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Empirical fragility curves for masonry buildings struck by the 2016 Central Italy earthquake

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Abstract

The prevention of seismic risk at urban scale can be pursued through the estimate of the probability to reach or exceed a certain damage grade given the seismic input. In this framework, seismic fragility curves are nowadays of large interest as they express this probability in a synthetic way, also extended to large-scale applications. Real damage data are crucial in making more reliable predictions of damage occurrence, although they can be influenced by a proper definition of the structural types and the completeness of observations. The paper shows the empirical fragility curves obtained for a sample of 2263 masonry buildings located within 19 historical centers struck by the 2016 Central Italy earthquake. The damage grade was evaluated according to the European Macroseismic Scale (EMS-98), also considering undamaged buildings, at the end of the sequence that spanned between August and October. The buildings largely underwent several repairs and strengthening actions with reinforced concrete elements starting from the 1980s. The systematization of the structural features led to a taxonomy for strengthened and original buildings, which, based on the observed damage patterns, was matched to the EMS-98 vulnerability classification. The sample ranges from class A (worst behavior) to D (best behavior). Class A was typically assigned to original buildings (without interventions) or ill-advisedly tampered ones, i.e., those in which interventions had an unfavorable contribution to their seismic behavior. Class D described buildings with properly designed strengthening interventions, classes B and C intermediate situations. Fragility curves were obtained per each vulnerability class, as a function of the highest peak ground acceleration (PGA) observed in the sequence from ShakeMaps. The results were then compared to other empirical fragility models.

Keywords: fragility curves; 2016 Central Italy earthquake; masonry buildings; strengthening; EMS-98; empirical data

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1. Introduction

Reliable damage and risk scenarios help in reducing the seismic vulnerability of ordinary masonry buildings in urban areas. For instance, for an asset at risk, fragility models enable to estimate the probability of reaching or exceeding a certain damage grade at a level of seismic intensity measure (IM), as a function of the vulnerability level or the structural type which describes that asset. The probability of reaching a certain damage grade is quantified by the distance between a fragility curve and the closest ones (Rossetto et al., 2015). The study of historical seismicity (Guidoboni & Ebel, 2009) helps in developing predictive models able to estimate the expected damage of buildings as a function of the seismic input, especially at regional and urban scales (da Porto et al., 2021).

Depending on the type of data available, fragility curves can be based on different approaches: (i) empirical (Ioannou et al., 2021; Menichini et al., 2022; Rosti et al., 2022); (ii) expert elicitation (Masi et al., 2021); (iii) analytical (Barbat et al., 2008; Donà et al., 2020; Masi et al., 2021); or (iv) hybrid (Jaiswal et al., 2011; Pomonis et al., 2014).

Empirical fragility curves are based on the real damage patterns caused by an earthquake. They provide a realistic scenario (Rossetto et al., 2015), as the specific conditions of buildings are considered, e.g., possible soil-structure interaction or pounding phenomena, damage to both structural and non-structural components, damage progression owing to aftershocks. As a downside, the results rely on the damage assessment phase: the data collected through empirical evaluations, such as onsite survey forms, may be affected by incompleteness, non-homogeneous distribution of building types, inaccuracy of the IM, site effects and a biased damage evaluation (Miano et al., 2020). In fact, as undamaged buildings are generally neglected, the sample becomes less complete as the earthquake effects are less severe, i.e., further to the epicenter.

In Italy, empirical fragility curves for ordinary buildings were obtained from data collected through the AeDES form (Italian acronym for the 'post-earthquake damage and usability assessment and emergency countermeasures in ordinary buildings'), which is the current standard for the usability assessment of seismic-damaged buildings. The data refer to 9 seismic events occurred in Italy from 1976 and they are stored in the Da.D.O. database (Observed Damage Database) (Dolce et al., 2019). For instance, Zuccaro et al. (2021) proposed a fragility model which gathers 8 events, from Irpinia (1980) to Emilia (2012) earthquakes; Rosti et al. (2022) referred only to Irpinia and L'Aquila (2009) events, whereas Ioannou et al. (2021) to Emilia earthquake (2012).

