake maps were calculated for the mainshocks and PGA was estimated for each building in the dataset. Finally, basic point-wise fragility was evaluated through DPM.

2. Seismic sequence

In the period between August 2016 and January 2017, Central Italy was hit by a series of important seismic sequences. On August 24, 2016, a first shock of magnitude 6.0 hit the area between the municipalities of Accumoli, Amatrice and Arquata del Tronto. On October 26, 2016, new shocks, were recorded with epicenter between the municipalities of Ussita, Visso and Castelsantangelo sul Nera, with magnitude up to 5.9. On October 30, a violent shock of 6.6 magnitude hit the area between the municipalities of Preci and Norcia. A final seismic sequence was recorded on January 18, 2017, with epicenters affecting the municipalities of Capitignano and Montereale. The main shocks of the aforementioned seismic sequences are shown in Table 1.

Table 1. Main shocks of the 2016-2017 Central Italy seismic sequences: the ones with moment magnitude ≥ 5 are reported.

Earthquake ID	Time	Municipality	Mw	Depth [km]	Epicentre lon. [°]	Epicentre lat. [°]
EMSC-20160824_0000006	24/08/2016 01:36	Accumoli	6.0	8.1	13.234	42.698
EMSC-20160824_0000013	24/08/2016 02:33	-	5.5	6.3	13.161	42.798
EMSC-20161026_0000077	26/10/2016 17:10	Visso	5.5	3.4	13.14	42.888
EMSC-20161026_0000095	26/10/2016 19:18	Castelsantangelo sul Nera	5.9	2.1	13.141	42.91
EMSC-20161030_0000029	30/10/2016 06:40	-	6.6	6.2	13.123	42.838
EMSC-20170118_0000027	18/01/2017 09:25	Capitignano	5.1	8.7	13.298	42.565
EMSC-20170118_0000034	18/01/2017 10:14	Capitignano	5.5	9.3	13.291	42.559
EMSC-20170118_0000037	18/01/2017 10:25	Montereale	5.4	8.6	13.293	42.531
EMSC-20170118_0000119	18/01/2017 13:33	Montereale	5.0	10.6	13.275	42.494

3. Buildings dataset

In this work, the damage observed in the buildings was obtained from AeDES forms, acronym of Habitability and Damage in Seismic Emergency. These forms are used for the post-earthquake damage detection and for the evaluation of the buildings usability. Typically, AeDES forms are filled out for damaged buildings only, except in cases where buildings are declared uninhabitable due to external causes, such as adjacent unsafe buildings. Therefore, for information on undamaged buildings, reference was made to the data from the 2011 census of population and dwellings (National Institute of Statistics). In the specific case, building-by-building unaggregated census data were used, provided under an agreement with the Agency for Territorial Security and Civil Protection for Region Emilia-Romagna.

The datasets involve 443 municipalities, in 14 provinces of Central Italy. In particular, referring to the AeDES forms, for ordinary masonry, i.e. unreinforced masonry (URM), and for reinforced concrete, there are respectively 40867 and 12614 damaged buildings. In the following, with reference to URM buildings only, DT1 refers to the dataset of 40867 AeDES buildings, while DT2 refers to the dataset consisting of 381236 census buildings. It should be noted that, clearly, DT1 is entirely contained in DT2 (except for a small number of buildings built between 2011 and 2016–2017). For each building of the two datasets, a geolocation of the corresponding address was performed, through a self-developed Matlab algorithm, using the OpenStreetMap database. When the geolocation of addresses was not possible, due to missing or incomplete addresses, for DT1 reference was made to the centroid of the hamlet, if present, or of the municipal area, otherwise, while for DT2 reference was made to the centroid of the census section. Subsequently, the DT1 and DT2 datasets were merged: in particular, the DT1 buildings were searched for within DT2, in order to obtain the portion of DT2 relating to undamaged buildings, for which no AeDES forms were requested.

