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Procedia Structural Integrity 44 (2023) 155–162

Structural Integrity
Procedia

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XIX ANIDIS Conference, Seismic Engineering in Italy

# Simplified seismic vulnerability analysis of historic residential buildings with fragility curves

Elsa Garavaglia[a], Grigor Angjeliu[a], Giuliana Cardani[a]*

[a]*Dept. of Civil and Environmental Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 32, Milano 20133,, Italy*

**Abstract**

In the disciplines dealing with the preservation of the built heritage, the assessment of the seismic vulnerability plays a decisive role. A high number of numerical models have been developed to simulate the behaviour of different building typologies subjected to seismic action, but requiring a in-depth knowledge of the object of study they are not suitable for urban scale analysis. The widespread historical built heritage in Italy, as in many other countries, requires the definition of rapid and reliable assessment procedures that allows a large-scale evaluation of the vulnerability of historical buildings before a seismic event. This analysis should be based on existing databases, such as the Reluis-Cartis database, without necessarily proceeding at this stage with detailed investigations of each individual building. Based on state-of-the-art procedures, a methodology is proposed for the fast construction of the fragility curves starting from information available on the Reluis-Cartis database. The curves define the relationship between the probability of reaching a safety factor or a vulnerability index in function of the seismic acceleration PGA. The methodology allows to understand the probability of loss of the structural safety in function of a given PGA. The developed methodology is applied here in two cases: (a) a small historic building hit by several earthquakes in order to calibrate the methodology and (b) to a set of historic building of the same typology in a historic center never hit by earthquakes in order to assess the level of the probability of loss of the structural safety given the code defined PGA, as well as to draw conclusions on prioritizing intervention strategies at the urban scale.



*Keywords:* Seismic Vulnerability; Fragility Curves; Built Heritage, Masonry.

* Corresponding author. Tel.: +39-02-2399-4204; fax: +39-02-2399-4220.
*E-mail address: giuliana.cardani@polimi.it*

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10.1016/j.prostr.2023.01.021

## 1. Introduction

The assessment of the seismic vulnerability of existing buildings not yet damaged by an earthquake is an important issue in order to carry out proper prevention and to manage the safety of historical residential buildings throughout Italy. Those buildings need a procedure that leads to the large-scale vulnerability classification, which should necessarily be simple and reliable. Furthermore, such a procedure should be able to provide elements in support of a possible classification starting from readily available data in the municipality archives or in national databases compiled through CARTIS survey forms, as in Zuccaro et al. (2015), without necessarily requiring additional visits and surveys on site. Approaches have been developed by the Italian scientific community, over the years, that address the issue of studying seismic vulnerability and the propensity of existing buildings to damage, but they often start from the post-earthquake assessment, as in Rosti et al. (2018), Sisti et al. (2019) or Zuccaro et al. (2021). In other cases the models are very elaborate and require in-depth knowledge of the building, which is not always available, skilled professionals for the computations and significant processing times, Saloustros et al. (2015) or Angjeliu et al. (2020).

The aim of the present research is to establish a procedure to estimate the safety of existing masonry buildings, which is reliable and to extend it with the concept of fragility curves to be easily applied for the assessment of an urban area. To this aim, a deterministic seismic assessment methodology presented in Borri et al. (2014), Borri and De Maria (2016) was chosen, and consequently extended into a probabilistic framework. Three simplified verifications are required: gravity check, global horizontal actions check and local mechanism check. The capacities are checked with the demand as required by the Italian Code NTC (2018) for the limit state for safeguarding human life (SLV). Results are expressed in terms of conventional safety factor and contribute to the definition of the building vulnerability class. This approach provides a deterministic safety factor ($SF_{VG}$) for each building which is associated with its' structural characteristics and the seismic zone to which it belongs. The deterministic method is then applied parametrically by varying the seismic input and extending in §2 within the fragility curves concept allowing for a probabilistic prediction of safety factor within a PGA range. In §3 the well-known vulnerability index method proposed by Benedetti and Petrini (1984) is adopted for comparison purpose. This method is based on a computed vulnerability index which correlates the expected damage in function of the acceleration. In §4 and §5 are discussed 2 applications: a) a simple residential building that presents the typical construction typology of Central Italy in order to evaluate the propensity to damage related to two documented earthquakes; b) a medium-sized residential center in Lombardy region, which has not previously suffered seismic damage and whose data was taken from the Reluis-CARTIS datasheet. In both cases the fragility curves, developed within the here proposed approach are compared with the vulnerability curves obtained by the established approach proposed in Benedetti and Petrini (1984) in order to verify their alignment.