The paper proposes an empirical fragility model for unreinforced masonry buildings, also in strengthened conditions, obtained from data collected in the seismic area of the 2016 Central Italy earthquake. The fragility curves are defined according to a continuous model, in which each curve is modelled as a cumulative lognormal curve, represented by its median and standard deviation. These curves describe a continuous correlation between the observed damage and the IM, given the same vulnerability level of the asset, based on the European Macroseismic Scale 1998 (EMS-98) vulnerability classes (Grünthal et al., 2019).

The novelty of the model stays in (i) the considerable number of masonry buildings inspected after the 2016 earthquake by the same group of technicians, and (ii) the evaluation of the effect of strengthening actions applied in the past. Curves are plotted as a function of the vulnerability class as described by the EMS-98, from A to D, i.e., the range of interest for masonry buildings. Each class gathers various types of buildings, in either original or strengthened conditions.

2. Dataset

The fragility curves proposed in this paper represent the probability that 2263 buildings in 19 historical centers hit by the 2016 Central Italy earthquake reached or exceeded a certain damage grade in the EMS-98 scale. These buildings are to be considered as structural units (SUs), i.e., parts of a construction with a homogenous structural system and behavior (MIT, 2018). The historical centers are in the districts of Ascoli Piceno (9), Fermo (1), Macerata (7) and Perugia (2) (Fig. 1); they all experienced the quakes on 24 August (Magnitude Mw=6.0), and 26 and 30 October (Mw=5.9 and Mw=5.4, respectively).

The data presented herein were collected by means of a 'detailed engineering survey'. To obtain a representative dataset (Rossetto et al., 2015) the case studies were chosen according to their orographic position (valley, hillside, or hilltop), historical background (according to the district and role in the past, e.g., fortress, rural center, bishopric), size (from 23 to 593 SUs), and Peak Ground Acceleration (PGA, from 0.10-0.65g, see §2.1). The settlements, referring to the old nuclei and their immediate outskirts, were inspected for the sake of homogeneity by the same group of technicians, including the authors, after the three main events, in a period which spanned from June 2018 to November 2019. Therefore, the damage accumulation is implicitly considered within the sample.

Data were collected building-by-building by the means of the MUSE-DV Masonry form (MUltilevel assessment of SEismic Damage and Vulnerability of masonry buildings), a novel schedule recently proposed by the authors (Saretta et al., 2020; Sbrogiò et al., 2022a) to evaluate the influence of structural interventions applied in the past on the seismic behavior of masonry buildings. The form is divided into four sections, which enable to assess both damage and vulnerability with an increasing level of analysis of a SU. The damage is evaluated as an EMS-98 grade (section 0), by dividing the building into structural components (section 1), and by recognizing the activation of collapse mechanisms (section 2). The evaluations are supported by the definition of vulnerability factors according to the level of analysis pursued by each section. At last, the empirical description of a building is completed by the cataloguing of its materials and structures (type and quality of masonry, type of horizontal structures and interventions) (section 3). In this work, the EMS-98 damage grade (section 0) and the structural features (section 3) of buildings were considered to derive the empirical model.

