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Seismic fragility curves via nonlinear dynamic analyses: derivation for three unreinforced masonry school buildings

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Abstract: This research deals with the seismic risk assessment of existing masonry buildings and, more specifically, it focuses on the fragility component, i.e. the development of fragility curves. In the paper, fragility curves are derived by using a numerical approach, based on the execution of nonlinear dynamic analyses (NLDA) according to the Cloud Method. Among other possible different approaches (i.e. empirical, analytical-mechanical based, hybrid), the numerical approach has been selected as one of most suitable when the risk study is addressed to portfolio of buildings, like the examined case that focused on Italian unreinforced (URM) schools. In the paper, the adopted procedure to interpret the huge data provided by NLDA and convert them into the attainment of synthetic damage level is described. It has been tentatively applied to three URM schools.
Finally, mechanical-analytical fragility curves and residential fragility curves, already available in literature, were used to compare and validate the derived numerical fragility curves.

Keywords: Numerical Fragility curves; Cloud Analysis; Portfolio of buildings; Damage Levels.

1. Introduction

Seismic events of the last 10 years as the Molise (Italy) 2002, Boumerdes (Algeria) 2003, Bingöl (Turkey) 2003, Kashmir (Pakistan) 2005, Peru 2007, Sichuan (China) 2008, Haití 2010 and Chile 2010, just to mention a few at international scale, have caused significant damage to school buildings and significant losses (Di Ludovico et al., 2019).
Considering the occupancy of future generation and the vulnerability of their lives in school time, it is considered being a timely requirement to make a seismic risk assessment of school buildings.

The national seismic risk assessment is an important risk mitigation tool as it can be used for the prioritization of regions within a country where retrofitting of the building stock or other risk mitigation measures should take place. The effective development of a seismic risk map involves the convolution of seismic hazard data, vulnerability predictions for the building stock and exposure data. In particular, this paper focuses on the fragility component, i.e. the development of fragility curves, aimed to support risk study on portfolio of buildings, i.e. the Italian Unreinforced (URM) schools. More specifically, the aim is to define a methodology to develop representative fragility curves by using a numerical approach.

The research has been developed within the more general context of MARS (Seismic Risk Maps) project (Masi et al., 2021). The project has been promoted by the Italian Civil Protection Department (DPC) and the Network of University Laboratories for Earthquake Engineering (ReLUIS), conveying the effort of several Italian Universities to update the National Risk Assessment already released in 2018 (Dolce et al., 2021), in order to include not only residential buildings but also other strategic classes, such as schools and churches.

Among possible methods to develop fragility curves (Rossetto et al., 2014; Rosti et al., 2021; Donà et al., 2021), i.e. empirical, analytical based on simplified approaches or numerical based on more accurate models, the numerical one has been selected in this paper as most effective in assessing risk assessment on a specific portfolio of buildings, like schools. Varying the adopted approach, different problems could arise and in general a quite tricky issue consists of applying a consistent approach in order to guarantee then a proper comparison among curves based on various methods. For example, the use of empirical approaches passing from an area to another is conventional, since in general the data on the observed damage are available only for specific territorial contexts. Moreover, although the empirical approach provides a valuable reference for validation aims, portfolio buildings are in general less representative from a statistical point of view and pose critical issues in the derivation of robust fragility curves. Conversely, the analytical approach (either numerical or mechanical-based) allows to better exploit the data collected at regional scale and differentiate the curves specializing the sub-types considered. Therefore, the research has been oriented to the numerical approach.

More specifically, the approach adopted is based on the execution of nonlinear dynamic analysis (NLDA) on archetype school buildings identified to be representative of the class of existing masonry school buildings in Italy. The NLDA follow the Cloud Method (Jalayer et al., 2015). Moroever, the procedure proposed in (Brunelli et al., 2022, Sivori et al., 2022) to interpret the huge data provided by NLDA and convert them into the attainment of synthetic damage level has been adopted. In the paper, the results obtained for three schools are presented. Finally, the curves obtained have been compared with others already available in the literature.