## 2. Methodology on the construction of fragility curves

The method consists in the construction of curves that allow a probabilistic prediction of the occurrence of a certain phenomenon when a certain condition varies, for example: the probability of reaching a certain damage threshold when the level of acceleration recorded varies, as in Garavaglia et al. (2008, 2020, 2021), but also in Singhal and Kiremidjian (1996), Flora et al. (2020) or Sandoli et al. (2021). The safety factor $SF_{VG}$ proposed in Borri et al. (2014) has this characteristic, as it is a function only of the distribution characteristics in plan and elevation and structural characteristics of materials. Hence, $SF_{VG}$ is the index of damage to be studied from a probabilistic point of view.

The construction of the curves starts from the modelling, with an appropriate probability density function (p.d.f.), of the values of the selected variable, here $SF_{VG}$, present in a certain range of the ground acceleration $a*$. Therefore, in the cases studied, the fragility curve defines the probability for a system to reach the loss of a certain value of $SF_{VG}$ at a defined acceleration $\bar{a}$. Once the damage threshold $\overline{sf}$ is defined, the probability of this threshold being reached at instant $a*$ is described by the area below the p.d.f. to the left (dashed area). On the opposite, the probability of exceeding this threshold is described by the area below the p.d.f. to the right in solid area (Fig.1a).

By constructing the probability density function for the chosen random variable for each of the chosen intervals, or acceleration values, it is easy to see how it is possible to construct the fragility curve linked to the experimental evidence or, better called, the experimental fragility curve $F_{\bar{A}}(a^*)$ (Fig. 1.b). The area above the threshold $\overline{sf}$ is calculated using the survival function reported in (1):

$$\Im_{sf}(SF, a^*) = \Pr\{sf > SF\} = 1 - F_{sf}(SF, a^*) \qquad (1)$$

where $F_{sf}(SF, a^*)$ is the cumulative distribution of *sf* at each acceleration $a^*$ and describes the probability that the variable *sf* reaches values greater than a certain value *SF*, in this case *SF*=$\overline{sf}$.

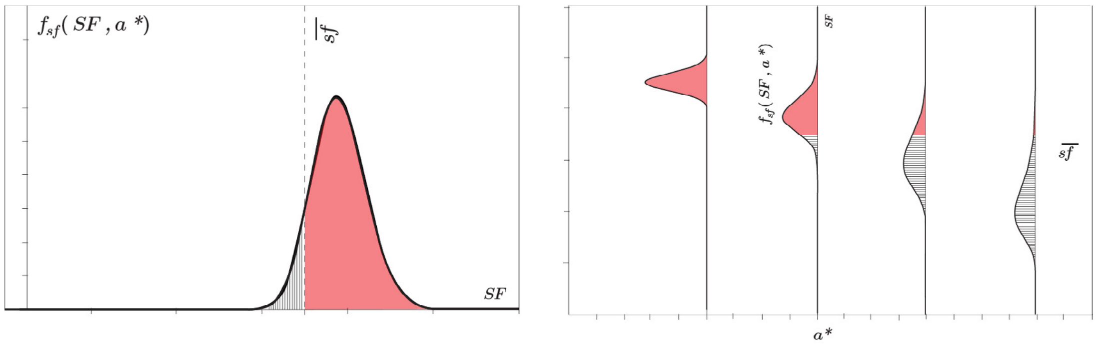



Fig. 1. Probability of reaching and exceeding threshold $\overline{sf}$: (a) qualitative p.d.f. for a given value of $a^*$; (b) p.d.f. built for different values of $a^*$.