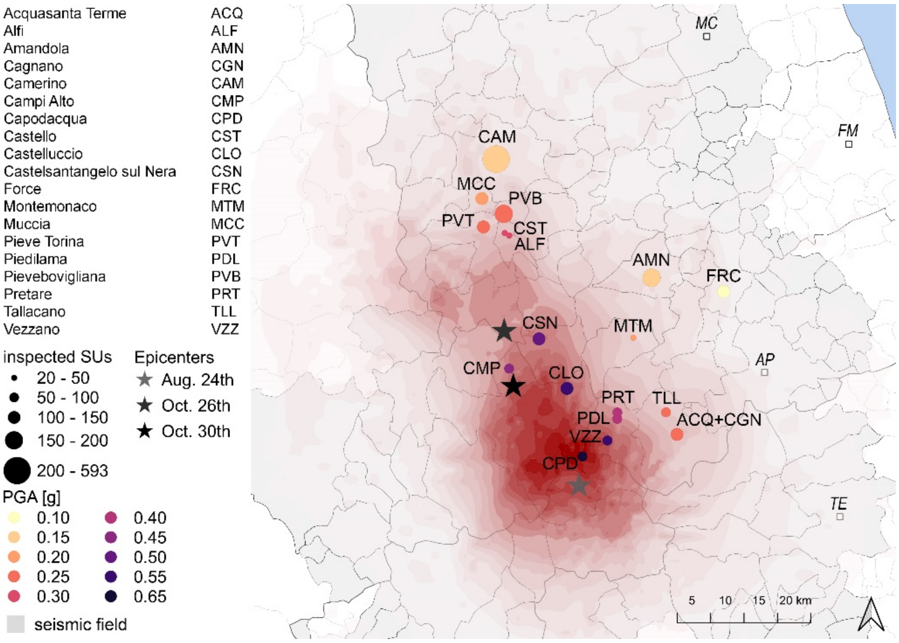

Fig. 1. Map of the inspected centers.

In the study area, a considerable number of buildings had undergone structural interventions as a consequence of the earthquakes in the recent past (1979, 1997), after which strengthening and reconstruction campaigns were promoted. Their main aim was to retrofit existing buildings, bringing them to the performance levels of new, code-conforming ones, through of rigid slabs, tie beams and jacketing and/or grouting of masonry walls. Those interventions targeted, respectively, redistribution of seismic loads, connections among structural elements and the shear strength of the walls. Interventions were designed neither ‘case-by-case’ nor carefully evaluating the preexisting structures. Therefore, the observed damage mechanisms highlighted that some interventions had an unfavorable contribution to the seismic behavior, especially in those buildings with poor masonry quality, i.e., stone rubble, random textures and weak mortars (Sbrogiò et al., 2022b). The ineffectiveness of interventions was caused by poor constructive details, incompleteness of the action (strengthening of horizontal diaphragms only) and incompatibility of the new elements with the pre-existing ones. These situations caused a substandard performance, which is in the following described as a ‘worsened’ or ‘downgraded’ building. The replacement of horizontal diaphragms with strengthening of bearing walls through (i) joint repointing or concrete plastering; (ii) grout injections and r.c. jacketing obtained respectively ‘improved’ or ‘upgraded’ performance levels than the reference building (Sbrogiò et al., 2022b).

2.1. Intensity measure

The IM adopted herein is the PGA, as recorded by the ShakeMaps (Russo et al., 2022). PGA seemed the most suitable seismic input (Rota et al., 2008) as it is the most widely adopted, thus enabling the comparison with already existing fragility models. Conversely, the macroseismic intensity can be biased by the damage assessment because of the subjectivity of the surveyor, site effects, and the variability of the considered assets. In addition, there are several macroseismic scales and intensity is not a continuous parameter; thus, fragility curves should be defined as piecewise functions. In this study, the PGA was obtained through an interpolation of the ShakeMaps referring to the three main events over the centroid of the 19 centers (the most severe event was considered for each).

As the number of observed SUs varies among the case studies, the calculated PGA values were binned by 0.05g, thus obtaining a smoother distribution. In Fig. 1 the central value of each bin is represented.

2.2. Observed seismic damage

A damage grade, on a discrete scale from 0 (no damage) to 5 (collapse), was directly assigned to each SU, according to EMS-98. This is a different approach from most works which are based on the AeDES damage data, as these need to cope with the absence of undamaged buildings (generally excluded from surveys) by specific statistical procedures (see e.g., Ioannou et al., 2021; Rosti et al. 2022) and the conversion of the peculiar damage description in the 0-5 scale. Differently from AeDES surveys, these ones occurred mainly from the outside and therefore an underestimation of the damage grade, especially for low damage situations, was possible. Conversely, the effect of aftershocks probably led to an overestimation of certain damage patterns.