2. Adopted procedure for deriving fragility curves through nonlinear dynamic analyses

There are several nonlinear dynamic analysis procedures available in the literature to statistically characterize the relationship between Engineering Demand Parameters (EDPs) and the Intensity Measures (IMs) of the recorded ground motions, such as the Incremental Dynamic Analysis (IDA, Vamvatsikos & Cornell, 2002), the Multiple-Stripe Analysis (MSA, Jalayer & Cornell, 2009), the Cloud Method (Bazzurro et al., 1998; Jalayer et al., 2015). Moreover, several scientific contributions address the choice of optimal intensity measures for probabilistic seismic demand analyses (Shome, 1999; Elenas & Meskouris, 2001; Luco & Cornell, 2007; Mollaioli et al., 2013; Minas & Galasso, 2019). In this context, the investigation should be aimed at the characterization of the statistical relationship between earthquake intensity and structural response and damage.

2.1. Definition of archetypes and modelling approach adopted

According to the inventory of Italian Ministry of Education, Italian URM schools are characterized by a number of stories rarely higher than three and the presence of rigid floors; moreover, in the case of ancient ones, a significant inter-story height and great distance between transverse walls are recurring features (Cattari et al., 2021).

Three school buildings have been selected from the regional database provided by the University of Naples and Genoa (Ottonelli et al., 2019); it groups data collected during the support activity made by the ReLUIS consortium and DPC (Di Ludovico et al., 2017a; Di Ludovico et al., 2017b), requested by the Reconstruction Commissioner, nominated after the 2016/2017 Central Italy earthquake.

Each building was chosen as archetype building of a defined sub-class because representative of the Italian masonry school building stocks. The classification was done on the basis of the taxonomy defined in MARS project. More specifically, the MARS-taxonomy for schools considers: *masonry typology* (e.g., regular, irregular); *age of* *construction* (before 1800, 1800 century, 1900-20, 1921-45, 1946-60, 1961-75, after 1976); *number of stories* (i.e., 1,2,3, >4); *plan area* (i.e., <500 m2, 500-1000 m2, 1000-2000 m2, 2000-5000 m2, and >5000m2); *diaphragm type* (e.g., concrete slab with clay units, wooden floor).

More specifically, the three archetypes are inspired by some schools located in Visso (MC), Caldarola (MC) and Montegallo (AP).

Visso's school (construction period 1921-45, 2 storey, area 500÷1000 m²) is inspired by a building permanently monitored by the Seismic Observatory of Structures of the Department of Civil Protection (DPC) and now demolished after the severe damage suffered after the Central Italy earthquake in 2016.

The second case study was inspired by the Caldarola school (construction period 1921-45, 2 storey, area 500÷1000 m²). Also this building has been demolished due to the severe damage suffered during the seismic sequence in central Italy in 2016.

The third case study was inspired by the Montegallo school (construction period 1946-60, 3 storeys, area 25÷500 m²). This case study building is a two-storey structure above ground and a semi-basement.

In Table 1 the main structural characteristics of the case studies are reported.

Table 1. Structural details of the three study cases

Case Study	Masonry Type	Floor Slab	R.C. curbs	Chains	Roof
Visso	cut stone	Concrete slab with hollow clay bloks	Yes; R.C. beams	No	Wooden beams with concrete slab
Caldarola	uncut stone	Concrete slab with hollow clay bloks	Yes; R.C. beams	No	Concrete slab with hollow clay bloks
Montegallo	cut stone; modern masonry	Concrete slab with hollow clay bloks	Yes; R.C. beams	No	Concrete slab with hollow clay bloks

The schools' 3D structural models were generated through the equivalent frame approach by adopting 3Muri software (Lagomarsino et al., 2013). Equivalent frame modelling, among other possible choices suited for masonry structures (D'Altri et al., 2020), is proposed not only in literature (Lagomarsino et al., 2013) but also by some Codes (NTC, 2018; CEN, 2004), since it reduces the degrees of freedom and therefore allows to perform nonlinear dynamic analyses of three-dimensional masonry structures with a reasonable computational burden. It is worth noticing the equivalent frame schematisation is particularly suitable if the walls geometry and the openings distribution in the building are characterised by a certain regularity, in particular with regard to the alignment of the openings. The equivalent frame models' 3D view of the schools are reported in Figure 1.