The area below the threshold $\overline{sf}$ is determined by the cumulative distribution $F_{sf}(SF, a^*)$=Pr$\{sf \leq SF\}$, which describes the probability that *sf* can assume values not exceeding *SF*, in this case *SF*=$\overline{sf}$. The investigated variable $SF_{VG}$ will be modelled using a Normal distribution, while the experimental fragility curves will be created using the Cumulative distribution function, $F_{sf}(SF, a^*)$ and then considering the dashed areas in Fig. 1.

## 3. The vulnerability index

The construction of the trilinear vulnerability curves, as proposed in Benedetti and Petrini (1984), Guagenti and Petrini (1989), is also based on the analysis of a series of data collected in special technical survey templates as in INGV (1993) for earthquake-damaged buildings of the same construction typology.
Vulnerability is estimated on the basis of a set of 11 parameters considered representative of the building susceptibility to damage following a seismic event and to which different classes of damage can be attributed, with different score *pi*. It is thus possible to define the vulnerability index $V = \Sigma_i\, p_i\, w_i$ as the weighted sum of the scores for each parameter. Scores and weights are determined through statistical analysis of damage data collected from earthquakes that have occurred, as reported Benedetti and Petrini (1984), Guagenti and Petrini (1989).

The damage index associated with this procedure is obtained through a weighted average, $d = \Sigma_{ij}\, S_i F_j D_{ij}$. *Dij* is the damage index in the $i^{th}$ construction component (vertical structures, horizontal structures, stairs, partitions) located in the $j^{\text{th}}$ floor, *Si* and *Fj* are weighted coefficients that characterize the component and the floor.

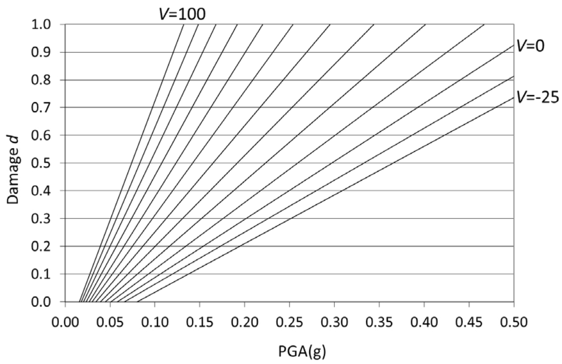



Fig. 2. Trilinear vulnerability plot for masonry buildings with parameters estimated on the basis of data collected after seismic events in a group of Italian towns, as in Grimaz et al. (1996).

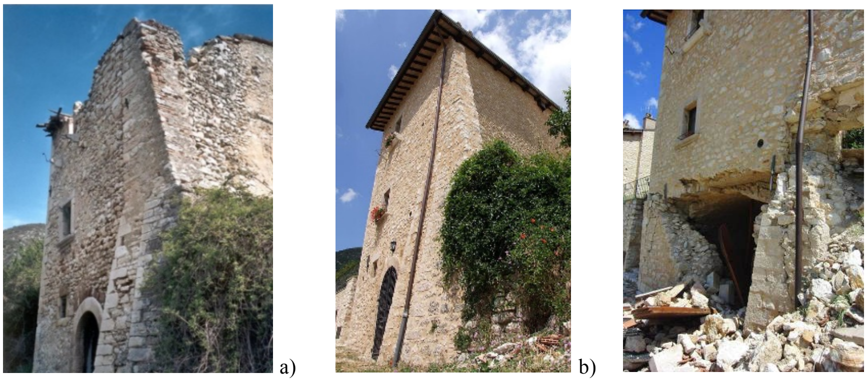
The vulnerability index *V* and the damage index *d* are then used to define the relationship between damage, vulnerability and seismic action *a*. The relationship *d (V, a)* is obtained through statistical analysis of survey data carried out on damaged buildings. From this relationship, different damage-acceleration curves are obtained for buildings with different values of vulnerability index (Fig. 2).

