

SEISMIC VULNERABILITY ASSESSMENT OF HISTORIC MASONRY BUILDINGS THROUGH FRAGILITY CURVES APPROACH

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Abstract. *The assessment of the seismic vulnerability of built heritage is still an open issue. Regarding this topic, in recent years many researchers have worked in the development of refined numerical models to simulate the behaviour of different building typologies subjected to seismic action. To be reliable, these models require in-depth knowledge of the building object of study.*

In many countries, such as Italy, where the widespread historical heritage is widely present, there is the need to define quick, but reliable, evaluation procedures, which allow, in advance, to assess the vulnerability of the historical heritage of an entire area using databases already present without necessarily proceeding with detailed investigations on each building.

Based on procedures in the literature, the authors have developed an assessment methodology focused on the construction of fragility curves, safety factor vs PGA and vulnerability index, which allows to formulate hypotheses on the probable behaviour of a specific type of building, to any similar actions and the probable expected damage. In the view of evaluating the seismic safety of a small historic centre in an area with a high seismic propensity, this procedure could be useful for prioritizing interventions in probabilistic terms.

1 INTRODUCTION

The assessment of the seismic vulnerability of existing buildings not damaged by the earthquake is an important topic for the classification and subsequent safety of the historic buildings of the entire Italian territory.

The procedure that leads to the large-scale vulnerability classification of existing buildings must necessarily be a simple and reliable procedure. It is believed that it should be able to provide elements in support of a possible classification starting from data that can be easily found in the municipal archives and in cards such as the CARTIS survey forms [1], without necessarily requiring visits and surveys on site (which, however, are not always possible).

Over the years, approaches have been developed by the Italian scientific community that address the issue of studying the seismic vulnerability and the propensity to damage of the existing one, but often we start with the post-earthquake assessment [2-4]. The models proposed are often very refined models that require in-depth knowledge of the building, not always available, qualified professionals in the use of calculation processes and important processing times [5,6].

The purpose of this research is to look for a procedure for estimating the vulnerability of existing buildings not yet damaged by the earthquake, which is reliable and easily extendable to the assessment of an entire urban area. The procedure can be useful for public administrations as a tool on which to base maintenance planning.

To this aim, rather than proposing a new method that would require a long and important validation, one already present in the literature was selected. The seismic assessment methodologies available are deterministic, hence it is necessary to incorporate them into a probabilistic framework.

Two approaches seem to be easily applicable to vulnerability assessment both for single buildings and for widespread contexts:

- The approach proposed by Borri and De Maria in [7-9] relating to three types of simplified verification: simplified gravity verification, simplified global horizontal loading verification and simplified local mechanisms verification. The results of the three simplified checks are compared with the safety levels required by the Italian NTC2018 [10] standards for the limit state of safeguarding human life (SLV) referred to the site in question, the building type considered and the intended use class. These results are expressed in terms of conventional safety factor and contribute to the inclusion of the building in a certain class of vulnerability.
- The approach presented by Benedetti and Petrini [11] based on the classification of existing constructions through a vulnerability index, as well as the definition of the associated damage (acceleration associated with the start of damage and acceleration associated with collapse) through the construction of suitable vulnerability curves.

The first approach is applied to each single building and provides a safety factor, SF_{VG} , associated with the characteristics of the building and the seismic zone to which it belongs. The method is lean and can be applied to several buildings, but it is a deterministic method that does not give any information on the probable behaviour of the building as the seismic action varies.

The second method provides, on a statistical basis, an indication of the level of damage that a specific type of building could suffer on a range of seismic accelerations. The estimate of the damage level depends not only on the characteristics of the building analysed, but also on

parameters determined on a statistical population considered reliable.

In order to arrive at a probabilistic forecast of the damage as the acceleration varies, the authors thought to implement the first method with the construction of fragility curves that relate the decrease of the safety factor to the variation of the recorded acceleration.