Fig. 2 shows the number of SUs within each PGA bin per damage grade. As one may observe, all the damage grades were included within the sample, comprising also no damage and collapse situations. None to moderate damage (D0-D2) prevails in the sample owing to the larger size of Camerino, which was far from the epicenters, if compared to the other case studies. Substantial damage (D3) appears in every PGA bin, moving to higher and more severe values (D4). Collapses (D5) were observed only with PGA≥0.25g.

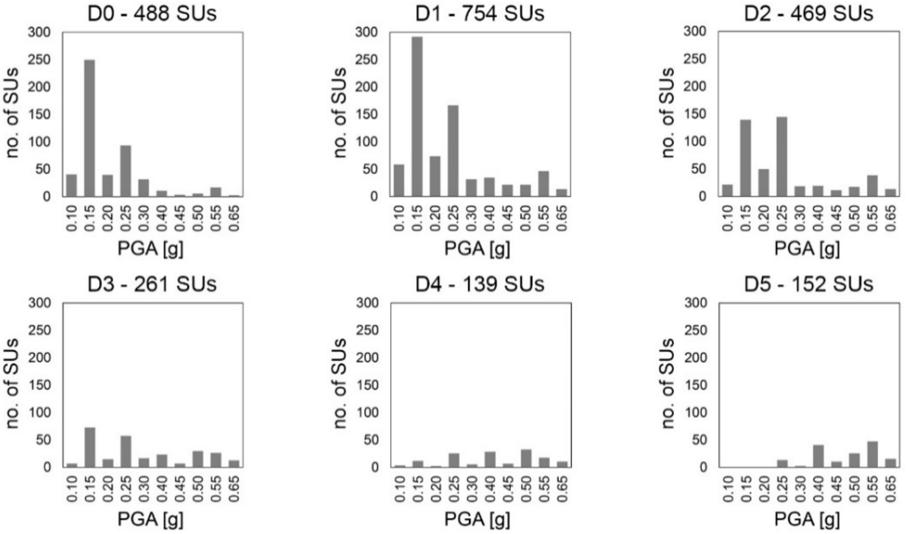

Fig. 2. Number of SUs per PGA bin as a function of the damage grades.

2.3. Building inventory and vulnerability classification

In literature, fragility curves have been obtained as a function of descriptive features (e.g., the structural system, type of materials, strengthening interventions, and number of floors; see e.g., Menichini et al., 2022; Pomonis et al., 2014; Rota et al., 2008). Alternatively, buildings can be grouped in EMS-98 vulnerability classes: by considering the seismic behavior, many descriptive features can be classified in the same way, thus obtaining a robust and consistent system (Rossetto et al., 2015) which is more suitable to an empirical approach.

Zuccaro et al. (2021) proposed fragility curves for vulnerability classes preliminary assigned to ordinary masonry buildings according to the vertical structural type and then adjusted by specific vulnerability factors. Rosti et al. (2022) adopted a machine learning clustering algorithm to group building types into vulnerability classes. Masi et al. (2021) worked on expert elicitation of vulnerability classes.

Referring to the same data sample considered in this work, the authors have recently proposed a vulnerability classification for strengthened building types compatible with the EMS-98 (Saretta et al., 2021). The taxonomy adopted in this work (Sbrogiò et al., 2022b) is based on masonry (M1 – random rubble; M2 – solid bricks; M3 – clay blocks), floor/roof (F – flexible; S – semirigid; R – rigid), and intervention types. These are classified as a function of their contribution to the observed behavior: (i) no intervention (original structure) and worsened or downgraded performance have no symbol, and the type is determined just by the masonry and the walls; (ii) improved and (iii) upgraded performances are marked by an R and a C respectively. Therefore, interventions can also reduce or keep the same performance levels of the buildings which they are applied to. The most probable vulnerability class, ranging from A to D, was preliminarily assigned to each taxonomic item, and then reassessed by considering specific conditions of individual SUs and the effects of interventions on the observed behavior. The highest vulnerability (class A) describes SUs in original conditions, i.e., those with random rubble or brick masonry and timber horizontal structures, whereas the least vulnerable type (class D) gathers recently built dwellings, with clay blocks and r.c. floors properly connected among each other. Poor interventions led to the same vulnerability of the former, whereas effective strengthening ensured the same behavior of the latter. Class C was assigned to SUs with rubble masonry walls strengthened with joint repointing, class B to solid brick masonry SUs (Tab. 1).