## 4. Applications

### *4.1. Benchmark – Stone Masonry Building in Campi Alto di Norcia*

As a first case study, a small isolated historic building in stone masonry was chosen, located in the historic center of Campi Alto di Norcia (PG), Umbria region, an area with high seismicity, see Binda et al. (2006 and 2007). The area has been subject to several earthquakes. The events of 1997 and 2016 are of particular interest since damage was documented afterwards (Fig. 3). It is noted here that after the 1997 earthquake the building was strengthened in 2000s. The masonry building consists of a simple structural unit of about 60 m$^2$ on each floor, with 3 floors, two of which are basements and the one on the ground floor has a barrel vault. The building consists of a load-bearing masonry made in compact limestone, the “roughly cut stone masonry (even irregularly shaped) with good texture", according to the definitions in Circular no.7 of 21-01-2019 of NTC (2018), with timber floor and roof. The building once appeared at the end of a series of houses arranged in rows along one of the many contour lines that characterize the steeply sloping terrain of Campi Alto, all of which are now absent, collapsed in the past. In Campi Alto di Norcia, the analyzed subsoil is rather rigid and rocky (Soil Class A and in class T3 as in NTC (2018).

The earthquake of October 2016 seriously damaged this building again, highlighting new vulnerabilities, perhaps also linked to the type of performed intervention (Fig. 3c) with the resulting effect of destroying both ground corners of the façade and the overturning out-of-plane of the lower part of the façade, corresponding to the ground floor only.



a) b) c)

Fig. 3. Photos of the case study in Campi di Norcia: a) after 1997 earthquake b) after the restoration in 2000s c) after the earthquake in 2016.

In the following the computed seismic vulnerability is compared to observed damage in 1997 (ag/g=0.2275) and 2016 earthquake (ag/g = 0.30256g), using data recorded before the seismic event. The purpose is to investigate the ability of the here presented method to assess the predicted level of damage associated with recorded levels of PGA.

### *4.2. Construction of the first fragility curves and vulnerability index*

Two simulations were carried out: a) the first to predict the propensity of the building to be damaged, before the 1997 earthquake - with the floor and wooden roof still present and with active iron tie-rods - and to verify the result after having seen the damage recorded; b) a second investigation will then be carried out on the same building repaired after 1997 (with the addition of modern brickwork within the two upper floors and the insertion of reinforced concrete floors), verifying the results with the observed damaged occurred after the 2016 earthquake. The aim is to investigate the ability to assess the probable loss of performance associated with PGA and, so, to calibrate the method with experimental observations of damage.

The fragility curves were then constructed for the building, describing the probability of passing certain thresholds of loss of the $SF_{VG}$ safety factor as a function of the varying PGA (Fig. 4). The acceleration interval chosen is between 0.036 ag/g and 0.28 ag/g as it is representative of the accelerations that characterize the Italian territory. The step adopted for the analysis is 0.02 ag/g. The safety factors, $SF_{VG}$, recorded for each step of the interval are modelled with a normal probability distribution. The construction of the experimental fragility curve is obtained as presented in section 2 using the cumulative distribution function $Fsf(SF,a*)$.

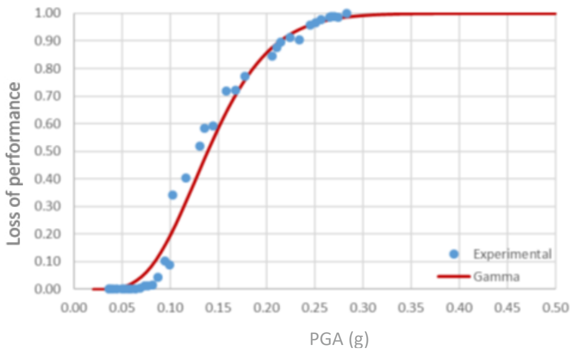



Fig. 4. Campi di Norcia: Fragility curve of the probability of reaching a value $SF_{VG} \leq SF_{VG}^*$ (for $SF_{VG}^* = 32.5\%$, Soil Categ. A, Topography T3).

The fragility curves were also studied as the transition probability of a given threshold of values for the overall safety factor $SF_{VG}$. The methodology used is that developed by Garavaglia et al. (2008). The following limit thresholds for loss of the safety factor $SF_{VG}$ are considered significant:

$$\overline{sf}=SF_{VG}=20\%;\ \overline{sf}=SF_{VG}=40\%;\ \overline{sf}=SF_{VG}=60\%. \qquad (2)$$

In Fig. 5a, the experimental fragility curves defined on 5 intervals are reported: (0.1-0.14), (0.14-0.18), (0.18-0.22), (0.22-0.26), (0.26-0.30) of g. These curves define the probability of reaching a value $SF_{VG}$ less or equal to the assumed threshold $\overline{sf}$. Therefore, the experimental curve $\overline{sf}=SF_{VG}=20\%$ suggests that for PGA less than 0.12g, there is a 40% probability that the safety factor $SF_{VG}$ has lost 20% of its initial value.