This operation was affected by a series of issues. In particular, for some municipalities, first of all, Arquata del Tronto, more AeDES forms than census buildings were found. This is due to various causes: i) for some buildings more AeDES forms were compiled at different times, given the different periods in which the seismic sequences were recorded (August 2016, October 2016 and January 2017); ii) sometimes, especially in historical centers, where the identification of structural units can be difficult, for a single census building registered in DT2, more AeDES forms were found, as during the inspections, evidently, different structural units were identified, hence the need to use different AeDES forms. One of the major difficulties in processing the data contained in DT1 was dictated by the non-uniqueness of the buildings to which some AeDES forms refer, a fundamental element in order to be able to identify all the forms compiled for a certain building. This operation was carried out in order to store in DT1 the most recent AeDES forms for each building, in case more than one exists. An additional difficulty lies in the fact that different teams responsible for compiling the forms, at different times, may have interpreted the building aggregates differently, and identified different structural units. These factors can lead to an overestimation of the number of damaged buildings, compared to the number of buildings included in the census. Indeed, the lack of a common coding between AeDES and the census often made it impossible to find a unique match between buildings in the two databases. For this reason, the DT1 and DT2 datasets were merged based the minimum distance between buildings with the same characteristics (construction period and storey number) within the municipal area.

In DT1, records reporting no damage were removed, except for municipalities with more AeDES records than census buildings. For these municipalities, given the impossibility of properly merging the two datasets, it was assumed that the AeDES records had been filled out for all buildings in the census, and the entire group of buildings in DT1 was annexed to DT3, ignoring DT2 (census). This generally occurred in municipalities particularly affected by the earthquake, where it is reasonable to assume that the AeDES forms covered almost entirely the population of buildings.

A series of building characteristics common to both datasets were identified, namely construction age and storey number. To analyze building characteristics and define taxonomies, eight different construction age intervals were identified: (1) before 1919, (2) 1919–1945, (3) 1946–1960, (4) 1961–1970, (5) 1971–1980, (6) 1981–1990, (7) 1991–2000, (8) after 2000. Five classes of storey number were identified: 1 storey, 2 storeys, 3 storeys, 4 storeys and ≥ 5 storeys. Consequently, buildings with more than 5 floors are treated as 5-storey buildings.

Fig. 1 shows the distribution of the number of buildings in DT3, as a function of the period of construction and the number of floors: a clear prevalence of old buildings, dating back to before 1919, can be noted. In particular,

almost 47% of the buildings in the sample were built before 1945, approximately 43% date back to the period 1946–1980, while only 10% were built from the 1980s onwards. Moreover, a marked prevalence of low and medium-rise buildings can be observed (2-3 storeys).

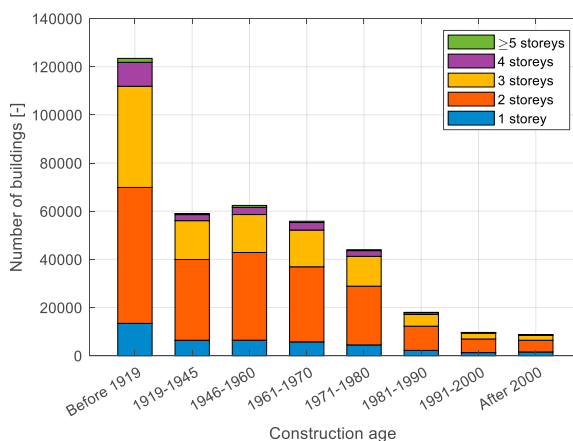


Fig. 1. Distribution of the number of storeys as a function of the construction age (DT3).

3.1. Damage analysis

With the future aim of developing fragility curves based on five damage levels, in accordance with the European Macroseismic Scale, EMS98 - Grüntal (1998) - the observed damage, reported in the AeDES forms, grouped into three macro-classes (slight, medium-severe and very severe damage), was converted into a scale from D1 to D5. D0 represents buildings that have not suffered damage. The conversion of damage between the different scales was performed according to Rota et al. (2008). In particular, damage to a building was assessed as the maximum damage to vertical and horizontal structural elements and to the roof. Damage to non-structural elements was considered only in absence of structural damage.

Fig. 2a shows the distribution of the observed damage as a function of the construction age; it is clearly noticeable how the number of buildings dated before 1919 is particularly high compared to other construction periods classes. In particular, older construction age classes have a higher percentage of damage level D5, compared to the recent ones (Fig. 2b).