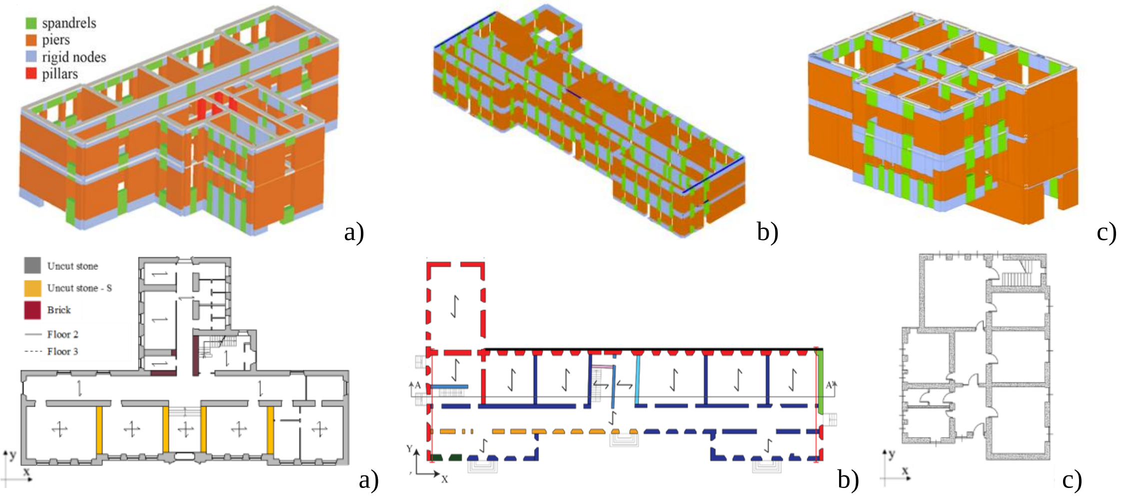


Fig. 1 – Equivalent frame model's 3D view and plant of Visso (a), Caldarola (b) and Montegallo (c) school

The numerical masonry building models were developed in previous research works, in particular for the Visso model (Brunelli et al., 2021) and Caldarola model (Cattari et al., 2022), allowing also a validation of the equivalent frame model reliability. For performing NLDA, the multilinear constitutive law developed by (Cattari and Lagomarsino, 2013), have been adopted simulate the in-plane nonlinear response and the hysteretic behaviour of masonry panels. Apart the numerical studies aforementioned, the efficiency of this modelling strategy has been proved in various works aimed to develop fragility curves (Angiolilli et al., 2021; Cattari et al., 2021).

The constitutive laws assumed to describe the resistance to shear (V_{dc}) or flexural (PF) failure mechanisms of the masonry types are reported in Figure 2, and are coherent with literature values (Cattari et al., 2021), in which the drift (θ) and strength decay values were calibrated to be as representative as possible of reality and were consistent with the up-to-date experimental evidence as reported in some databases (Vanin et al., 2017; Morandi et al., 2018; Rezaie et al., 2020).