The method proposed in Benedetti and Petrini (1984), Guagenti and Petrini (1989) is applied on the single masonry building. The obtained vulnerability index is computed for two cases: a) before the 1997 seismic event, and b) before the 2016 seismic event, after a strengthening intervention. These trilinear curves are reported in Fig. 5b, expressing the damage in function of recorded PGA. In pre 1997 earthquake conditions, the continuous line indicates an early damage acceleration of 0.037 ag/g and a collapse acceleration of 0.325 ag/g with a vulnerability index $V$=33.99. The structural interventions carried out in 2000s, as shown by the dashed line, improves the vulnerability index of the building by increasing the collapse PGA to 0.379 with $V$=25.85 (Fig. 5b).

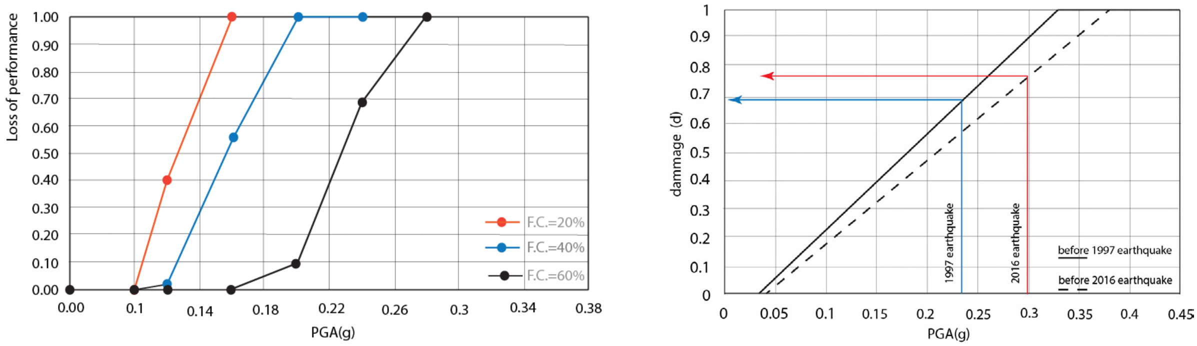



Fig. 5. Building in Campi di Norcia: a) Experimental fragility curves describing the probability of loss of performance, evaluated in terms of $SF_{VG}$, for different possible loss thresholds (Soil Category A, Topography T3). b) Vulnerability index method expressing damage as a function of peak-ground-acceleration before 1997 and 2016 earthquake, following the approach in Benedetti and Petrini (1984).

Compared to the acceleration recorded in 1997, ag/g=0.2275, the method predicts a damage up to 0.6. Considering the earthquake of 2016, ag/g=0.30256g, the damage predicted in the structure is still high despite the improvements made in early 2000s (Fig. 5b). The computed vulnerability of the structure before the 1997 and the 2016 earthquakes matches the damage observations. In particular, during 1997 earthquake moderate damage was observed on the top of the building, despite the lack of maintenance, while near collapse conditions were observed during 2016 earthquake, despite the seismic strengthening. The results in Fig. 5b show that the maintenance performed has improved the vulnerability index and lowered the probability of damage as the acceleration varies, but due to the intensity of the

2016 earthquake, a propensity to damage close to 0.78 is still noted. This suggests that the interventions carried out, although of an ameliorative nature, have raised issues of incompatibility with the type and materials of the original construction. This raises an important issue on taking into account the consolidation interventions for the protection of the historical heritage during analysis, as well complications on finding suitable repair techniques, without demolishing parts of the original construction.