The proposed method is here applied to a simple residential building showing the typically Central Italy construction typology to evaluate the propensity to damage before the 1997 earthquake and before the earthquake of 2016. The fragility curves, implemented here are used to evaluate the decrease in the safety factor for the considered range of PGA, will be compared with the a more consolidated approach as the vulnerability curves proposed in [11] in order to check their alignment. The results are reported in the following sections.

2 MATERIALS AND METHODS

The aim of the research is to evaluate the seismic vulnerability of a masonry structure starting from already available data. Following the application of the fragility curves concept it is then necessary to identify a damage index that is significant, but easily calculable starting from available data.

The safety factor SF_{VG} proposed in [7,8] has this characteristic, as it depends only on the distributional characteristics in plan and elevation and on the characteristics of the materials readily available from visual investigations or with non-destructive tests. Therefore, SF_{VG} is the magnitude index of the damage that we are going to study from the probabilistic point of view.

2.1 Definition of fragility curves

The fragility curves are a forecasting method already used in the seismic field [12-17]. The method consists in the construction of curves that allow a probabilistic definition of the occurrence of a certain phenomenon when a certain condition varies, for example: the probability of reaching a certain damage threshold as the lifetime varies or the level of recorded acceleration varies [18-20].

The construction of these curves is quite simple, and the reliability seems good. Being a probabilistic method, it certainly suffers from uncertainties: epistemic uncertainties linked to the interpretation of the phenomenon and the consequent modelling, as well as to the sample size; random uncertainties linked for example (but not only) to the quality of the data.

The construction of the fragility curves starts from the modelling, with an appropriate probability density function (p.d.f.), of the values of the chosen variable, in our case it will be SF_{VG} , present in a certain range or detected for a certain value of the 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 certain acceleration \bar{A} .

Thus, having defined the damage threshold \bar{sf} , the probability that it is reached in the instant a^* , is described in the area underlying the p.d.f. to the left of the threshold. On the contrary, the probability of exceeding this threshold is described by the underlying area to the right of the threshold itself (Figure 1a).

By constructing the probability density for the chosen random variable for each of the selected intervals, or acceleration values, it is immediate to understand how it is possible to construct the fragility curve linked to the experimental evidence or experimental fragility curve

$F_{\bar{A}}(a^*)$ (Figure 1b).

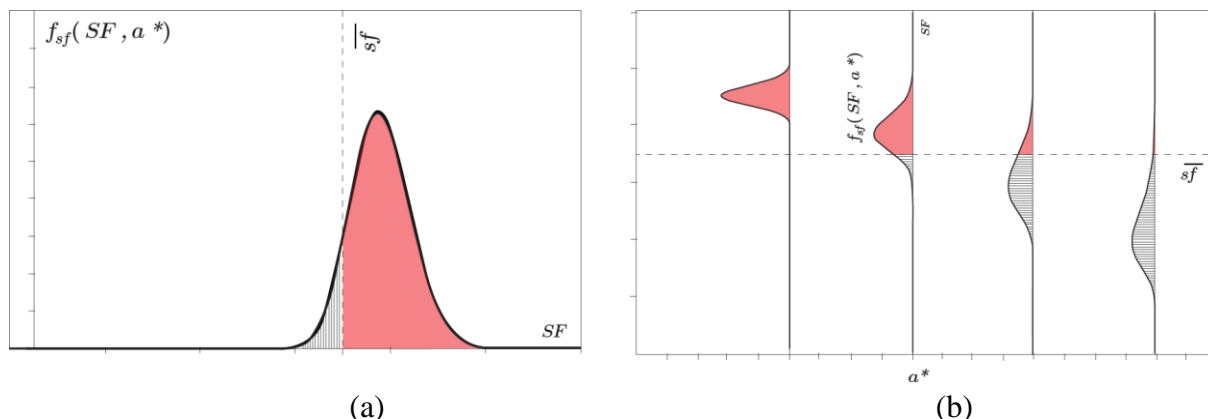


Figure 1: Qualitative probability of reaching and exceeding the threshold \overline{sf} : the probability of reaching \overline{sf} , defined by $F_{sf}(SF, ta^*)$ is dashed; in color the probability of exceeding the threshold \overline{sf} , defined by the survival function $\mathfrak{S}_{sf}(SF, a^*)$, (a) qualitative p.d.f. for a value of a^* ; (b) p.d.f. built for several values of a^* .