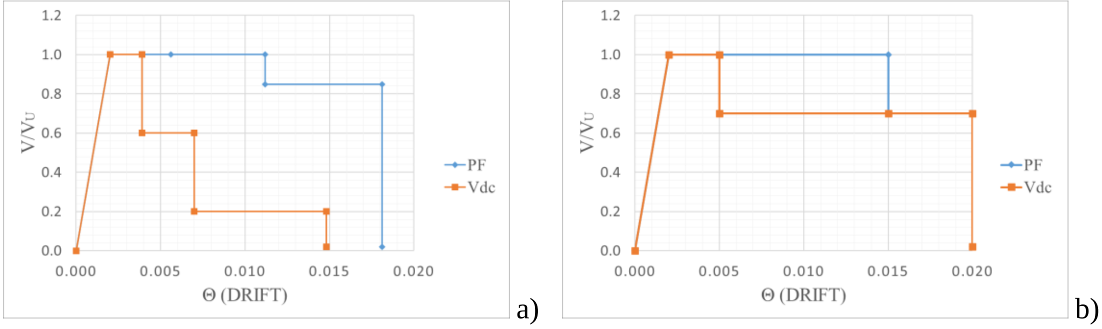


Fig. 2 – Constitutive laws for a) piers and b) spandrels, assumed according to (Cattari et al., 2021)

The values assumed as mechanical parameters (e.g. shear strength (τ_0), masonry compressive strength (f_c), Young modulus (E) and density (ρ)) for the three masonry type schools are reported in Table 1 and calculated on the basis of the minimum and maximum value of the Italian Circular table C8.5.II (Circolare, 2019), increased due to possible improving coefficients (e.g. good mortar; good transversal connection between walls).

Table 2. Mechanical parameters assumed for the schools of Visso (a), Caldarola (b), Montegallo (c)

School model	Masonry Type	f_c [N/mm^2]	τ_0 [N/mm^2]	E [N/mm^2]	ρ [kN/m^3]
Visso, Montegallo	Cut Stones	4.09	0.084	1965	21
Caldarola	Uncut Stones	3.55	0.061	1434	20
Montegallo	Modern Masonry	8.55	0.240	10182	18

2.2. Selection of seismic input

The nonlinear dynamic analyses were carried out with a selection of 155 accelerograms per A/B soil category (Paolucci et al., 2020). Each accelerogram is described by different characteristics in the two components H1 and H2, such as magnitude, station, Vs30 (m/s), PGA (m/s^2), PGV (m/s).

More specifically, the set of considered accelerogram is made by: 115 natural accelerograms; 20 accelerograms scaled to approximate the target spectrum, with return period (Tr) equal to 5000 years; 20 accelerograms scaled to approach the target spectrum, with return period Tr equal to 10000 years.

It has been chosen to carry out the non-linear dynamic analyses assuming each building deterministic and described by the mechanical parameter's values shown in Table 2. Thus, the fragility curves obtained are only characterised by record-to-record variability.

Thus, a total of 310 nonlinear dynamic analyses were performed by applying once the EW component of the accelerogram to the X-direction and the NS component of the accelerogram to the Y-direction, once by reversing (H2-X & H1-Y).

3. Procedure adopted to correlate EDP to DL

The nonlinear dynamic analyses were carried out using the Cloud Method (Jalayer et al., 2015). The results have been interpreted to establish a statistical correlation between a measurable parameter – representative of the seismic response – and the simulated level of global damage (DL).

The Engineering Demand Parameter (EDP) chosen is the ultimate displacement of the structure (d_u). The parameter chosen as intensity measure (IM) is the maximum peak ground acceleration (PGA_{max}) between the two PGAs of the accelerogram (PGA_{H1} and PGA_{H2}).