### *4.3. Brick Masonry Buildings in historic center of Desio city not damaged by earthquakes*

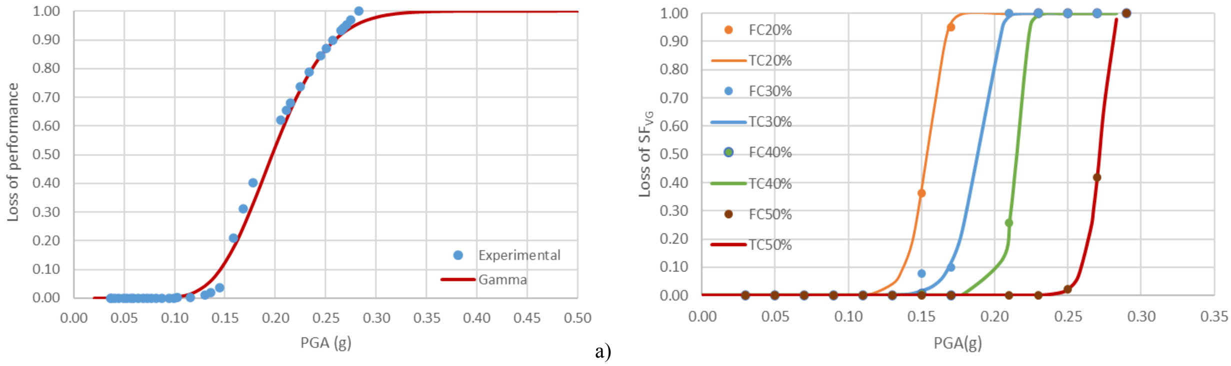
The survey was carried out on a homogeneous set of 10 buildings located in the municipality of Desio, province of Monza-Brianza, catalogued as a recurrent typology in the historic center (named MUR1 of CO1 through the CARTIS form). The buildings have a simple geometry, all brick masonry, two-story with an average inter-floor height of 3m (Fig. 6); they represent 63% of the buildings in the subdivision, despite the size of the town (41 646 inhabitants) and its predominantly industrial characterization. The town of Desio recently changed from seismic zone 4 (the lowest) to seismic zone 3, according to seismic risk criteria that categorizes Italy into four zones. It has a subsoil category C (medium thickened coarse-grained soil deposits or medium consistent fine-grained soils), topographic category T1 (flat). The choice of this location is justified by the intention to apply the procedure presented here to investigate the seismic response (in terms of reduction in safety factor) of certain structural types as the seismic hazard changes.

Fig. 6. Recurrent masonry building typology named MUR1 in the historic center of Desio (MB).

### *4.4. Construction of the fragility curves and vulnerability index*

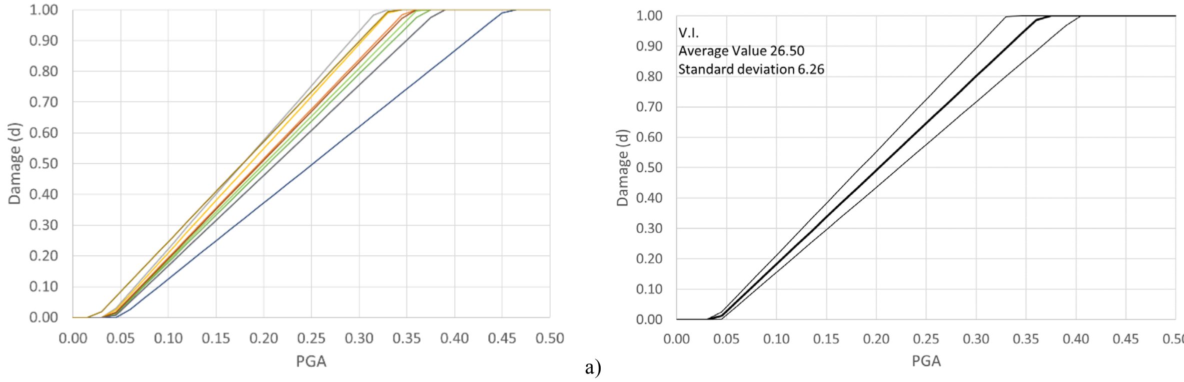
The investigation of seismic response in terms of global safety factor ($SF_{VG}$) was based exclusively on data extracted from the Cartis database. A fragility curve was then constructed for each building, describing the probability of reaching a certain minimum safety value recorded for the maximum acceleration value investigated as the accelerations varied (Fig. 7a). Fragility curves describing the probability of passing certain thresholds of SFVG factor loss as the PGA changes were then constructed for each building (Fig. 7b). The studied acceleration intervals range from 0.06 ag/g to 0.30 ag/g with an amplitude of either 0.02 or 0.04 ag/g, depending on the data reading requirements. The experimental curves were then modelled with Weibull-type probability distributions. The choice of this family of distributions is related to the physical interpretation of the studied phenomenon. If a certain threshold has never been exceeded before, the probability that it will be exceeded in the next acceleration increment interval increases more and more as the acceleration value increases; the Weibull distributions have an increasing hazard rate tending to infinity, which seems to interpret well the expected behaviour in the threshold transition just described.