Table 1. EMS-98 vulnerability classes for building types with strengthening interventions. On the right, the composition of each class is reported.

Type ID	Type of structure	Membership				Composition [%]			
		A	B	C	D	A	B	C	D
M1-F	Unreinforced random rubble and flexible floors	🟥	🟨			47	9		
M1-S – M1-R	Unreinf. or worsened random rubble and rigid/semirigid floors	🟥	🟧			48	55		
M1R-F – M1R-S – M1R-R	Improved random rubble and flexible/semirigid/rigid floors		🟧	🟥	🟨		30	85	4
M1C-S – M1C-R	Upgraded random rubble and rigid/semirigid floors			🟧	🟥			9	54
M2-F	Unreinforced solid bricks and flexible floors	🟥	🟨			5	1		
M2-S – M2-R	Unreinforced solid bricks and rigid/semirigid floors		🟥	🟧			4	1	
M2R-F – M2R-S – M2R-R	Improved solid bricks and flexible/semirigid/rigid floors		🟨	🟧	🟥		1	4	15
M3-R	Clay blocks with r.c. floors			🟨	🟥			1	27

🟥 Most likely vulnerability class 🟧 Probable range 🟨 Exceptional cases

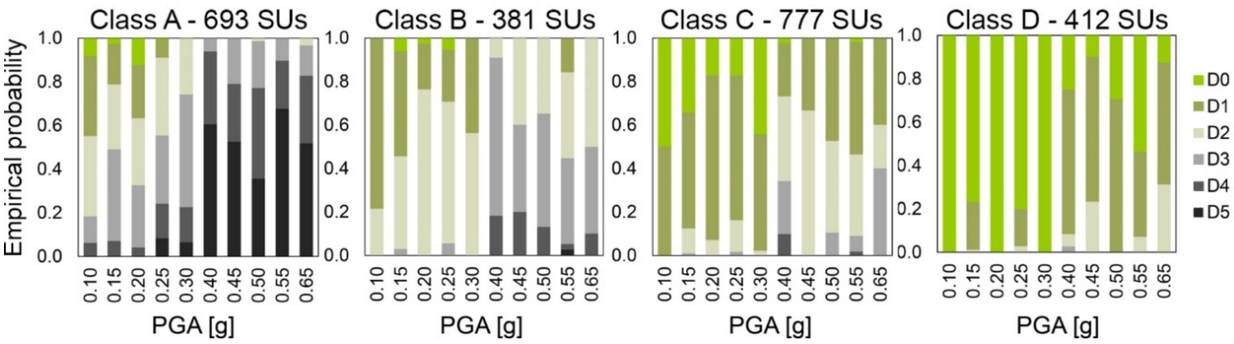

Fig. 3. DPMs for PGA bins as a function of vulnerability classes and total number of SUs in each class.

3. Empirical fragility model

For each vulnerability class, the frequency of occurrence of each damage grade (D_i, i=0÷5) was computed, obtaining the Damage Probability Matrices (DPMs) for the PGA bins (Fig. 3). The sampled SUs mainly belong to classes A and C (693 and 777 SUs respectively); moreover, higher damage grades were registered for SUs in classes A and B, especially at the higher PGA values. No D5 and a few D4 were observed for class C, whereas class D mainly gathers D0 and D1.