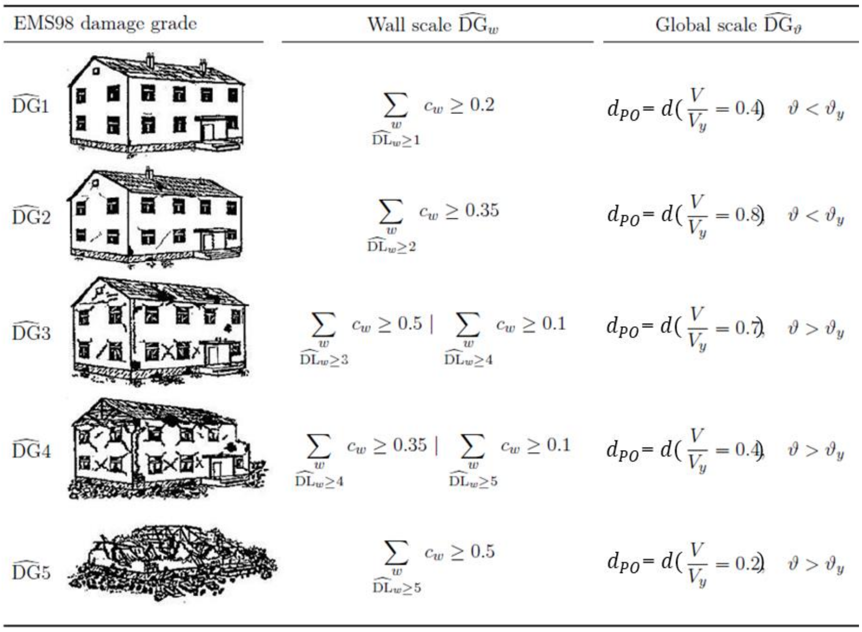
The procedure adopted to correlate the EDP to the DL was developed and already applied in other research works (Sivori et al., 2022; Brunelli et al., 2022). Damage levels aim to conceptually refer to those adopted in post-earthquake macroseismic assessment, such as those proposed in the European Macroseismic Scale (Grunthal, 1998).

Two different checks were carried out to determine the damage level reached by the structure for each analysis. In particular, checks are performed at:

- *global response scale*: by identifying the ultimate displacement reached by the structure through NLDA with respect to the displacement defined for each damage level (DL) on the pushover curves, depending on proper thresholds of strength drop of the base shear estimated from nonlinear static analyses. These thresholds are defined in terms of proper fractions of the overall base shear (V_b), namely: before the attainment of the maximum value ($V_{b,max}$), to define the DL1 (equal to 0.4 $V_{b,max}$) and DL2 (equal to 0.8 $V_{b,max}$); after the attainment of the maximum value, i.e. on the softening phase of the curve, to define the DL3 (equal to a residual capacity equal to 0.7 $V_{b,max}$), DL4 (equal to a residual capacity equal to 0.4 $V_{b,max}$) and DL5 (equal to a residual capacity equal to 0.2 $V_{b,max}$); in this way we can obtain the damage grade of the structure at the global scale DG_θ.
- *wall response scale*: looking at both the damage reached by each wall at each level, and the spread of damage in the building considering the total number of walls; the aim of this control is to monitor the spread of damage along the building. The check is based on the evaluation of the damage severity and diffusion on vertical walls through the cumulative rate of walls that reached a given DL. More specifically, the attainment of the DL on a wall is checked in terms of the DL_{min} variable, as introduced in (Marino et al., 2019). This variable assigns a damage level to the wall based on the minimum DL attained by all the masonry elements of a certain floor. The thresholds assumed for the cumulative rate have been defined to be consistent with the linguistic description of the damage grades proposed by the EMS98 (Grunthal, 1998); in this way we can obtain the damage grade of the structure at the wall scale DG_W.

For each record, the worst criterion (i.e. the one that occurs at first) is adopted to assign the final resulting global DL. According to this procedure, results of records can be properly grouped as those associated to the same DL.

The relationship between DG and damage level according to the two controls is therefore summarised with proper thresholds, which are reported in Figure 3.