The area above the threshold \overline{sf} is easily calculated using the survival function,

$$\mathfrak{S}_{sf}(SF, a^*) = \Pr\{sf > SF\} = 1 - F_{sf}(SF, a^*) \quad (1)$$

where $F_{sf}(SF, a^*)$ the cumulative distribution of sf at each acceleration a^* . It describes the probability that the variable, sf , takes on values greater than a certain value SF , in our case $SF = \overline{sf}$:

The area below the threshold \overline{sf} is given 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 our case $SF = \overline{sf}$.

The computation of $F_{sf}(SF, a^*)$, like the computation of its complementary $\mathfrak{S}_{sf}(SF, a^*)$, is possible through the numerical integration of the probability density function $f_{sf}(SF, t^*)$ respectively in the intervals $(-\infty; \overline{sf}]$ and $(\overline{sf}; +\infty)$. In this way, the areas calculated on different thresholds \overline{sf} provide the experimental fragility curves, $F_{\bar{A}}(a^*)$, for each of the established performance thresholds. Commercial codes of probability and statistics allow this integration to be carried out with ease.

The investigated variable (SF_{VG} safety factor) will be modelled with a normal distribution. The experimental fragility curves will be constructed using the cumulative distribution function, $F_{sf}(SF, a^*)$ and then considering the hatched areas in Figure 1.

2.2 Definition of vulnerability index

The construction of the trilinear vulnerability curves proposed in [11,21] is also based on the analysis of a series of information collected in technical data templates [22] for buildings of the same construction type and damaged by the earthquake.

The vulnerability is estimated on the basis of a certain number of parameters considered

representative of the predisposition of the building to suffer damage as a result of a seismic event. For masonry buildings, the parameters identified as significant for the estimation of a vulnerability index are 11. For each parameter found in the building, a detailed description is given in the technical data templates that allows it to be classified in a specific damage class (from A best class, a D worst class). To construct the numerical index, V , each class was assigned a score p_i , different from parameter to parameter, and a weight w_i which measures the impact that this parameter has on the global vulnerability of the building.

The vulnerability index is therefore defined as the weighted sum of the scores of each parameter:

$$V = \sum_i p_i w_i \quad (2)$$

Scores and weights are determined through statistical analysis of damage data collected on the occasion of earthquakes that have occurred [21].

The damage index associated with this procedure is obtained by means of a weighted average of the type:

$$d = \sum_{ij} S_i F_j D_{ij} \quad (3)$$

where D_{ij} is the damage index in the i -th construction component (vertical structures, horizontal structures, stairs, partitions) located in the j -th floor, S_i and F_j are weight coefficients that characterize the component and the floor. In this case too, the information is obtained from the already mentioned technical data templates.

The vulnerability index V and the damage index d are finally used to define the relationship between damage, vulnerability and seismic action a . The relationship $d(V, a)$ is obtained through the statistical analysis of the survey data on damaged buildings. From this relationship, the different damage-acceleration curves for buildings with different vulnerability index values are obtained (Figure 2). The construction of analogous curves will be used as a comparison with the proposed methodology.