The probability of reaching or exceeding a damage grade D_i, with i=1÷5, as a function of the PGA$_j$, with j=0÷1, is obtained by cumulating the empirical frequencies of damage from the highest to the lowest grade and then fitting them with a lognormal cumulative distribution (1):

$$P(dg \geq D_i | PGA_j) = \Phi\left[\frac{ln\,(PGA_j/\theta_{Di})}{\beta Di}\right] \quad (1)$$

Where Φ[.] is the standard normal cumulative distribution, θ_{Di} is the median value of the fragility function corresponding to the damage grade D_i and β_{Di} is the logarithmic standard deviation. θ_{Di} and β_{Di} represent the unknown parameters of the function; their optimal values were estimated through the maximum likelihood method (Baker, 2015); their values are given in Tab. 2 whilst Fig. 4 shows the curves. The D0 curve was not considered as its cumulation would be equal to 1.

Table 2. Median (θ_{D1}) and standard deviation (β_{Di}) values obtained from the maximum likelihood method for EMS-98 classes.

Vulnerability class	θ_{D1} [g]	β_{D1}	θ_{D2} [g]	β_{D2}	θ_{D3} [g]	β_{D3}	θ_{D4} [g]	β_{D4}	θ_{D5} [g]	β_{D5}
A	0.03	1.03	0.10	0.67	0.18	0.60	0.32	0.49	0.49	0.47
B	0.03	1.17	0.16	0.83	0.52	0.55	1.17	0.60	1.67	0.50
C	0.10	1.01	0.53	0.92	1.10	0.79	2.39	0.83	-	-
D	0.34	0.88	1.43	0.94	-	-	-	-	-	-

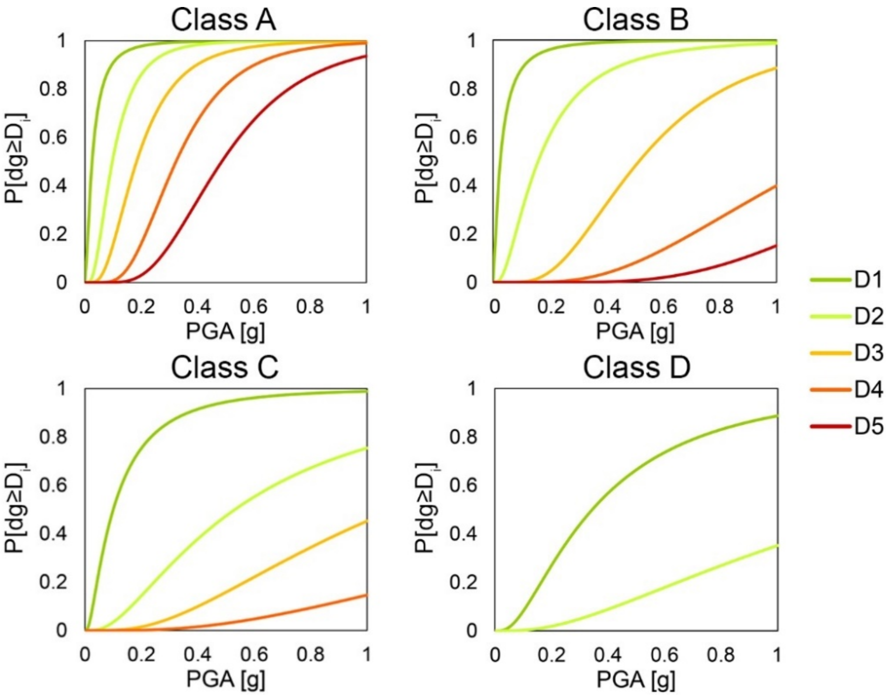

Fig. 4. Empirical fragility curves for 2016 Central Italy earthquake grouped by vulnerability classes.

Per each vulnerability class, the median value of each D_i was imposed to be at least that of the preceding one (except for class A), whilst the standard deviation was calculated separately per each curve and class. This restraint only applies to the D1 curve of B class, which has the same median as class A. Class A curves are much closer than every other class, and classes B and D are much more dispersed because of a smaller sample. The median PGA that determines a D5 in class A finds a D3 in class B, a D2 in C and D1 in D. Therefore, it seems that the vulnerability level of class A is a little overestimated, and that of classes C and D underestimated. This is probably an effect of extensive brittle failures in the poorest SUs, also caused by interventions, and conversely, of the impossibility to assess internal damage in slightly or negligibly damaged SUs.