The results obtained for all 10 buildings were then used to construct the fragility curves of the investigated typology, both for the range of considered input acceleration. For each building, the vulnerability index was meant to be calculated by following the methodology described in section 3, in Benedetti and Petrini (1984) and, again, using data collected in CARTIS database. For all buildings, the vulnerability index is around 30 (Fig. 8). The damage-PGA curves were constructed, for each of the studied buildings. The results are consistent despite some small differences between buildings, showing a good reliability of the proposed method when applied to an entire category of buildings (as MUR1). Obviously, although most of the buildings belonging to a given typology will tend to have similar response, deviations of structural behavior might be observed in practice due to specific characteristics of each case.




a)
b)

Fig. 7. Desio: (a) fragility curve describing the probability for a MUR1-type building, (b) example of experimental (FC) and theoretical (TC) fragility curves constructed for each individual building of the group of selected buildings in MUR1 typology.




a) b)

Fig. 8. Damage acceleration ratio for all buildings surveyed of the MUR1 typology in Desio (MB): a) vulnerability index calculated for all surveyed buildings; b) average vulnerability index for MUR1 typology.

## 5. Conclusions

The research developed in the present study aims to define a procedure for seismic vulnerability assessment at of historical masonry buildings applied at the urban scale. The safety is expressed in terms of a fragility curve describing the probability of reaching a certain minimum safety value versus the recorded maximum acceleration PGA. An important feature of the proposed procedure is the use of already available inputs from databases such has Reluis-CARTIS, which allows to apply the procedure with simplicity to large urban areas (e.g. a historic center).

The definition of the safety factor is based on a method already proved in the literature, which is based on the requirements of the Italian Code NTC 2018. A deterministic safety factor $SF_{VG}$ is computed as the minimum of three simplified verifications: gravity check, global horizontal actions check, and local out-of-plane mechanisms check. The chosen method allows to compute a safety factor, $SF_{VG}$ for each seismic input defined as PGA value. Considering a range of acceleration, the methodology was extended here in a probabilistic framework with the concept of the fragility curves. This helps to formulate hypotheses on the possible loss of performance of the building, measured as a decrease in the safety factor $SF_{VG}$, as the intensity of shaking in PGA increases. The procedure was programmed through VBA (Visual Basic for Applications) and Excel in order to automate all the steps into a simple tool.

The procedure was demonstrated through two applications. The first case study is a small residential building in Campi di Norcia, hit by earthquakes in 1997 and 2016 and for which pre-earthquake and post-earthquake information was available. The results show that the predicted loss of performance matches quite well the observed structural response. The second application aims to test the procedure applicability in a large-scale analysis rather than a single building, based on data extracted from the Reluis CARTIS database. The results show the possibility to analyze urban areas with the proposed method in a suitable timeframe and with a considerable level of automation.

Furthermore, the fragility curves were compared with the trilinear vulnerability curves (a consolidated method proposed by Benedetti and Petrini (1984) more than three decades ago). Even in the case the results between the two methods are quite aligned. The comparison between the two methods seems to validate the assumption of the safety factor as a quantity of damage index of the damage for an undamaged building and it seems to suggest a combined use of the fragility curves and the vulnerability index to arrive at a seismic classification of the buildings.

Future work will aim at applying the developed procedure in large urban areas for seismic vulnerability prediction with different masonry building typologies.


## Acknowledgements

The research is framed within the Laboratories University Network of Seismic Engineering, projects ReLUIS 2019-2021 and 2022-24 from the Italian Civil Protection Department.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