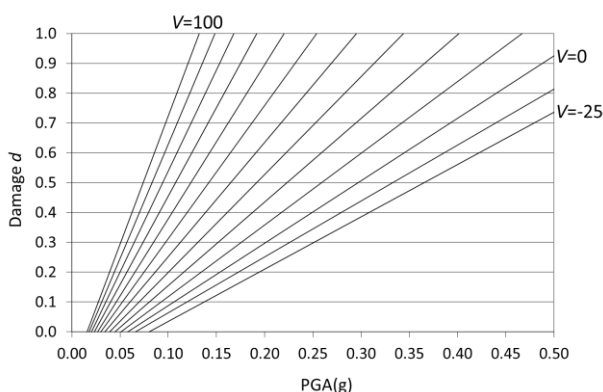


Figure 2: Trilinear vulnerability graphic for masonry buildings with parameters estimated on the basis of data collected after seismic events in Italian municipalities [23]

3 CASE STUDY

As a first case study to test the effectiveness of the methodology, a small, isolated stone masonry building was chosen, in the historic centre of Campi Alto di Norcia (PG), an area of high seismicity [24,25]. The subsoil is rather rigid and rocky; according to the Italian legislation it can be classified in Soil Class A [10]. The territory has slopes with an inclination between 15° and 30° so, for the Italian Design Code the site has to be considered in topographic class T3.

The site was hit by a moderately strong earthquake in 1997 but also in 1979. The building, selected as a case study, underwent several damages and strengthened in early 2000. In 2016 Campi Alto suffered a new strong earthquake and the case study again suffered major damage despite the seismic strengthening of early 2000.

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

3.1 Structural unit

The unit consists of a simple structural unit of about 60 m³ per floor, on 3 floors, two of which are basements, and a barrel-vaulted floor on the ground floor (Figure 3). The building consists of load-bearing compact limestone masonry, of the “Roughly cut stone masonry (even irregularly shaped) with good texture”, according to the definition in circular no.7 of 21-01.2019 of [10], with timber floor and roof. It is noted here that the building in the past has been located at the end of a series of houses arranged in a row along one of the many contour lines that characterize the steeply sloping territory of Campi Alto, and now all of them were absent and collapsed in past times.

The earthquakes that hit Campi di Norcia along history are many, but a part of the building has been able to resist and at the end of the twentieth century. Two buttresses of different size are present in the South-East corner (Figure 4), while the other corner of the facade features a good connection between orthogonal walls. The buttresses probably served to stabilize a wall originally part of the adjacent structural unit, which no longer exists. The building, before the restoration presented iron tie rods in the upstream-valley direction and one parallel to the façade.

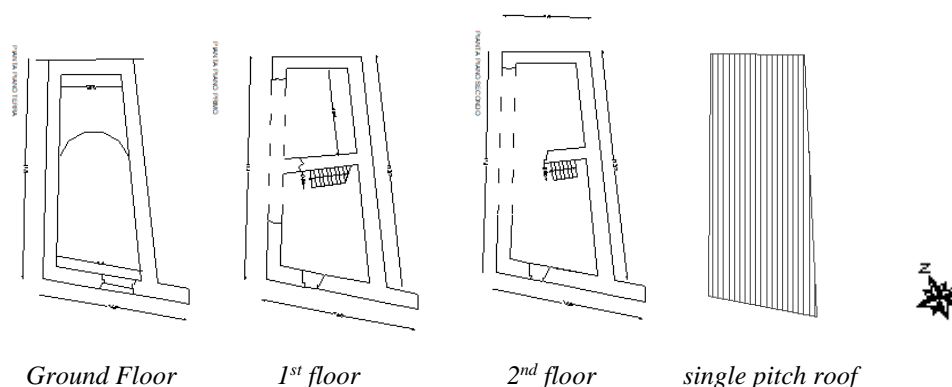


Figure 3: Plans on the selected case study (dashed lines for collapsed masonry portions after 1997 earthquake).