4. Discussion

The fragility curves proposed in this paper refer to the 2016 Central Italy earthquake; therefore, they reflect a specific event and a delimited area, where building materials and techniques are similar. The fragility model was compared to those proposed in literature works, which consider different earthquakes and data samples, but referring to the D2 damage (Fig. 5). For classes A and B, the proposed model ($\theta_{D2,A}$=0.10, $\theta_{D2,B}$=0.16) is more fragile than those of Masi et al. (2021) ($\theta_{D2,A}$=0.11, $\theta_{D2,B}$=0.19) and Rosti et al. (2022) ($\theta_{D2,A}$=0.14, $\theta_{D2,B}$=0.18); the standard deviation is comparable (β_{D2}=0.60-0.8), although in these studies it is fixed for all the damage grades and vulnerability classes. For class C, the proposed curves are less vulnerable, and the median value ($\theta_{D2,C}$=0.53) is closer to those by Zuccaro et al. (2021) ($\theta_{D2,C}$=0.62) as it more than doubles that by Rosti et al. (2022) ($\theta_{D2,C}$=0.22); the divergence increases with class D, whose median ($\theta_{D2,D}$=1.43) is almost five times that by Rosti et al. (2022) ($\theta_{D2,D}$=0.30) and twice Masi et al. (2021) one ($\theta_{D2,D}$=0.54); Zuccaro et al. (2021) do not propose curves for this class. The standard deviation becomes larger and closer to the value by Zuccaro et al. (2021) (β_{D2}=0.80-0.90).

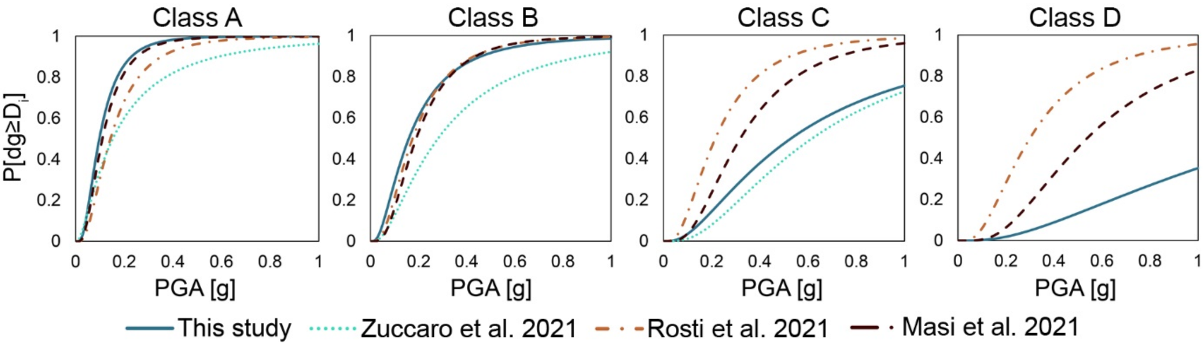

Fig. 5. Comparison of the D2 fragility curve per vulnerability for the proposed model and other works using an empirical approach.

5. Conclusion

In this paper, empirical fragility curves for unreinforced masonry buildings in original and strengthened conditions were proposed. The damage was directly obtained as an overall grade in the 0-5 range, according to the EMS-98, and buildings were grouped according to their vulnerability class of that scale, in the A-D range. The vulnerability classification takes into consideration the positive (reduced vulnerability) or negative (increased or equal vulnerability) effect of structural interventions. For the sake of comparability with other works, the fragility curves were obtained considering a lognormal cumulative distribution. Results shows that the proposed model is slightly more fragile than most of the already published works for A and B classes, and less fragile for the least vulnerable ones (C and D). This is a probable consequence of the damage assessment phase, which occurred from the outside of buildings, thus disregarding possible internal damage, which could have led in a re-evaluation of slightly or negligibly damaged buildings. Moreover, interventions increased the brittleness of poor-quality buildings, whereas they improved the ductility when properly executed.

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