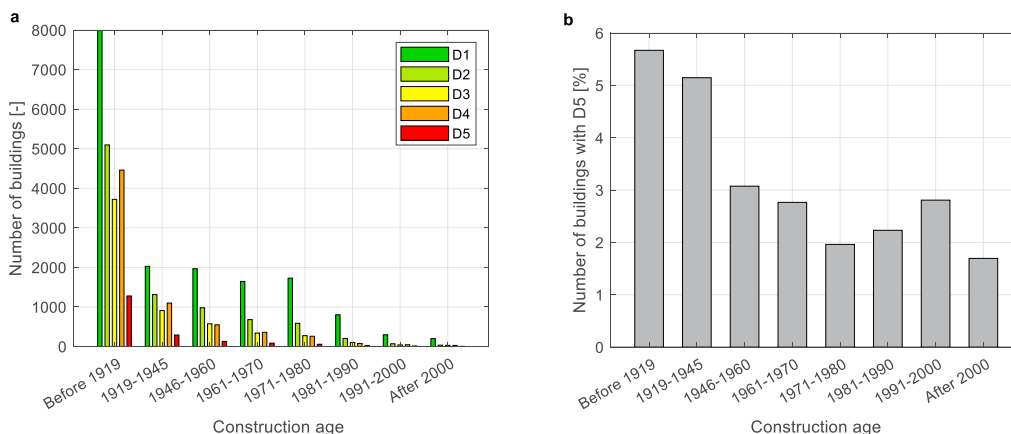


Fig. 2. (a) Damage data distribution grouped by construction age (DT1). (b) Percentage of damage class D5 with respect to the total damaged building of various construction age classes.

Fig. 3 shows the damage distribution for municipalities within a distance of 25 km from the epicenter of the nearest seismic event, among the nine reported in Table 1.

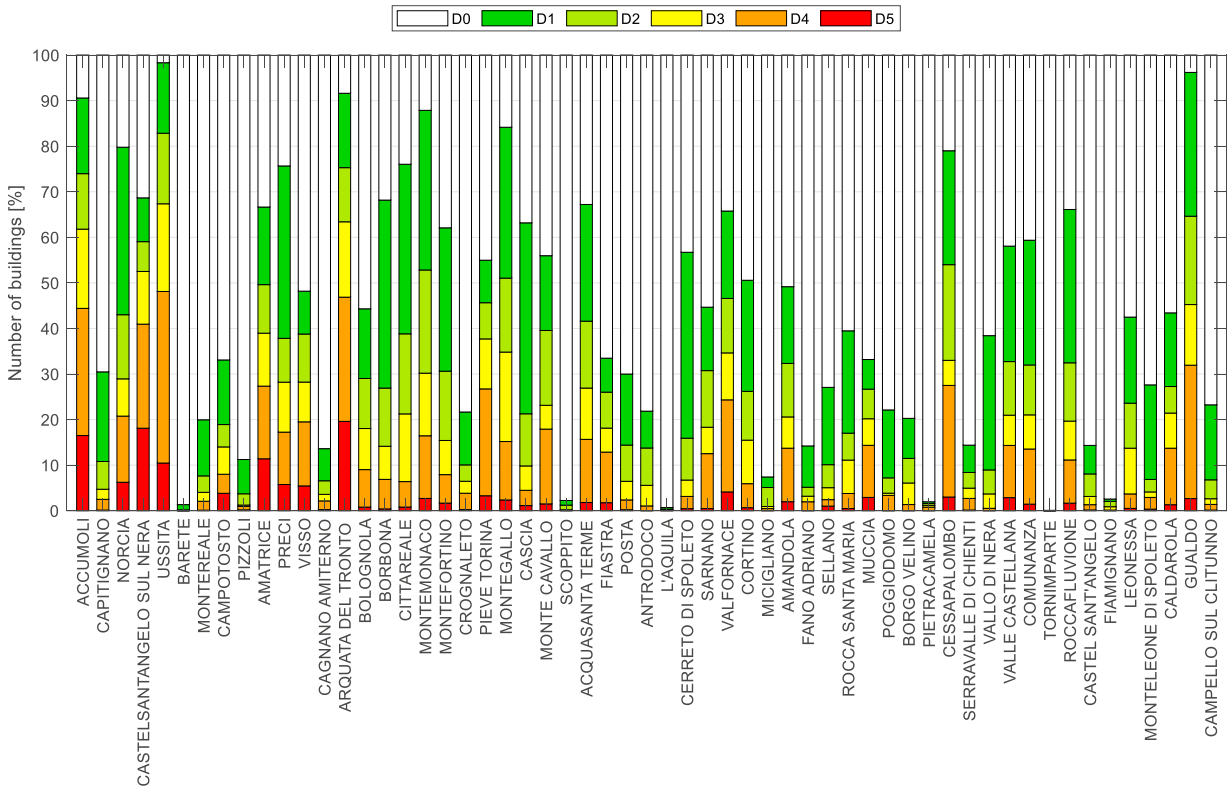


Fig. 3. Damage distribution for the municipalities within 25 km from the epicentres of the seismic events (DT3).