3.2 Earthquake damages

After the 1997 earthquake, it appeared without roofing and with a large part of the masonry at the top collapsed, some diagonal cracks and vegetation inside, therefore floors certainly partially collapsed (Figure 4a). In the early 2000s, a structural consolidation intervention was undertaken that brought the building back to being inhabited, but the material transformations were numerous (Figure 4b). Due to the 2016 earthquake, the municipal archives, necessary to understand the exact type of structural interventions carried out, cannot be consulted. However, a consolidation of the ground floor with the preservation of the masonry barrel vault can be recognized, but with an additional r.c. floor above it and the consolidation of the external stone masonry lief with and additional new one made with clay block masonry inside. The earthquake of 26th and 30th October 2016 seriously damaged it again, highlighting the new vulnerabilities of the intervention, perhaps also linked to the type of intervention performed (Figure 4c). The renovated part above the barrel-vaulted ground floor is rotated rigidly, destroying the ground corners of the façade and only the lower part of the façade has overturned out-of-plane.



Figure 4: Photos of the case study: a) after 1997 earthquake b) after the restoration in 2000s c) after the earthquake in 2016.

4 RESULTS

The analyses carried out two simulations: 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 then to verify the result in the light of the damage recorded. The same investigation will then be done for the building repaired after 1997 (with the addition of modern brickwork within the two upper floors and the insertion of reinforced concrete floors) and damaged again by the 2016 earthquake. The aim is to investigate the ability of the expeditive method to assess the probable loss of performance associated with recorded levels of PGA.

4.1 Fragility curves

Following the procedure described above, the fragility curves were then constructed for each building describing the probability of passing certain thresholds of loss of the SF_{VG} safety factor

as a function of the varying PGA (Figure 5). The acceleration interval chosen is between 0.036 ag/g and 0.28 ag/g as it is representative of the accelerations of 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 the previous paragraphs using the cumulative distribution function $F_{sf}(SF, a^*)$.

Table 1: Safety factor SF_{VG} for different values of PGA and the adopted parameter for gamma distribution.

SF_{VG}	Gamma distribution					
	70%	50%	30%	10%	α	β
PGA(g)	0.117	0.129	0.167	0.215	7.8309	0.0185

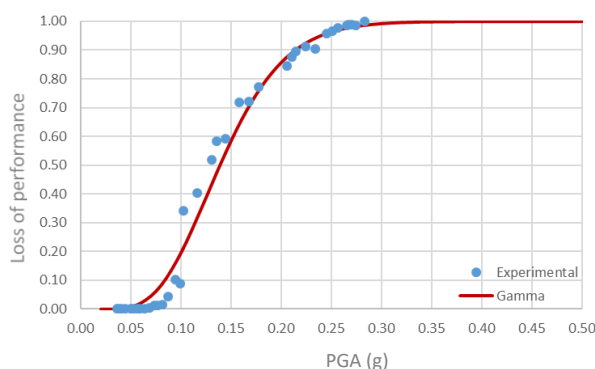


Figure 5: Fragility curve of the probability of reaching a value $SF_{VG} \leq SF_{VG}^*$ (for $SF_{VG}^* = 32.5\%$, Soil Category A, Topography T3).

4.2 Performance loss thresholds

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. [18].

The range of accelerations and the step of analysis are the same of the previous section: 0.06-0.28ag/g and step of 0.02 ag/g. The values of the SF_{VG} recorded for each interval are modelled with a normal probability distribution. The construction of the experimental fragility curves is obtained as presented in the previous paragraphs using the cumulative distribution function $F_{sf}(SF, a^*)$.

It was considered that significant limit thresholds for loss of the safety factor SF_{VG} could be:

$$\overline{sf} = SF_{VG} = 20\%; \overline{sf} = SF_{VG} = 40\%; \overline{sf} = SF_{VG} = 60\%. \quad (4)$$

In Figure 6 are reported the experimental fragility curves defined on 5 intervals: (0.1-0.14]; (0.14-0.18]; (0.18-0.22]; (0.22-0.26]; (0.26-0.30] 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.