EMS98 damage grade	Wall scale $\widehat{DG}_w$	Global scale $\widehat{DG}_\vartheta$
$\widehat{DG}1$	$\sum_{\substack{w \\ \widehat{DL}_w \geq 1}} c_w \geq 0.2$	$d_{PO}= d(\frac{V}{V_y} = 0.4) \quad \vartheta < \vartheta_y$
$\widehat{DG}2$	$\sum_{\substack{w \\ \widehat{DL}_w \geq 2}} c_w \geq 0.35$	$d_{PO}= d(\frac{V}{V_y} = 0.8) \quad \vartheta < \vartheta_y$
$\widehat{DG}3$	$\sum_{\substack{w \\ \widehat{DL}_w \geq 3}} c_w \geq 0.5 \mid \sum_{\substack{w \\ \widehat{DL}_w \geq 4}} c_w \geq 0.1$	$d_{PO}= d(\frac{V}{V_y} = 0.7) \quad \vartheta > \vartheta_y$
$\widehat{DG}4$	$\sum_{\substack{w \\ \widehat{DL}_w \geq 4}} c_w \geq 0.35 \mid \sum_{\substack{w \\ \widehat{DL}_w \geq 5}} c_w \geq 0.1$	$d_{PO}= d(\frac{V}{V_y} = 0.4) \quad \vartheta > \vartheta_y$
$\widehat{DG}5$	$\sum_{\substack{w \\ \widehat{DL}_w \geq 5}} c_w \geq 0.5$	$d_{PO}= d(\frac{V}{V_y} = 0.2) \quad \vartheta > \vartheta_y$

Fig. 3 – Relationship between DL and Cloud Method controls at global and local scale

In Figure 3: *w* stands for wall, thus c_w is the cumulate of the building walls; DL_w is the damage level reached by each wall; *PO* stands for pushover (nonlinear static analysis), thus d_{PO} is the displacement obtained by nonlinear static analysis in correspondence of certain thresholds of base shear strength drop (V/V_y).

4. Results

Finally, about the approach to fit the data and finally derive the fragility curves, a lognormal distribution has been assumed as usual in risk analyses (Baraschino et al., 2019).

Thus, fragility curves were computed by estimating the probability of exceeding (p_{DLi}) the different damage levels, DLi (i = 1 … 5), given a level of ground shaking quantified through the IM. The p_{DLi} was computed from the lognormal distribution of the IM values causing the ith DL. The fragility curve is expressed by the median value IM_{DLi} and the lognormal standard deviation σ_{DLi}, according to Equation 1, where Φ is the standard cumulative probability function.

$$p_{DL_i}(DL > DL_i|IM) = \Phi\left(\frac{log(IM|IM_{DL_i})}{\sigma_{DL_i}}\right) \tag{1}$$

The Cloud Analysis allowed to associate a DL to each analysis performed. The maximum PGA between the two component H1/H2 of the accelerogram has been considered to define the IM. Then, the results were grouped as a function of the DL achieved in order to estimate σ_{DLi} and IM_{DLi}. As an example, Figure 4 reports the grouped records of the Caldarola's school.

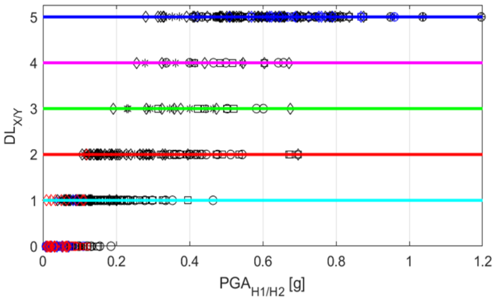
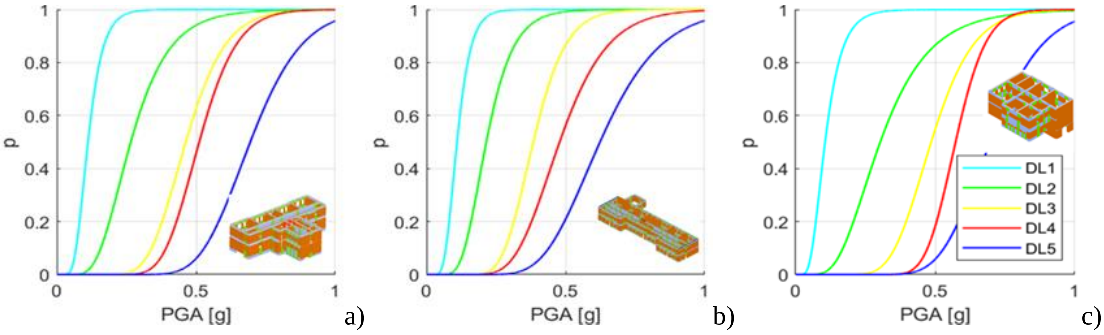