4. Ground Motion Intensity

A key step lays into correlate the observed damage to a ground motion Intensity Measure (IM). Initially, this study only considers the widely used peak ground acceleration, PGA, although, as is well known, there are IMs that sometimes better correlate with the damage experienced by structures – Buratti (2012). For each point in the space corresponding to a building in DT3, the PGA was calculated using a software tool developed by the authors. The shake maps calculation applies the method described in Buratti et al. (2023), based on the procedures proposed by Bradley (2014) and Bruce Worden et al. (2018). The logarithm of the IM is represented by a multivariate normal distribution. In particular, the prediction of the logarithm of the IM is obtained as a combination of a ground motion attenuation model, here calibrated by the authors on the nine main shocks of the 2016–2017 Central Italy seismic sequences (Table 1), and a spatial correlation model – Goda and Hong (2008). The spatial correlation model influences the prediction of the IM in the proximity of a ground motion recording station. In calculating the PGA, directionality was considered; in particular, in the following, reference was made to the PGA_{RotD50} (Boore et al. (2006)), corresponding to the median of the PGA evaluated in the various spatial directions.

The PGA shake map for the October 30 2016 mainshock is reported in Fig. 4a. The position of each building in DT3, marked with different colors as a function of the corresponding damage is shown in Fig. 4b, overlapped to the PGA envelope for the nine mainshocks considered in the study. For each building in DT3, the maximum PGA among the nine values, related to the different mainshocks, was used, given the impossibility to establish with absolute certainty the shock that caused the associated damage.

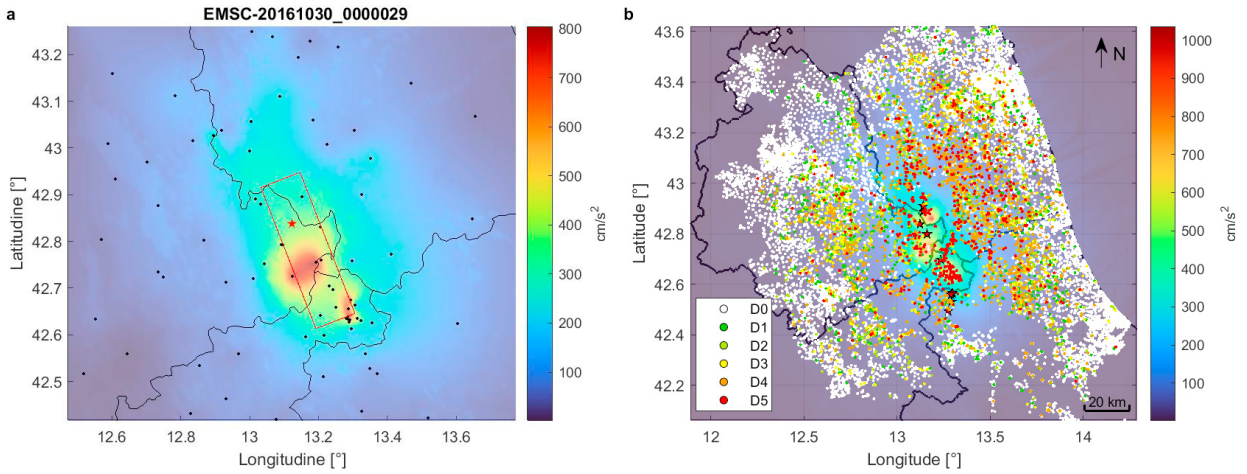


Fig. 4. (a) Shake map in terms of PGA for the mainshock of October 30, 2016. (b) PGA envelope and spatial distribution of the building damages.

5. Point fragility assessment

The following shows a point-based fragility model, i.e. a graphical representation of the damage probability matrix. DPM is the most basic fragility model, and should be considered as a preliminary result. Since the DT3 dataset contains a very large and territorially extensive sample of buildings, a significant portion of the buildings have experienced relatively low PGA values. For this reason, 12 PGA intervals were defined, characterized by a non-constant number of buildings in each of them. A uniform number of buildings per interval would have unbalanced the interval widths in terms of PGA, with a large number of small intervals for low PGA values and very large intervals for high PGA. The cumulative damage matrix is shown in Table 2, where $D \geq D_i$ indicates the number of buildings reporting a damage level greater or equal to D_i , within the PGA interval. Table 3 shows the DPM, where the probability p_i to exceed a certain damage level D_i , given a certain PGA interval, corresponds to the ratio between the number of building experimenting the damage D_i in the corresponding interval, and the total number of buildings that fall within the PGA range. The point-wise fragility is reported in Fig. 5. It can be noted how the probability to exceed D5 became significant above PGA values of around 200 cm/s².