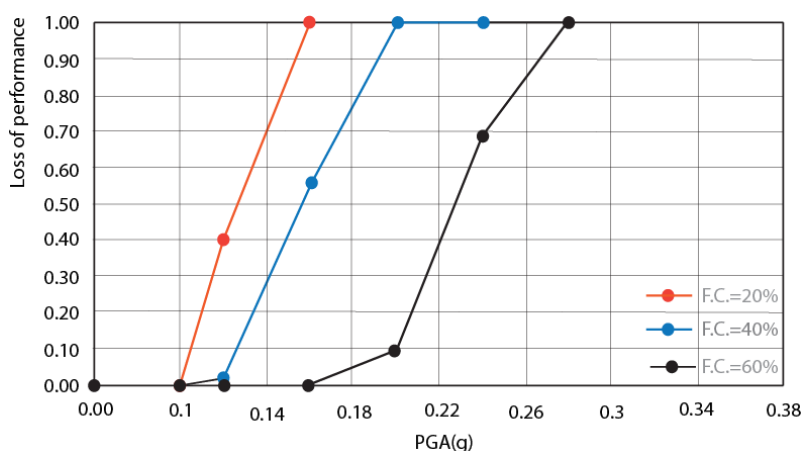


Figure 6: Experimental frailty curves describing the probability of loss of performance, evaluated in terms of SF_{VG} , for different thresholds of possible loss (Soil Category A, Topography T3).

4.2 Trilinear vulnerability curves

The method proposed in [11,21] is applied in the selected case study. The vulnerability index is calculated as a weighted sum of the numerical values expressing the ‘seismic quality’ of structural and non-structural elements which play a significant role in the seismic response of the structure.

The obtained vulnerability index is computed for two cases:

- a) Pre 1997 seismic event,
- b) Pre 2016 seismic event.

The obtaining parameters based on the data collected with vulnerability index survey form are reported in **Table 2**.

Table 2: Vulnerability Index VI global parameter.

	Damage onset PGA y_i	Collapse PGA y_c	Vulnerability index V
Pre 1997 earthquake	0.037	0.325	33.99
Pre 2016 earthquake	0.0423	0.379	25.85

These data are reported in Figure 7 in terms of two graphs expressing the damage in function of recorder PGA. About the situation pre-earthquake of 1997 the graphic 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 improves the vulnerability index of the building by increasing the collapse PGA to 0.379 with $V=25.85$.

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. However, if we compare the two graphs, we note that if there had been no improvements, the damage, the building would have suffered, would have been 0.9.

The computed vulnerability of the structure before the 1997 and before 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 Figure 7 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. However, the damage recorded is much higher and is close to collapse almost as if maintenance had not been performed. This suggests that the interventions carried out, although of an ameliorative nature of the vulnerability, were incompatible with the type and materials of the original construction.

This raises in an important way the problem of the evaluation of the new consolidation techniques for the protection of the historical heritage, as well as now finding a solution to repair it again, without demolishing it.