Fig. 4 – Cloud Analysis of the Caldarola model, reporting the DL reached by the structure under each accelerogram (the dots) applied, according to its maximum PGA

The fragility curves obtained for the three models analysed are represented in Figure 5.



a) b) c)

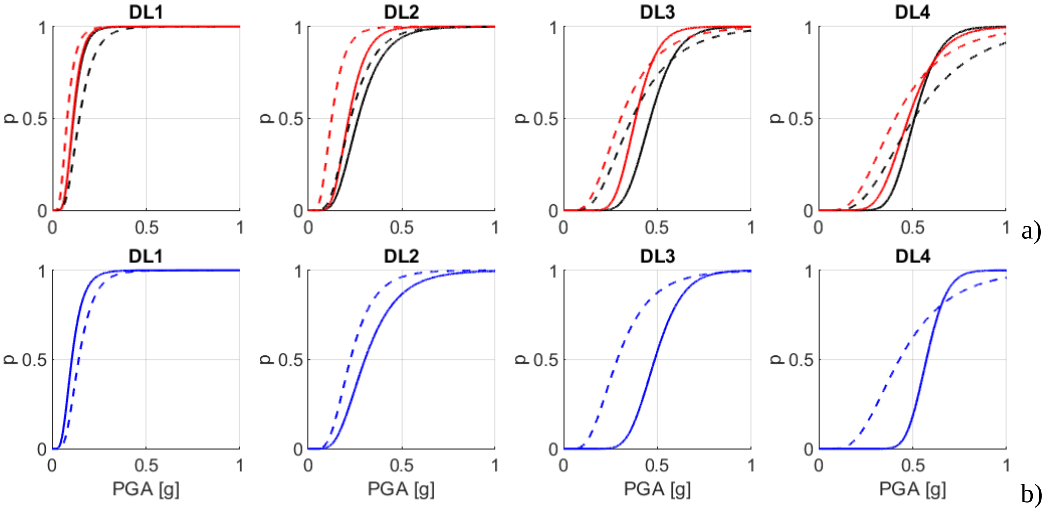
Fig. 5 – Fragility curves for Visso (a), Caldarola (b) and Montegallo (c) schools

4.1. Comparison of derived fragility curves with other available in literature

To validate the obtained results, the numerical fragility curves have been compared with other ones already available in literature.

Firstly, the fragility curves developed in (Cattari et al., 2021) through an analytical-mechanical approach (i.e. the DBV-masonry model) have been adopted. More specifically, the latter have been derived for 14 archetypes selected to be representative of the Italian URM school buildings: the three schools examined in the paper belong to this selection.

For the purposes of a fully consistent comparison with the numerical curves herein developed, the DBV-model has been applied by adopting the same mechanical parameters' values reported in Table 2 (actually, in Cattari et al. 2021, reference parameters were adopted to be representative of a masonry type class rather then those specific of each school) and constitutive law, so to have deterministic models. The comparison is reported in Figure 6: continuous lines refer to the numerical fragility curves, while the dashed ones to those derived from the analytical-mechanical approach. Only the first four DLs are reported since the estimate of DL5 is considered quite conventional from the mechanical-approach.



a) b)

Fig. 6 – Numerical (continuous line) and analytical-mechanical (dashed line) fragility curves compared; in a) the curves of Visso (in black) and Caldarola (in red) schools are reported, in b) the ones of Montegallo (in blue) school.