Table 2. Cumulative damage matrix.

PGA interval [cm/s²]	PGA mean [cm/s²]	$D \geq D0$	$D \geq D1$	$D \geq D2$	$D \geq D3$	$D \geq D4$	$D \geq D5$
[2; 15[	11.68	32764	210	115	66	48	2
[15; 30[	21.53	112345	1595	932	498	247	20
[30; 50[	37.91	85874	2623	1535	811	425	39
[50; 75[	60.93	59299	6849	3724	1915	852	92
[75; 100[	87.25	32335	5331	2788	1531	821	92
[100; 125[	110.73	20758	5003	2811	1611	913	104
[125; 150[	137.54	9377	2844	1492	896	515	67
[150; 180[	162.28	5716	2041	1102	693	409	52
[180; 220[	195.35	6405	2981	1730	1056	635	102
[220; 280[	241.25	5690	3303	2038	1351	797	120
[280; 380[	316.32	4291	3006	2214	1767	1225	412
[380; 818[	487.97	6382	4687	3339	2623	1915	785

Table 3. Damage probability matrix.

PGA interval [cm/s^2]	PGA mean [cm/s^2]	$D \geq D1$	$D \geq D2$	$D \geq D3$	$D \geq D4$	$D \geq D5$
[2; 15[	11.68	0.0064	0.0035	0.0020	0.0015	0.0001
[15; 30[	21.53	0.0142	0.0083	0.0044	0.0022	0.0002
[30; 50[	37.91	0.0305	0.0179	0.0094	0.0049	0.0005
[50; 75[	60.93	0.1155	0.0628	0.0323	0.0144	0.0016
[75; 100[	87.25	0.1649	0.0862	0.0473	0.0254	0.0028
[100; 125[	110.73	0.2410	0.1354	0.0776	0.0440	0.0050
[125; 150[	137.54	0.3033	0.1591	0.0956	0.0549	0.0071
[150; 180[	162.28	0.3571	0.1928	0.1212	0.0716	0.0091
[180; 220[	195.35	0.4654	0.2701	0.1649	0.0991	0.0159
[220; 280[	241.25	0.5805	0.3582	0.2374	0.1401	0.0211
[280; 380[	316.32	0.7005	0.5160	0.4118	0.2855	0.0960
[380; 818[	487.97	0.7344	0.5232	0.4110	0.3001	0.1230

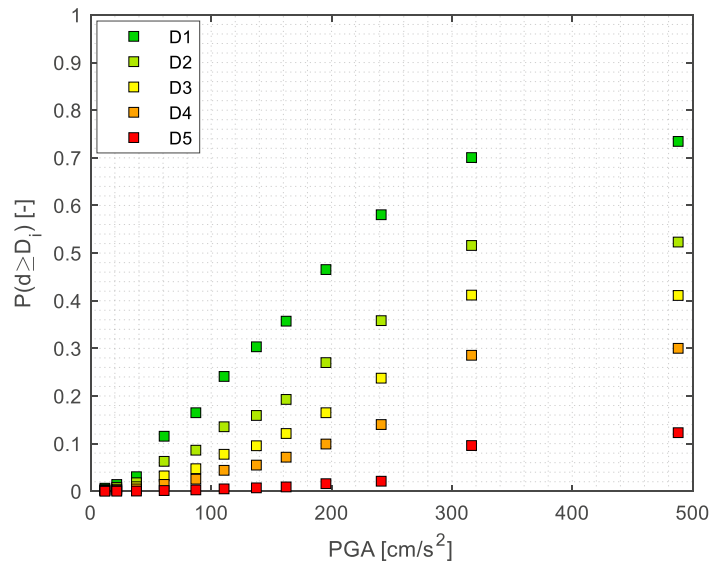


Fig. 5. Point-based fragility model, based on the damage probability matrix.

6. Conclusions

In the present work, data on damaged buildings from the AeDES forms, related to the 2016-2017 Central Italy seismic sequences, were analyzed in detail, while data on undamaged building were derived from census. A set of taxonomies based on construction age and number of storeys was defined, and the distribution of the damage was studied. Shake maps in terms of PGA were calculated for the mainshocks and the maximum IM corresponding to each building of the dataset was carried out. Finally, point-wise fragility was evaluated, based on DPM. This basic model represents the first step on the development of continues fragility models for the Central Italy area.

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