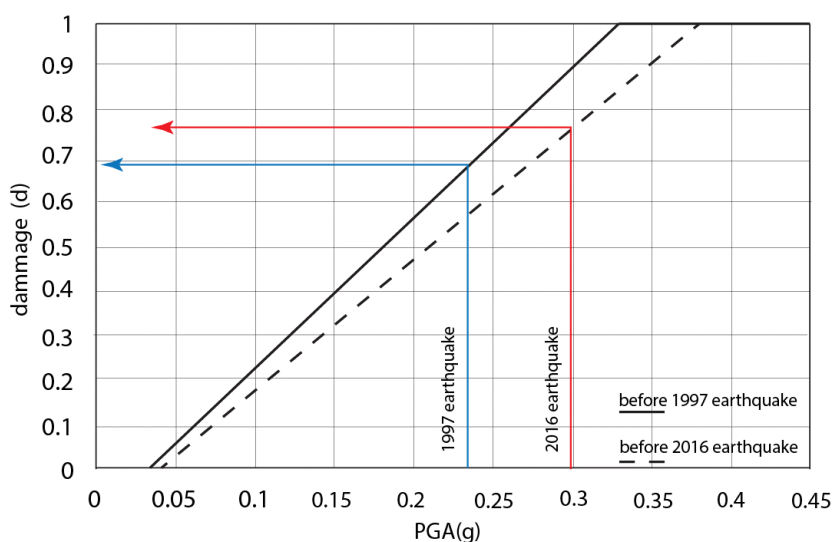


Figure 7: Damage degree as a function of peak-ground-acceleration before 1997 and 2016 earthquake Following approach [7]. Blue arrow: expected damage for an acceleration equal to that of the 1997 earthquake. Red arrow: expected damage for an acceleration equal to that of the 2016 earthquake.

5 CONCLUSIONS

The research developed in the present study aims to define a procedure for estimating the seismic vulnerability of historic residential buildings before a seismic event occurs. The procedure should be characterized by simplicity, reliability and use of the data derived from the current survey forms to be applied to large urban areas (e.g. a historic centre).

The choice of adopting parts of approaches already tested in literature and extending them to a probabilistic reading, made it possible, on the basis of data available in a national database, such as CARTIS, to evaluate the structural safety of masonry structures. The chosen procedure allows to compute a safety factor, SF_{VG} calculated on the basis of the geometric, material and

site characteristics of the buildings examined. It was extended here in a probabilistic framework with the concept of the fragility curves, which helped 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 increases. The procedure was then programmed through VBA and Excel in order to automate all the steps into a simple tool.

The procedure was applied in a case study 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. Furthermore, the results were always compared with trilinear vulnerability curves (a consolidated method proposed by Benedetti and Petrini [11] 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 in the application to apply the developed procedure in large urban areas for seismic vulnerability prediction.

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REFERENCES

- [1] G. Zuccaro, M. Dolce, D. De Gregorio, E. Speranza, C. Moroni, La scheda CARTIS per la caratterizzazione tipologico-strutturale dei comparti urbani costituiti da edifici ordinari. Valutazione dell'esposizione in analisi di rischio sismico, *Proceedings of the GNGTS* (2015).
- [2] R. Sisti, M. Di Ludovico, A. Borri, A. Prota, Damage assessment and the effectiveness of prevention: the response of ordinary unreinforced masonry buildings in Norcia during the Central Italy 2016–2017 seismic sequence, *Bulletin of Earthquake Engineering* 17 (10) (2019) 5609-5629, doi:10.1007/s10518-018-0448-z.
- [3] G. Zuccaro, F.L. Perelli, D. De Gregorio, F. Cacace, Empirical vulnerability curves for Italian masonry buildings: evolution of vulnerability model from the DPM to curves as a function of acceleration, *Bulletin of Earthquake Engineering* 19 (8) (2021) 3077-3097.
- [4] A. Rosti, M. Rota, A. Penna, Damage classification and derivation of damage probability matrices from L'Aquila (2009) post-earthquake survey data, *Bulletin of Earthquake Engineering* 16 (9) (2018) 3687-3720.
- [5] S. Saloustros, L. Pelà, P. Roca, J. Portal, Numerical analysis of structural damage in the church of the Poblet Monastery, *Engineering Failure Analysis* 48 (2015) 41-61, doi:<https://doi.org/10.1016/j.engfailanal.2014.10.015>.
- [6] G. Angjeliu, D. Coronelli, G. Cardani, T. Boothby, Structural assessment of iron tie rods based on numerical modelling and experimental observations in Milan Cathedral, *Engineering Structures* 206 (2020) 109690, doi:<https://doi.org/10.1016/j.engstruct.2019.109690>.
- [7] A. Borri, M. Corradi, G. Castori, A. De Maria, A method for the analysis and classification of historic masonry, *Bulletin of Earthquake Engineering* 13 (9) (2015) 2647-2665.