Another comparison was made with the fragility curves illustrated in (Da Porto et al., 2021), that refer to those developed for the Italian National Risk Assessment (NRA) of residential masonry buildings (Dolce et al. 2021). In this case, fragility curves refer to sub-types defined according to a taxonomy based on the ISTAT (ISTAT, 2011) census (i.e. on basis of the age of construction and height). Figure 7 shows the results of such a comparison. The filled areas indicate the range outlined by the various methods adopted in NRA for residential buildings. More specifically, the adopted models rely on various approaches, namely: the pure empirical one, in three cases by referring to the data collected in the Da.D.O. platform (Rosti et al. 2021 and Zuccaro et al., 2021); the analytical approach (Donà et al., 2021); the heuristic one (Lagomarsino et al., 2021). Although results refer to two different assets (i.e. residential buildings and schools), the comparison still appears suitable and useful. In fact, the geographical context is the same thus with analogies in some recurring structural details and design practice (apart the physiologic differences produced in the architectural configurations by the different usability exigences). The curves are in a quite good agreement in terms of median IM value; the difference in the dispersion is mainly ascribable to the fact the numerical curves account only for the record-to-record variability.

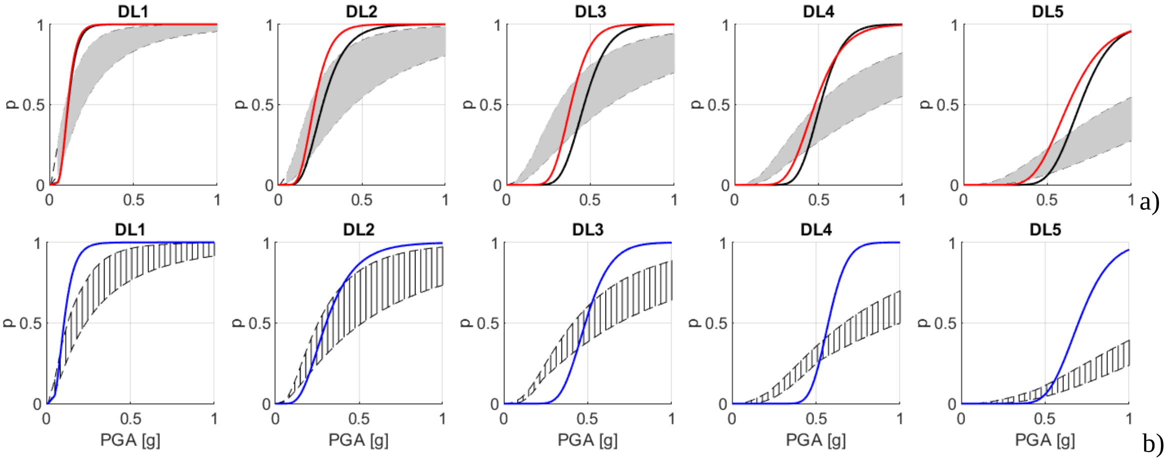


Fig. 7 – Numerical fragility curves of a) Visso (in black) and Caldarola (in red) schools, and b) Montegallo (in blue) school, compared with the literature (Da Porto et al., 2021) ones (grey screen for the 1919-1945 age, 2 floors of Visso and Caldarola; black striped screen for the 1946-1960 age, 3 floors of Montegallo).

It is worth noticing that the fragility curves obtained by numerical approach considers only the record-to-record variability. However, watching the results only referring to the median IM value, the numerical fragility curves are in good agreement with the fragility curves of references.

5. Conclusions

The paper presents a study on the use of numerical methods for deriving fragility curves of Italian masonry school buildings.

The comparison done between the derived numerical fragility curves and other ones available from literature is promising. The potential of the numerical approach consists of accounting in an explicit way of specific features of this building stock.

Of course, with the aim of using these curves to support seismic risk assessment at regional scale, a higher number of archetypes must be investigated to statistically describe in a more robust way the corresponding class of buildings with homogeneous behavior. To increase the number of archetypes for each class will allow to properly account for the inter-building variability (and thus also include this source of uncertainty on the combined fragility curves).

Acknowledgements

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