- [8] A. Borri, A. De Maria, S. Casaglia, The EAL-M method for the seismic classification of the existing masonry buildings: A comparison between different methods and preliminary evaluations of other typologies, *Progett. Sismica* 5 (2014) 11-29.
- [9] A. Borri, A. De Maria, La Classificazione Sismica: Un Protocollo Metodologico Già Operativo Applicabile Agli Edifici Esistenti in Murature, *Ingegno-Web*, 2016.
- [10] NTC, Italian Building Code, adopted with DM 18/01/2018, 2018.
- [11] D. Benedetti, V. Petrini, On seismic vulnerability of masonry buildings: proposal of an evaluation procedure, *L'industria delle Costruzioni* 18 (2) (1984) 66-74.
- [12] A. Singhal, A.S. Kiremidjian, Method for probabilistic evaluation of seismic structural damage, *Journal of structural engineering* 122 (12) (1996) 1459-1467.
- [13] S. Dunn, S. Wilkinson, D. Alderson, H. Fowler, C. Galasso, Fragility curves for assessing the resilience of electricity networks constructed from an extensive fault database, *Natural Hazards Review* 19 (1) (2018) 04017019.
- [14] D. Mina, D. Forcellini, H. Karampour, Analytical fragility curves for assessment of the seismic vulnerability of HP/HT unburied subsea pipelines, *Soil Dynamics and Earthquake Engineering* 137 (2020) 106308.
- [15] A. Flora, G. Perrone, D. Cardone, Evaluating Collapse Fragility Curves for Existing Buildings Retrofitted Using Seismic Isolation, *Applied Sciences* 10 (8) (2020) 2844.
- [16] M. Akhoondi, F. Behnamfar, Seismic fragility curves of steel structures including soil-structure interaction and variation of soil parameters, *Soil Dynamics and Earthquake Engineering* 143 (2021) 106609.
- [17] A. Sandoli, G.P. Lignola, B. Calderoni, A. Prota, Fragility curves for Italian URM buildings based on a hybrid method, *Bulletin of Earthquake Engineering* 19 (12) (2021) 4979-5013.
- [18] E. Garavaglia, A. Anzani, L. Binda, G. Cardani, Fragility curve probabilistic model applied to durability and long term mechanical damage of masonry, *Materials and structures* 41 (4) (2008) 733-749.
- [19] E. Garavaglia, M.R. Valluzzi, S. Perego, C. Tedeschi, Probabilistic damage evolution in masonry strengthened with FRCM subjected to aggressive environment, *Construction and Building Materials* 239 (2020) 117718.
- [20] E. Garavaglia, R. Pavani, L. Sgambi, The Use of Fragility Curves in the Life-Cycle Assessment of Deteriorating Bridge Structures, *Computation* 9 (3) (2021) 25.
- [21] E. Guagenti, V. Petrini, The case of ancient constructions: toward a new damage-intensity law, *Proc. Proc. of the 4th National Conference of Seismic Engineering, Milan*, Vol. 1, 1989, pp. 145-153.
- [22] INGV, Survey Forms, <https://emidius.mi.ingv.it/GNDT2/Strumenti/Schede/Schede.ht>.
- [23] S. Grimaz, F. Meroni, V. Petrini, R. Tomasoni, G. Zonno, Il ruolo dei dati di danneggiamento del terremoto del Friuli, nello studio di modelli di vulnerabilità sismica degli edifici in muratura, *La Scienza ei Terremoti-Analisi e prospettive dall'esperienza del Friuli-1976/1996* (1996) 14-16.
- [24] L. Binda, G. Cardani, A. Saisi, M. Valluzzi, Vulnerability analysis of the historical buildings in seismic area by a multilevel approach, (2006).
- [25] L. Binda, G. Cardani, A. Saisi, M. Valluzzi, M. Munari, C. Modena, Multilevel Approach to the Vulnerability Analysis of Historic Buildings in Seismic Areas Part 1: Detection of Parameters for Vulnerability Analysis through on Site and Laboratory Investigations, *Restoration of Buildings and Monuments* 13 (6) (2007) 413-426.